Visual-Motor Learning in Minimally Invasive Surgery

Alan Daniel White

Submitted in accordance with the requirements for the degree of
Doctor of Medicine

The University of Leeds
Institute of Psychology
Faculty of Medicine and Health

November 2016

The candidate confirms that the work submitted is his 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.

This thesis includes sections from jointly authored publications. The chapters that comprise this work are listed below:

Chapter 2: White, A.D., Skelton, M., Mushtaq, F., Pike, T.W., Mon-Williams, M., Lodge, J.P.A. and Wilkie, R.M., 2015. Inconsistent reporting of minimally invasive surgery errors. The Annals of The Royal College of Surgeons of England, 97(8), pp.608-612.

Chapter 3: Alan D White, Faisal Mushtaq, Oscar Giles, Emily Burns, Megan Wood, Callum Mole, Peter R Culmer, Richard M Wilkie, Mark Mon-Williams, J Peter A Lodge. Laparoscopic motor learning and workspace exploration. The Journal of Surgical Education 2016 Jun 16. pii: S1931-7204(16)30039-3.

Chapter 4: Alan D. White, Faisal Mushtaq, Rachael K. Raw, Oscar T. Giles, Imogen C. Crook, James Tomlinson, Danilo Miskovic, J Peter A Lodge, Richard M. Wilkie & Mark Mon-Williams. To what extent does monitor position influence performance during minimally invasive surgery? The Journal of Surgical Simulation (2016) 3, 1–7.

Chapter 5: White AD, Giles O, Sutherland RJ, Ziff O, Mon-Williams M, Wilkie RM, Lodge JP. Minimally invasive surgery training using multiple port sites to improve performance. Surgical Endoscopy. 2014 Apr;28(4):1188-93.

Acknowledgements

I would like to thank my supervisors, Professor JPA. Lodge, Professor Mark Mon-Williams and Dr Richard Wilkie along with my (unofficial supervisor) Dr Faisal Mushtaq for all their help, advice and most importantly patience in guiding me through my research.

To the wonderful group of research assistants, undergraduate and post graduate students that I have had the fortune to work with over the past five years; Oscar Giles, Rachel Raw, Oliver Ziff, Rebekah Sutherland, Megan Skelton, Emily Burns, Callum Mole, Megan Wood, Imogen Crook, Flora Rees and Ella James-Brabham. Without your help I would have been lost.

I would also like to thank the Leeds Teaching Hospitals Charitable Foundation and the Wellcome Trust for their contributions to funding this research.

To my long-suffering wife, my parents and my sister for their support and encouragement, I am eternally grateful.

Abstract

The purpose of this thesis was to develop an in-depth understanding of motor control in surgery. This was achieved by applying current theories of sensorimotor learning and developing a novel experimental approach. A survey of expert opinion and a review of the existing literature identified several issues related to human performance and MIS. The approach of this thesis combined existing surgical training tools with state-of-the-art technology and adapted rigorous experimental psychology techniques (grounded in the principles of sensorimotor learning) within a controlled laboratory environment. Existing technology was incorporated into surgical scenarios via the Kinematic Assessment Tool - an experimentally validated, powerful and portable system capable of providing accurate and repeatable measures of visual-motor performance. The Kinematic Assessment Tool (KAT) was first established as an appropriate means of assessing visual-motor performance, subsequently the KAT was assessed as valid when assessing MIS performance. Following this, the system was used to investigate whether the principles of 'structural learning' could be applied to MIS. The final experiment investigated if there is any benefit of a standardised, repeatable laparoscopic warm-up to MIS performance. These experiments demonstrated that the KAT system combined with other existing technologies, can be used to investigate visual-motor performance. The results suggested that learning the control dynamics of the surgical instruments and variability in training is beneficial when presented with novel but similar tasks. These findings are consistent with structural learning theory. This thesis should inform current thinking on MIS training and performance and the future development of simulators with more emphasis on introducing variability within tasks during training. Further investigation of the role of structural learning in MIS is required.

Contents

List of Tables

List of Figures

Abbreviations

ANOVA: Analysis of variance

ASGBI: Association of Surgeons of Great Britain and Ireland

CNS: Central Nervous System

CO_2: Carbon Dioxide

EWTD: European Working Time Directive

GB: Gallbladder

HPB: Hepato-pancreatic-biliary

KAT: Kinematic Assessment Tool

LAP-KAT: Laparoscopic Kinematic Assessment Tool

LC: Laparoscopic Cholecystectomy

LGI: Lower Gastrointestinal

LIMIT Suite: Leeds Institute for Minimally Invasive Therapy

LS: Laparoscopic Surgery

MIS: Minimally Invasive Surgery

MIST-VR: Minimally Invasive Surgical Trainer - Virtual Reality

MT: Mean Movement Time

NJ: Normalised Jerk

NHS: National Health Service

NICE: National Institute for Health and Clinical Excellence

NOTES: Natural Orifice Transluminal Endoscopic Surgery

NPSA: National Patient Safety Association

PL: Path Length

RAS: Robotic Assisted Surgery

RCS: Royal College of Surgeons

SACF: Speed Accuracy Composite Function

SILS: Single-port Laparoscopic Surgery

SJUH: St. James's University Hospital

SL: Structural Learning

UGI: Upper Gastrointestinal

VR: Virtual Reality

2D/3D: Two/Three dimensional

1. Introduction

1.1. Background

Patient safety is the foundation of good healthcare (1), however, ‘to err is human’ (2). The Harvard Medical Practice Study showed that 3.7% of hospitalisations lead to ‘adverse events’ (i.e. injuries caused by medical professionals) (3). These errors in healthcare can lead to delayed or prolonged medical care and patients may suffer unnecessary pain and/or be rendered disabled (4). An analysis of malpractice claims in the USA showed that the majority of errors in surgery were actually due to technical errors during routine procedures performed by experienced surgeons. It was concluded that surgical safety research should therefore focus on improving decision-making and performance in routine operations for complex patients and difficult circumstances (5).

The issue of surgical performance has become particularly relevant with the advent of new surgical techniques that offer great advantages to the patient but that require an incredibly high level of visual-motor skill from the surgeon. One example of a new beneficial technique is Minimally Invasive Surgery (MIS). Minimally invasive surgeries, such as laparoscopic (‘keyhole’) surgery (LS) and robotic assisted surgery (RAS) are recommended by the National Institute for Clinical and Health Excellence (NICE) for many procedures. For example, 57,000 laparoscopic cholecystectomies were performed in the UK in 2012 (6). Also, MIS is particularly beneficial in cases of upper and lower gastrointestinal (UGI/LGI) cancers and bariatric surgery as MIS is associated with reduced pain, shorter hospital stays and a decreased risk of operative and 30-day mortality (7). However, MIS has inherent risks. The working environment created during MIS imposes important changes on normal perceptual-motor organization. MIS limits and/or transforms the visual information and haptic information (touch and kinaesthetic sense) that is used to guide skilled movements during surgery. In most laparoscopic surgery in the UK, the surgeon will see a 2D representation on a monitor of the 3D abdominal cavity of the patient resulting in loss of depth perception for the surgeon. The vast majority of MIS in the UK is performed in this manner. Additionally, the surgeon is unable to directly manipulate tissue and uses instruments that tend to impair dexterity and tactile sensation which increases the risk of inadvertent injury to the patient.

Despite these difficulties, the number of major catastrophic disasters in MIS is remarkably low. Anecdotal evidence suggests that many operations have errors that can be described as a ‘near miss’: where the procedure was conducted in a sub-optimal manner (owing to human error) but the errors did not result in a catastrophe (i.e. significant morbidity or mortality). One study suggested a mean of four consequential errors per surgical procedure (8). Thus, sub-optimal performance may occur on a reasonably regular basis, and would likely carry considerable cost. For instance, remedial work to correct errors will prolong the time spent by skilled staff on a single procedure with immediate financial impact on the department/trust/NHS. The need to keep a patient under anaesthesia for a longer duration might have a number of covert adverse consequences on the patient’s ultimate outcome. For example, prolonged anaesthesia time has been shown to have a deleterious effect on a patient’s later cognitive ability and the speed with which they recover from the operation (9).

The possibility of surgical error may also be a factor that hinders wider uptake of MIS. Minimally invasive techniques were introduced into abdominal surgery in the late 1980s (10) and promised to revolutionise surgical practice. This has been the case for technically less demanding procedures, such as cholecystectomy and appendicectomy, yet the clinical uptake has been slow for more complex procedures (such as those involving visceral resection, particularly in cancer surgery) in spite of the documented patient benefits. Recent advances in MIS have shown significant patient benefits and, in 2006, NICE recommended laparoscopic resection as an alternative to open resection for colorectal cancer (11). However, in 2004/5 only 5% of colorectal cancers were resected laparoscopically, rising to 30% in 2011 and 40% in 2012 according to the National Training Programme for Laparoscopic Colorectal Surgery (http://lapco.nhs.uk/). This slow uptake of new surgical technologies and its detrimental effects on NHS patients has been highlighted in a Royal College of Surgeons (RCS) report "From theory to theatre: Overcoming barriers to innovation in surgery", which calls for a greater proportion of national funding for surgical research (12).

To improve MIS performance we need to understand how surgical knowledge and skills are acquired and then put into practice. Primarily, current senior surgeons learnt open surgical techniques and then transferred their knowledge and skills to MIS, whilst subsequent generations of surgeons are now learning their operative skills almost exclusively laparoscopically. Thus, the visual-motor learning process of new surgeons may be entirely different to those providing their training. Changes in the delivery of training, structure of the NHS and on-going developments in MIS (for example natural orifice transluminal endoscopic surgery aka NOTES) necessitates a re-appraisal in the current approach to training surgeons and intra-operative performance to ensure consistently high surgical standards for patients.

1.2. Minimally Invasive Surgery

Minimally invasive surgery (MIS) has revolutionised present day surgery. Previously procedures comprised large incisions into the abdominal cavity, whilst today even the most complex of operations can be performed via several small incisions, summing merely a few centimetres in length. As well as being cosmetically more acceptable, MIS reduces trauma due to wound access following retraction of tissues, can shorten operating times and significantly reduces post-operative hospital stay for patients. The principles of MIS were first reported over a century ago, however, it took the development of video computer chips for the potential of MIS to be realised and applied.

1.2.1. A (Brief) History of Minimally Invasive Surgery

The first effective endoscope was developed in around 1853 by Desormeaux. This instrument was used to examine the urethra, with the bladder being lit using a paraffin lamp. By the 1930's the first laparoscopic procedures, such as diagnostic biopsies, had been reported. As such, laparoscopic surgery initially gained a niche in gynaecological and urological surgery, yet prior to the video era the practicalities of laparoscopic surgery limited its uptake. This is illustrated in Figure 1-1; half of the operating light is taken by the assistant who had to move the laparoscope to keep the 'action' in view. This was very difficult because the surgeon had to move their head synchronously with the assistant. In addition, the rest of the staff in the operating theatre had no idea what was happening.

Many forms of MIS have developed including thoracoscopy (surgery within the thoracic cavity), endoscopy (an endoscope is introduced into a hollow organ such as the stomach or bowel) and arthoscopy (surgery within a joint). However, the primary techniques practiced in hospitals around the world are laparoscopic 'key-hole' surgery (LS) and robotic-assisted surgery (RAS).

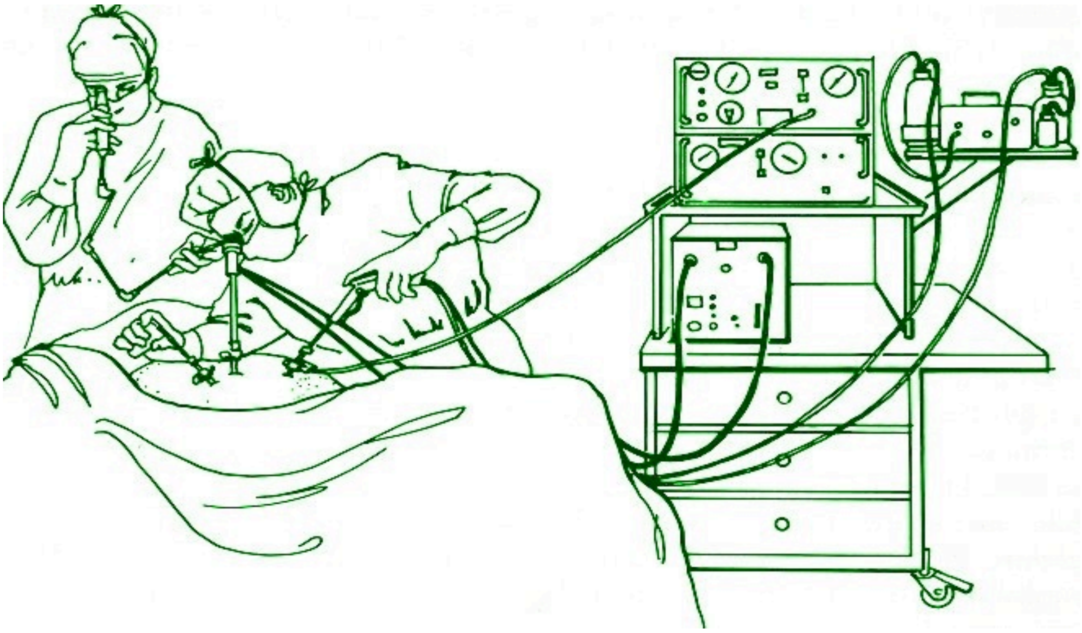


Figure 1-1: Laparoscopic surgery prior to the video era

The advent of the computer chip television camera allowed the surgical image to be projected on a monitor that could be seen by both the surgeon and assistant, whilst enabling the surgeon to use both hands to operate. The first laparoscopic cholecystectomy (removal of the gallbladder) in a human was performed by Muhe and took place in 1985. However, the technique was popularised by Mouret in 1987. This precipitated a rapid acceptance of the technique and MIS has now crossed traditional boundaries into all specialities and disciplines.

1.2.2. Laparoscopic Surgery

In LS the patient is positioned on the operating table and an incision is made in the patient's skin - usually above or below the belly button. A port is inserted either by dissecting through the abdominal wall or under direct vision. A gas supply is attached to fill the abdominal cavity with CO_2, establishing a pneumoperitoneum. The purpose of this is to create the space within the abdomen within which to perform the operation. A laparoscopic camera is inserted through this central port and further ports are inserted under direct vision to allow access for the laparoscopic instruments. Display of the laparoscopic tools and the surgical site are usually via a 2D monitor positioned at the surgeon's discretion. Figure 1-2 depicts a common operating room setup for laparoscopic surgery.

There are several advantages to LS over traditional open surgery. Most operations have a reduced overall wound size resulting in a decrease in rates of wound infection, wound breakdown, and herniation. Patients have reduced post-operative pain and increased mobility resulting in quicker recovery and reduced hospital stay (13). As well as the patient benefits, there are clear financial benefits for health services linked with fewer complications and less time in hospital (13).

One of the issues for the surgical trainee is that the procedures themselves are often complex to perform. In contrast to open surgery, LS creates a variety of constraints on the surgeon, such as restricted movement, compromised dexterity, degradation or loss of haptic feedback, reduced visual depth perception, amplification of hand tremor and the fulcrum effect (where the hand needs to move in the opposite direction to that in which the tip of the instrument needs to move) (14). These constraints mean that, during MIS, surgeons need to learn new complex and challenging mappings between the visual input and the movement output.

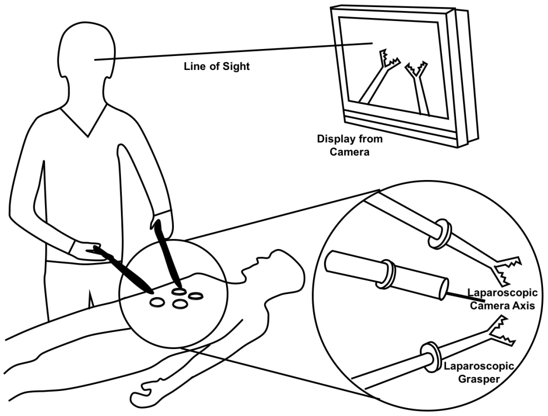


Figure 1-2: A typical operating room set-up for laparoscopic surgery

The position of the camera, assistant and monitor(s) varies with the operation being performed and each surgeon's particular preference. Different laparoscopic cameras with angulation at the tip (0º, 30º and 45º) can assist the surgeon to 'look round corners' i.e. around tissue or an organ that is obscuring the view.

1.2.3. Robotic Assisted Surgery

A surgical robot is a mechanical device that performs automated physical tasks under direct control of the surgeon. The origins of today's RAS systems can be traced to the US army; they became interested in a system to provide medical assistance on the battlefield from a remote location. One of the areas where RAS gained early prominence in mainstream surgery was in urological, specifically in prostate resection for cancer. This type of surgery takes place deep within the pelvis where there is little room, making delicate movements difficult and vision can be obscured by larger laparoscopic instruments or an assistant surgeon's hands. However, in recent years surgeons have recognised the advantages and begun to practice RAS in fields such as paediatric surgery, antireflux surgery, cardiac procedures and in obstetrics and gynaecology.

The main commercial system currently in widespread use is the da Vinci system® Figure 1-3. As in LS, the patient is positioned on the operating table, a pneumoperitoneum is established and several ports are inserted into the patient's abdomen. The camera and surgical instruments are inserted through these ports and connected to the robot's 'arms'. The surgeon sits in a console that controls the movements of the instruments and camera using the hands and feet. The console is usually in the same operating room as the patient or in an adjacent room, but procedures could be controlled by an expert surgeon in another hospital, potentially in a different country.

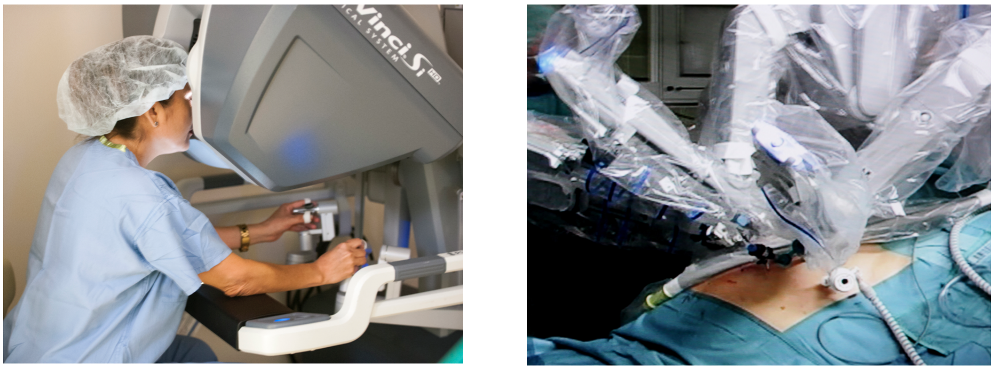


Figure 1-3: RAS Set up: The da Vinci System®; the operator sits in a 'booth' and controls the robotic arms remotely using his/her hands and feet. The robotic 'arms' (seen here on the right) are introduced in a similar manner to ports/instruments during laparoscopic surgery

Robotic-assisted surgery has the potential to overcome several of the limitations of conventional LS. In particular it can offer instrumentation with seven-degrees of freedom, reduction of physiological tremor and elimination of the fulcrum effect. It allows the surgeon to sit in a comfortable ergonomic position, and offers 3D visualization (15). However, RAS systems are very expensive with start-up costs such as the robotic system itself and associated training for theatre staff. They may also require additional staff to operate the system, have limited or no haptic feedback and are currently of unproven patient benefit (16).

1.2.4. Surgical Training

The surgical learning mantra of 'see one, do one, teach one' has existed for generations (11). A trainee will observe a proficient trainer completing the operation, then he/she will perform the task with decreasing levels of input and supervision (depending on the difficulty of the task) until deemed proficient. The trainee will then perform the task independently and may progress to train others. This traditional teaching method is commonly practised in surgery, however, there are a myriad of limitations to this method; chiefly, the increased likelihood of intra-operative errors during the initial training period. Also, the difficulties associated with surgical training are exacerbated by the costs of clinical training, constantly evolving innovations, reduced training time, the requirements of high-quality service provision and increasing awareness of patient safety requirements (11). Centralisation of services from district hospitals to large, specialist, teaching hospitals, in response to work demonstrating better patient outcomes in high-volume centres has further reduced training opportunities over the last decade (11,17). The RCS estimates that training time prior to becoming a consultant has decreased from 30,000 hours in 1998 to 8,000 hours for current trainees (18). This is reflected in studies which have shown that only 34% of current trainees feel their trainer has adequately prepared them to become a consultant (19). The move towards competency-based assessment of surgical trainees has shifted focus from the number of hours of training to the quality of those training hours (11). As such, the concept of surgical training has evolved from ad-hoc ‘on-the job-training’ to safe, standard and reproducible simulated environments to shift learning away from operating rooms and patients (11). Simulated surgery allows the trainee prolonged and/or repetitive practice in a controlled environment in which to hone their skills with no risk to the patient.

There are several components to a successful operation and many facets that contribute towards an expert surgeon. These include knowledge of the operation and the steps required to complete it successfully, an understanding of the surrounding anatomy and its possible variants together with the ability to plan ahead and communicate with other members of the team. Underlying all the procedural knowledge of carrying out a successful operation is ensuring the surgeon has the requisite visual-motor skills to become adept at very intricate and difficult procedures. It has been suggested that surgery is 75% decision-making and 25% dexterity (20), however, this statement is based upon expert opinion and not empirical evidence and is of questionable logic. It does, however, highlight the central components of successful surgery. The UK National Patient Safety Organisation review of the Reporting and Learning System demonstrated that whilst the proportion of complications resulting in patient harm during surgery were low (3.4%), of these, 60% were due to surgical technique (21). Reduction in training opportunities, coupled with a paradigm shift towards MIS, has led to a deficit in the understanding of how to train the next generation of surgeons. Whilst it is anticipated that simulation (VR or otherwise) will play an important role in filling the training gap resulting from reduced training hours, the current challenge is how to deliver high-quality training to produce surgeons of consistent quality down the years. Motor performance and visual-motor learning is only one element of this, however, in order to maximise performance (simulated or otherwise) a better understanding of how to train surgeons in MIS is needed.

1.2.5. MIS Training

As stated previously, current senior surgeons primarily learnt open surgical techniques and then transferred their knowledge and skills to MIS whereas the current and future generations of surgeons will learn their operative skills almost exclusively laparoscopically. This, in combination with more recent developments in the field of MIS such as robotic surgery, natural orifice transluminal endoscopic surgery (NOTES) and single-port laparoscopic surgery as well as on-going technological advances such as 3D displays, necessitates a re-appraisal in the current approach to training the surgeons of the future to maximise every scenario, be it ‘simulated’ or ‘real-life’. This will increase the likelihood of developing the best visual-motor skills possible, with the ultimate aim of delivering high standards of intra-operative performance. There are a variety of training devices that exist, a representative selection of which are detailed below.

1.2.5.1. Box Trainers

The most basic box trainer consists of an opaque box to approximate the abdominal cavity with holes or slits on the anterior surface through which MIS instruments can be introduced (22). A laparoscopic camera can be introduced via another slit (or ‘port-site’) and held by a flexible arm or a camera, such as a webcam, connected to a computer monitor or laptop (22). These can even be homemade. However, numerous more technologically advanced variations are available such as the Ethicon™ laparoscopic trainers, laparoscopic stacks, the laprotrain™ box trainer and I-sim™. Actual MIS instruments are used to perform tasks when training with box simulators, such as laparoscopic graspers, needle holders and ‘real’ needle and thread – as opposed to simulated VR sutures - which is the real strength of these systems (22). There are several variations available on the market and in dedicated simulation centres, described below.

Figure 1-4: An Ethicon™ laparoscopic box trainer with 6 port-sites and two laparoscopic instruments in-situ.

The Ethicon™ trainer has been developed to be portable and easy to set-up. It comes with an 'activity-set' such as pegs and bands etc. for practicing tasks. No assistant is required and these systems are relatively low cost. Trainees can practice tasks such as transfer of objects from one hand to another, laparoscopic cutting and knot tying.

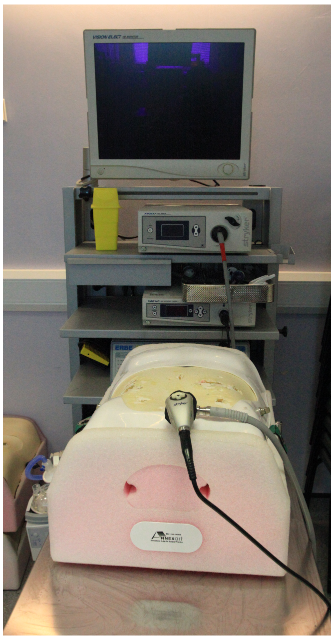


Figure 1-5: An example of a Laparoscopic Stack system. A box-trainer can be seen in the foreground with a laparoscopic camera. On the shelving unit in the background the display monitor and light source are seen.

This is essentially a stack system, identical to those used in the operating theatre, combined with a box trainer. It consists of a laparoscopic camera connected to an adjustable monitor and a light source. The camera is introduced to a box trainer via ‘port-sites’. Adjustable camera stands are available to ‘hold’ the camera in a fixed position so trainees can practice on their own and don’t require an assistant to manipulate the image for them.

Due to their size and cost, the laparosocopic stacks systems tend to only be available in dedicated training centres. Several systems exist so that educational courses can be run to train several individuals at a time. Trainees can learn about operating the stack itself (light, camera etc), as would be expected in an operating theatre, and practice tasks such as cutting and suturing. Dedicated training centres mean these skills can be practised using fresh specimens such as animal tissue (which requires health and safety approval and dedicated storage facilities) or procedure specific models (such as cholecystectomy or appendicectomy) which can be bought in bulk for specific training courses to reduce expenses which may be prohibitive to the individual trainee. However, for this, trainees require a dedicated centre with staff who can provide such models with the associated facilities and licenses. Often these are only accessible during ‘working hours’ and demand can be high with only a limited number of stacks per centre.

During the course of surgical training, trainees move between different hospitals often with no dedicated training facilities. In this scenario a portable system, such as the Laprotrain (see Figure 1-6), offers several advantages to such a trainee. and allows practice outside of working hours, away from the hospital at the trainee’s leisure..

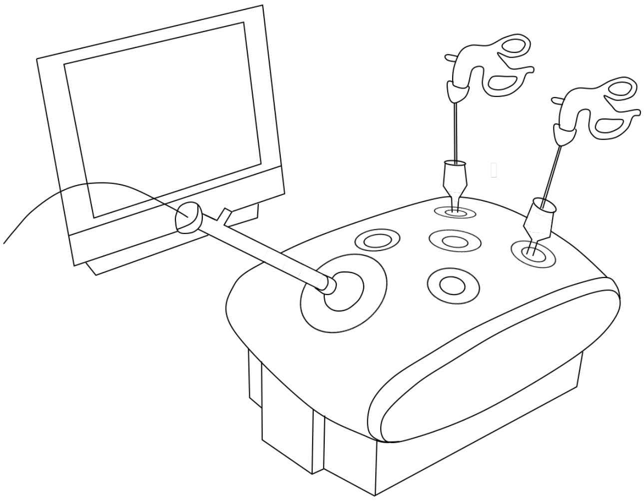


Figure 1-6: A diagrammatic representation of the Laprotrain™ system. A monitor, camera and two laparoscopic instruments are demonstrated.

This system incorporates an integrated camera to enable camera navigation tasks, is portable, and can link to any television; therefore it does not need an additional laptop/webcam. Possible tasks include cutting, object manipulation and knot tying.

1.2.5.2. Virtual Reality Trainers

The first VR surgical simulator was the MIST-VR (Minimally Invasive Surgical Trainer; Virtual Reality) which comprises of a frame holding two laparoscopic instruments which are electronically linked to a PC. It constructs a VR environment that shows the position and movements of the instruments in real time. It comprises of a number of reaching, grasping and manipulating tasks of three levels of difficulty (23).

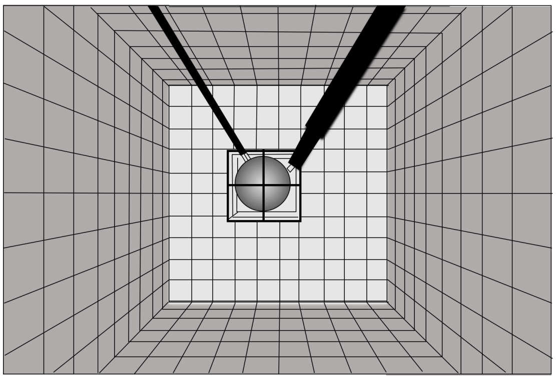


Figure 1-7: A typical display of a laparoscopic task on the MIST-VR Simulator System

Subsequently, several VR MIS simulators have entered the market with varying degrees of visual and haptic fidelity. The more modern VR systems are designed to have more of the ‘look and feel’ of MIS compared to the MIST-VR. One example in common usage is the Simbionix LAP Mentor™.

The current generation of VR systems have a number of tasks and procedures for trainees to use. For example there are step-by-step laparoscopic suturing modules with or without guidance to teach intracorporeal suturing and knotting techniques for all fields of laparoscopic surgery. Other examples include basic suturing skills such as needle loading, needle insertion, knot tying, interrupted and continuous suture. Advanced tasks include practicing ‘backhand’ technique and suturing in difficult suture line angles. The LAP Mentor™ also has full procedures in general surgery (such as gastric bypass, cholecystectomy and incisional hernia repair) as well as urological procedures (e.g. nephrectomy) and gynaecological operations (e.g. salpingostomy, salpingectomy and salpingo-oophorectomy). Most VR simulators calculate a series of pre-determined metrics to assess performance. The metrics calculated by LAP Mentor™ are shown below (Table 1-1).

Figure 1-8: The Simbionix LAP Mentor ™ VR system.

The Simbionix LAP Mentor ™ is a laparoscopic surgical virtual reality simulator. It has a large variety of laparoscopic tasks, such as basic familiarisation tasks, aimed at improving orientation, eye hand coordination and manual skills; for example, passing objects from hand to hand, use of electro-cautery and pattern cutting

Table 1-1: LAP Mentor™ Outcome Metrics

Metrics related to time and economy of movements	Metrics related to safety and electrosurgical dissection	Metrics related to safety/errors of performance
Total Procedure Time	Total Cautery Time	Number of organ perforations
Number of movements right/left instrument	Inappropriate Cautery Time	Number of non-cauterised bleeding
Total path or right/left instrument	Cautery Efficiency	Number of possible damage vital structures
Average speed right/left instrument	Safe cautery (%)	

1.2.6. Advantages and Disadvantages of Box Trainer Systems

The box trainer system is an established method of laparoscopic surgical training and laparoscopic stack systems, such as those described above, are used in teaching courses in the UK and have been used as methods of assessments for entry into higher surgical training. Limited evidence exists to demonstrate the effectiveness of box trainers in improving surgical performance. The vast majority of studies focus on VR simulation as these have received the majority of interest within the surgical literature. In these studies, box simulators are often used in parallel with no training as a ‘control’ group (these studies are discussed in section 1.2.7: Box Trainers vs VR Simulators. However, box trainer systems have been shown to improve operative performance when incorporated within a structured surgical training curriculum (24) and have been shown to decrease the learning curve in laparoscopic suturing (25).

In these systems, participants use real laparoscopic instruments (needle holders, graspers etc.) identical to those used in actual MIS. Various targets are manipulated within the box and images transferred via the camera to a display monitor (typically a monitor screen) in a system comparable to those used in operating theatres (22). Therefore, the required visual motor transformation from 2D representation on screen to a 3D working environment is also identical to that which is encountered in MIS. In addition, the haptic feedback to the trainee and the image displayed on the monitor from the camera is real (i.e. not a simulated approximation). Haptic feedback is limited in MIS due to the use of surgical instrument and this is replicated when using a box trainer. This means that the box trainer mimics several of the characteristics of MIS and trainees can learn the visual-motor environment that will be experienced during MIS surgery (haptic feedback, tolerance of instruments, tissues etc.) (22).

Tasks such as stacking sugar cubes, threading string through ‘the mint with the hole’ and opening and closing a matchbox, have long been established as methods of teaching laparoscopic manipulation, depth perception and the fulcrum effect. These tasks were first developed in the early days of MI and are easily reproducible (and cheap) compared to the more complicated models, such as appendicectomy and cholecystectomy, which require input from a technician to set up, or in the case of animal models, procure and store the required tissue. However, these tissues may not acurately represent human tissues.

While these simple tasks are accepted practice for basic training, no formal validation of their effectiveness exists. Recent advancements mean that the technology exists to develop an array of tasks with which to train surgeons. However, in comparison with ‘real’ surgery, these systems may lack the face validity offered by other systems (22).

There may be no capacity to practice with standard laparoscopic equipment, such as diathermy and suction/irrigation. In addition, the ability to measure performance is limited to the subjective opinion of the trainee and trainer. Tasks are not standardised and more difficult tasks are harder to reproduce exactly. It is not possible to reliably vary the parameters of the task and it is difficult to vary the complexity of a task and therefore to develop a meaningful experiment to investigate learning paradigms. Box trainers do not directly record performance metrics meaning comparison from one performance to another tends to be subjective.

Dedicated tasks informed by current educational and motor learning knowledge could improve the current training as opposed to relying on methods established years ago based on what was available at the time.

1.2.6.1. Advantages and Disadvantages of VR Simulators

Virtual reality simulators present a true VR environment to the trainee and include a wider range of laparoscopic tasks and procedures that are reproducible at the touch of a button. This is of particular benefit to junior trainees developing an awareness of the laparoscopic environment (for example the fulcrum-effect), learning the steps of a procedure and particularly intracorporeal suturing. Many VR simulators (such as the LAP Mentor™) not only include basic laparoscopic training skills but also have part and full procedure options. Trainees are able to practice the specific steps of an operation (for example forming the pouch for a roux-en-y gastric bypass) or the whole procedure from start to finish.

However, VR simulators incur very high start-up costs. Similar to the laparoscopic stacks, a dedicated training centre is usually required with associated staff costs and limited access. In addition, whilst some VR simulators (e.g. the LAP Mentor™) purport to provide haptic feedback to the trainee, this technology is in its infancy and is limited. One study highlights the benefit of haptic feedback in laparoscopic suturing and demonstrates no benefit of VR training over box trainer training for intra-corporeal suturing (26). Equally, it is not clear how appropriate the forces applied and the tissue properties are to actual tissue. Whilst VR simulators do generate measures of performance, it is not possible to vary specific parameters of a task, resulting in limited meaningful investigation of a trainee’s learning. Whilst there are varying levels of difficulty to each task, investigation is limited to the design of the programmers. As such, it is not possible to manipulate the tasks in order to empirically examine the visual motor learning process in MIS.

1.2.7. Box Trainers vs. VR Simulators

A Cochrane meta-analysis compared VR training vs. other forms of training (e.g. video training, standard training) vs. no training (27). Outcomes measured were time taken, accuracy and incidence of errors. They showed that, in novice trainees, VR training improved performance in all three domains, although most of the trials included were at high risk of bias. For example the majority of studies did not utilise random task sequence generation or participant sequence allocations for their tasks (selection bias). No studies were blinded for participants, personnel and outcome assessment (performance and detection bias), although this is pragmatically very challenging considering the nature of the investigations. Several studies had incomplete data (attritional bias) and evidence of selective reporting such as not all of a trial's pre-defined primary outcomes reported (reporting bias). In the majority of studies any conflicts of interest of the investigating team or trial funder such as virtual reality trainer manufacturer were not explicitly clear (vested interest bias).

Gallagher et al group and others have shown VR training improves operative performance (24,28,29). However, there is limited evidence comparing methods of simulator training. Nagendran et al concluded that VR training improves operative performance including decreased operating time compared with no training or with box-trainer training (27). However, the meta-analysis only included eight trials in total, encompassing 109 participants, and only two trials compared VR training to box-trainer training (30,31). Again, most of the trials were at high-risk of bias due to flaws in study design (24). Diesen et al have demonstrated that simulator training improves operative performance in trainees with no prior surgical experience, with no difference between box trainers and VR simulators. Similar results were also described by Korndorffer et al (32,33).

Box trainers are established training tools. A variety exist which are relatively low-cost and are, to varying extents, portable. Actual laparoscopic instruments are used and the same visual-motor transformation required in MIS is learnt. They are limited by the variety of tasks that can be practiced, the measures that can be recorded and the degree to which MIS can be simulated (e.g. use of tools such as diathermy). Many of these limitations are addressed by VR simulators.

1.3. Evidence for the Use of Simulators in MIS Training

Gallagher and Satava (2002) demonstrated that virtual reality simulators can be used to evaluate the psychomotor skills necessary for laparoscopic surgery by demonstrating superior performance (time, error, economy of movements and consistency) in experienced MIS surgeons compared to inexperienced and novice surgeons (23). This study also demonstrated the capacity of inexperienced surgeons and novices to adapt to the task(s) and improve with practice. Exploiting the phenomenon of the learning curve by better understanding how novices develop into experts is key to maximising learning opportunities for surgical trainees and developing strategies to train the next generation of surgeons. However, studies regarding the relationship between visual-motor ability and surgical performance are limited. A systematic review of predictors of surgical performance identified a number of relevant studies (34). These studies and their outcomes are summarised in Appendix .

Two of the studies suggested that visual-motor abilities may be good predictors of surgical performance (35,36) whilst three others found that motor performance correlated with the amount of time required training on the VR trainer to reach a pre-set level of proficiency (37–39). One study demonstrated a negative correlation between assessment of manual dexterity and ability to perform a bowel anastomosis (40). Schijven et al (2004) found no predictive value between performance on the Xitact simulator, surgical simulator and dexterity (41) and Wanzel et al (2003) found only limited correlation between dexterity and performance on a dental bench top model (42). These studies use a variety of methodologies to measure baseline and outcome visual-motor performance, ranging from pegboard, reaction time and finger tapping tests through to simulated surgical procedures in VR or on fresh porcine bowel. In general, the metrics used have been crude so do not really improve understanding of the relationship between visual-motor performance and surgical ability.

Whilst the relationship between surgical performance and underlying visual-motor skills is clearly important, there is also the question of the amount and type of training required to ensure a surgeon is performing without error. Reductions in surgical training time have led to a desire for optimised training regimes. Training and assessment in MIS has largely concentrated on the use of virtual reality simulators such as the MIST-VR (Minimally Invasive Surgical Trainer; Virtual Reality). However, VR simulators have high start-up costs and there is considerable debate as to how to incorporate simulation into the surgical curriculum. This is compounded by reduced NHS finances, increasing trainee workloads and the resistance of some trainers and trainees to engage in simulation training. In addition, the geographic layout of hospitals and surgical simulators in the UK compounds the difficulties of delivering an effective simulator curriculum. For example, The Yorkshire and the Humber School of Surgery has trainees spread across 21 hospitals with 7 laparoscopic VR simulators split between 7 different centres.

The MIST-VR system has been used to demonstrate differences between novice, intermediate and experienced surgeons in the time taken to complete tasks, economy of movements and use of the diathermy tool (23). Using the MIST-VR and box trainers to test experienced surgeons, these authors have demonstrated it is possible to detect basic laparoscopic psychomotor skills deficits, with the performance of between 2% and 12% of surgeons falling more than two standard deviations away from the mean (43). They have also shown that training on the MIST-VR helps laparoscopic novices adapt to the fulcrum effect faster compared to two simple laparoscopic maze tasks (44) and that structured training using box trainers and the MIST-VR improved performance of novices when tying an intracorporeal knot (measure: time and errors) (45). Training on the MIST-VR to a pre-determined level versus no training in 16 surgical trainees significantly improved the operative performance of laparoscopic cholecystectomy (28), a finding corroborated by several subsequent reviews (46–49) Whilst others have demonstrated that ‘warm-up’ on a VR simulator prior to surgery improves operative performance (50).

Gallagher’s group have suggested that hand tracking and measurement of error are valuable measures of motor performance (43,51) whilst Mason et al’s (2012) review of several methods of assessing laparoscopic skill concluded that motion analysis was a valid tool for assessing MIS skill and that time taken, path length and number of hand movements were valid parameters (20).

From the evidence available it seems that simulation based training can be used to assess and train surgeons and transfers to the operating room, however, there are some limitations to the evidence. Whilst there is a great deal of interest in simulation training, the practicalities and expense of such studies results in a relatively small evidence base and sample sizes within studies are often small (typically n less than 20). The majority of studies fail to blind the assessors to training groups, usually due to the practicalities of the study design. There are a variety of simulation methods used as different groups have access to different VR simulators and skill laboratories. There is also considerable variation in study design, endpoints and parameters measured. A good example of this is the use of performance time as a measure, which is recorded in the majority of studies. Although time taken is a recognized feature of expert performance, this does not give any indication of the quality of the task performed, and caution should be taken when interpreting this measure without any additional objective quality data (46). Whilst some studies test several variables over a number of procedures or assessments such as number of errors, error scores, time to a particular point of the procedure, ‘success rate’ and completion of task (yes/no), without a strict hypothesis driven basis this can increase the likelihood of type I error (46).

1.4. Principles of Visual-Motor Learning

In order to understand how to accelerate skill acquisition in laparoscopic surgery, it is necessary to consider the fundamental principles of motor learning. The processes involved in learning a new motor skill, such as a laparoscopic cholecsyectomy (removal of the gall bladder) (LC), can be broken down into a number of interacting components; (1) gathering of task relevant sensory information (2) learning the key features of the task (3) developing predictive and reactive control mechanisms that generate appropriate motor commands including compliance controls and (4) learning higher level skills such as anticipating anatomical variance or post-operative consequences of particular actions/decisions (52).

1.4.1. Information Extraction

Skilled performance requires effective and efficient gathering and processing of relevant sensory information (52). Extracting task-relevant sensory information is a highly active and learned process in which we select what sensory information to sample and process from the task and how to extract the information in an efficient manner (53). Tactile sensory information can take into account the properties of external objects, such as laparoscopic instruments, such that the haptic signal is treated as coming from the tool-tip and not the hand – the sensation of ‘feeling’ the tip of a knife or in this case the laparoscopic instrument (52,54).

The crucial element during LC is the identification of the cystic duct and artery. Incorrect identification can result in dire consequences for the patient. Way et al’s analysis of 252 laparoscopic bile duct injuries identified that these were not errors of skill, knowledge, or judgment but primarily in misidentification of the cystic duct (55). The surgeon’s ability to correctly identify these structures is reliant upon his or her knowledge level, previous experience and the visual and tactile information available during the procedure.

1.4.2. Key Features of the Processes of Motor Learning

Learning the relevant key feature of a task is critical to developing a new motor skill. The surgeon must learn the transformation between muscle commands and movement of the instrument, learn how to credit errors to different aspects of the performance and determine how the context, such as size of the patient, affects the task (56). Where a task has similar structural transformations to previously learnt tasks (such as learning to use a laparoscopic diathermy hook once a surgeon is familiar with other laparoscopic instruments such as a grasper) appropriate equations are formed that link the similar actions (56). This occurs in conjunction with learning the particular parameter settings for a given structure or task (such as the mass, weight distribution and sharpness of a particular pair of laparoscopic scissors or the steps of a particular procedure such as a laparoscopic cholecystectomy)(56). Wolpert et al observed that once we have learnt a particular motor skill, such as ice-skating, we can generalise it to a novel task, such as rollerblading. This is achieved by learning the structure and the parameters of the motor task and is particularly relevant when learning tasks on a simulator prior to transfer to 'real-life' (56).

Studies have shown that applying this principle by exposing individuals to a variety of tasks that share a common structure but vary in their parameters can dramatically speed up learning of new tasks . This suggests that the motor system relies on structural learning for skill acquisition (53,57). However, in complex tasks no improvement is seen during initial exposure. This is thought to represent an initial exploratory phase during which the participant establishes basic mapping rules between manual actions and eye-movement commands (58). Thus, when training surgeons in a new laparoscopic procedure, one would expect an initial period of no/slow progress followed by a period of quantifiable improvement and for those with previous laparoscopic experience to develop quicker than those with none and be able to transfer these skills to other forms of MIS. This has been demonstrated in laparoscopic colorectal surgery, robotic surgery and single incision laparoscopic surgery (59–61). In addition several studies have also demonstrated that laparoscopic simulator training provides trainees with skills that transfer to actual surgical procedures (62,63).

1.4.3. Developing Control Mechanisms

Most tasks involve three classes of control that interact to optimise motor performance; predictive control, fast reactive feedback loops and varying the compliance and biomechanical properties of the participant. The purpose of these systems is to alleviate the problems of time delay inherent in sensorimotor feedback loops (56). Each of these systems can undergo learning and practice in conjunction with one-another depending on the task at hand (52,56).

1.4.3.1. Predictive Control

This is used to generate appropriate motor commands to compensate for upcoming and predictable perturbations in anticipation of the task requirements (56). For example, when manipulating the gall bladder to maintain tension across the tissues to aid dissection during a LC, the surgeon anticipates the properties of the gall bladder and applies an appropriate force through the hand and arm down the instrument (52). Prediction is supported by previously learned correlations (called priors). When lifting an object, individuals use prior knowledge about the composition and size of an object to predict it’s properties (52). This method of control also predicts the consequences of motor commands such as the events associated with ‘lift-off’ when picking up an object. If a mismatch occurs, the system interacts with reactive control mechanisms to initiate task-protective corrective actions and updates knowledge of the object to improve future actions (52,56)..

1.4.3.2. Fast Reactive Feedback Loops

Fast reactive feedback loops use sensory inputs to update on-going motor commands (52,56). The fastest of these (such as the mono-synaptic stretch reflex) can rapidly drive motor responses, however, modification of these reflexes, even by extended experience, is limited (56). Studies have shown that modification of longer loop reactive feedback loops (such as those that involve supraspinal mechanisms) can occur in a task-dependent manner and may be tuned by learning (64,65).

1.4.3.3. Biomechanical Control

The third mechanism of control is achieved by varying the compliance and biomechanical properties of the participant and therefore the tools with which they are interacting. For example, by controlling the muscles of the arm, it is possible to vary the stiffness at the tip of an instrument held in the hand. This allows the motor system to exercise control over the response to external perturbations (52).

1.4.3.4. Higher Level Skills

Recent work into motor learning has begun to blur the traditional boundaries between sensorimotor, perceptual and cognitive components of a task, including action selection and decision-making. Studies in explicit cognitive tasks have shown people make suboptimal decisions when faced with a set of options each with an uncertain outcome. However, when confronted with motor variants of the same task people demonstrate near-optimal decisions (52,66) When lifting a weight, if an object looks small and of low mass, the motor and cognitive system will apply to lifting the object accordingly. However, after repeated attempts the motor system will adjust to apply a greater force to the object, however, when lifting weight of equal mass but varying sizes, participants will assign the larger as the heaviest based on visual clues (67).

In MIS, the presence of blood within the visual field causes degradation of the image on the screen. Whilst the visual-motor system might compensate adequately for this in the short term, the cognitive influence may cause the surgeons to respond by being over cautious with their subsequent actions, possibly resulting in them leaving behind tissue which ideally should have been removed.

Decision making ability is one of the most important personality traits required for a competent surgeon. In LS minor mistakes may lead to serious consequences and complications. However, there is little data addressing intra-operative judgments and decision-making.

1.5. The Current Work

This thesis investigates visual-motor performance during MIS. Its purpose was to establish what issues exist currently through review of literature and garnering of expert opinions and then break these issues down to their constituent parts and investigate them in a controlled laboratory environment. A novel approach was developed combining existing surgical training tools with state of the art surgical technology and adapting a rigorous experimental psychology approach rooted in the principles of motor learning.

Part I: Establishing Current Issues in MIS

A survey was developed using expert opinion and a review of existing literature to identify current issues in MIS. It was distributed via the Association of Surgeons of Great Britain and Ireland (ASGBI) which has a membership of over 2000 and a wealth of knowledge and experience in MIS. Using these results several issues were identified, many of which of currently under-reported using conventional reporting methods, which we investigated the fundamental principles of in a controlled laboratory setting.

Part II: Investigating the Role of Constraint when Learning a New MIS-related Task

Results of the survey highlighted technical skills as one of the most important factors in MIS and that trainees are more likely to make an error. This experiment investigated whether it is beneficial to constrain trainee movements when learning a MIS-related task or to allow them to learn the parameters of the task unconstrained.

Part III: Investigating Methods to Optimise Intra-Operative Performance

Variation exists between different operating suites within and between different hospital. As trainee surgeons move between hospitals during their training period they are constantly required to adapt to different environments. Depending on the theatre room and the equipment available the positioning of vital equipment such as the operative display monitor can influence performance. The first experiment of a series of three investigated whether it is possible to positively or negatively influence performance by varying a single factor in the operative set-up. The second experiment investigated whether the principles of structural learning could be applied to MIS. MIS in general and LS in particular involve a series of reach-to-grasp movements. The hypothesis was that variation in learning the structure of MIS task versus no-variation would result in better performance when a novel task was attempted. The third part of the series investigated if there is any benefit of a standardised, repeatable laparoscopic warm-up to MIS performance.

2. Quantifying Non-catastrophic Intra-operative Errors

2.1. Introduction

Humans spend most of their day engaged in skilled behaviours – driving a car, typing on a computer, cooking food etc. These skilled behaviours involve complex motor and cognitive processes and are a testament to the incredible capacity of the human nervous system. Nevertheless, everyone has experienced an ‘off-task-moment’ where movements are clumsy and/or on-line decisions are not as fast or accurate as required. The impact of an ‘off-task-moment’ depends on the behaviour being executed: errors when typing tend to have minimal cost, whereas driving errors can have catastrophic consequences.

While a great deal of research has concentrated on surgical ‘never events’ (serious yet preventable errors), the safety mechanisms within a surgical setting mean that most errors do not result in a cataclysmic outcome (i.e. patient death). Nevertheless, the errors that do occur can still have a high cost to the patient and the NHS and the probability of a cataclysmic outcome must logically become greater as the incidence of ‘near miss’ errors increases.

The Harvard Medical Practice Study showed that 3.7% of hospitalisations lead to ‘adverse events’ (i.e. injuries caused by medical professionals) (3). Errors within a health care setting can lead to delayed or prolonged medical care and patients may suffer unnecessary pain and/or be rendered disabled (see (4) for a review). An analysis of malpractice claims in the USA suggested that the majority of errors in surgery were due to technical errors during routine procedures performed by experienced surgeons. It was concluded that surgical safety research should therefore focus on improving decision-making and performance in routine operations for complex patients and difficult circumstances (5).

The issue of surgical errors has become particularly relevant with the advent of new surgical techniques that offer great advantages to the patient, but require a high level of visual-motor skill from the surgeon. MIS, such as LS and RAS are recommended by NICE for many procedures. For example, MIS is particularly beneficial in cases of UGI and LGI cancers and bariatric surgery as it is associated with reduced pain, shorter hospital stays and a decreased risk of operative and 30-day mortality (68). However, MIS has inherent risks. In contrast to open surgery, MIS creates a variety of constraints on the surgeon, such as restricted movement, compromised dexterity, degradation or loss of haptic feedback, reduced visual depth perception, amplification of hand tremor and the fulcrum effect (14). These constraints mean that, during MIS, surgeons need to learn new complex and challenging mappings between the visual input and the movement output. Minimally invasive surgery limits and/or transforms the visual information and haptic information (touch and kinesthetic sense) that is used to guide skilled movements during surgery. In most LS in the UK, the surgeon will see a 2D representation on a monitor of the 3D abdominal cavity of the patient resulting in loss of depth perception for the surgeon. As the surgeon is unable to manipulate tissue directly, they must use instruments that tend to impair dexterity and tactile sensation while amplifying hand tremor. This increases the risk of inadvertent injury to the patient. Despite these difficulties, the number of major catastrophic disasters in MIS is remarkably low. Nevertheless, It seems probable that many operations have technical errors that can be described as a ‘near miss’, where the procedure was conducted in a sub-optimal manner (owing to human error) but the errors did not result in a catastrophe (i.e. patient death). Based on perceptual-motor performance in other domains (e.g. skilled sportsmen) we might expect errors to occur on a reasonably regular basis (69). There is a large body of evidence suggesting that errors in general are under-reported and this is likely to also be the case for intra-operative errors (2)(70). However, delineating the frequency and magnitude of the problem is the first step in building effective safeguards in the future. Thus, the purpose of this study is to try to quantify the incidence of non-catastrophic intra-operative errors, both subjectively and objectively.

2.2. Methods

An electronic survey was sent via email to all ASGBI members gathering demographic information and their experience over the preceding 12 months of MIS errors, the reporting of such errors and a rating of the important factors affecting error prevalence during MIS. The survey was developed following discussion with several surgeons with considerable experience of MIS. A focus group of surgeons, psychologists and translational research fellows with experience of qualitative research reviewed, assessed and modified several iterations of the survey before the final version was approved. Prior to dissemination a pilot study of 5 surgeons completed the survey. Respondents were assured their responses would be anonymous.

Ethical approval was granted by the University of Leeds School of Psychology Research Ethics Committee (Ethics reference: 13-0152) and conducted in accordance with the 1964 Declaration of Helsinki. All information was gathered anonymously with each respondent given a numeric identifier automatically by the survey software so investigators could not identify any individual respondent.

2.2.1. Important Factors in Surgical Performance

Several factors were identified as potentially influencing the likelihood of an error during MIS surgery from existing frameworks examining technical and non-technical skills in surgical and non-surgical (such as the aviation industry) performance (55,71–79). These frameworks broadly categorise surgical outcome into patient factors, technical performance, ergonomic factors, team coordination and leadership factors, organisational culture, situational awareness and decision making (80). This was used as a basis to explore the relative importance of several factors in the incidence of MIS errors in the opinion of the surgeons surveyed.

2.2.2. Defining Error

The role of error is complex and incorporates a spectrum from the non-consequential error, to one which can directly or indirectly end the life of someone or accelerate patient’s decline. Medical error can be defined as

> “an unintended act or one that does not achieve its intended outcome, the failure of a planned action to be completed as intended the use of a wrong plan to achieve an aim or a deviation from the process of care that may or may not cause harm to the patient.” (1,81–83)

However, what constitutes an error can be subjective. Whilst an inadvertent act during surgery (for example perforation of a hollow viscus or major blood vessel) that leads to immediate mortality is obviously an error the threshold that a particular surgeon defines an error is likely to vary between individuals, therefore, it was decided not to define error explicitly at the beginning of the survey but rather explore this issue in the free text responses.

2.2.3. The Survey

The full survey can be found in Appendix 2 and consists broadly of 6 parts:

1. Introduction: a brief explanation of the study purpose
2. Anonymised demographic background information of the participant: surgical specialty, grade, number of MIS procedure per annum etc.
3. Participant perceived importance of factors affecting surgery
4. Experience of errors in past 12 months: reflecting participant’s own errors, those of their trainees and those of their colleagues
5. Participant experience of error reporting in their institution

6. Participant-perceived factors affecting likelihood of reporting an error made during MIS

2.3. Results

Two hundred and forty-nine ASGBI members completed some of the survey from a total membership of circa 2,300, with 203 individuals completing >80% of the questions. Of these, 168 (83%) were consultant surgeons, 25 (12%) were specialist registrars, 3 (1%) were associate specialists, one was a research fellow, one was a core trainee, one was a foundation trainee and 4 classified themselves as ‘others’. Of the 249 respondents, 42% listed their speciality as UGI, 31% as LGI, 15% as hepatopancreatobiliary (HPB) surgery, 2% as breast surgery and 10% as ‘other’.

2.3.1. Incidence of Intra-operative Errors

In the preceding 12 months, 47% of surgeons had reported a significant error in their own performance that may have contributed to a post-operative complication, adverse patient outcome or serious untoward incident (SUI)(Figure 2-1). Almost 40% of respondents had experienced a significant error during MIS performed by a trainee when they were present in theatre (Figure 2-2) whilst 30% had experienced a significant error during MIS performed by a trainee when they were not present in theatre (Figure 2-3).

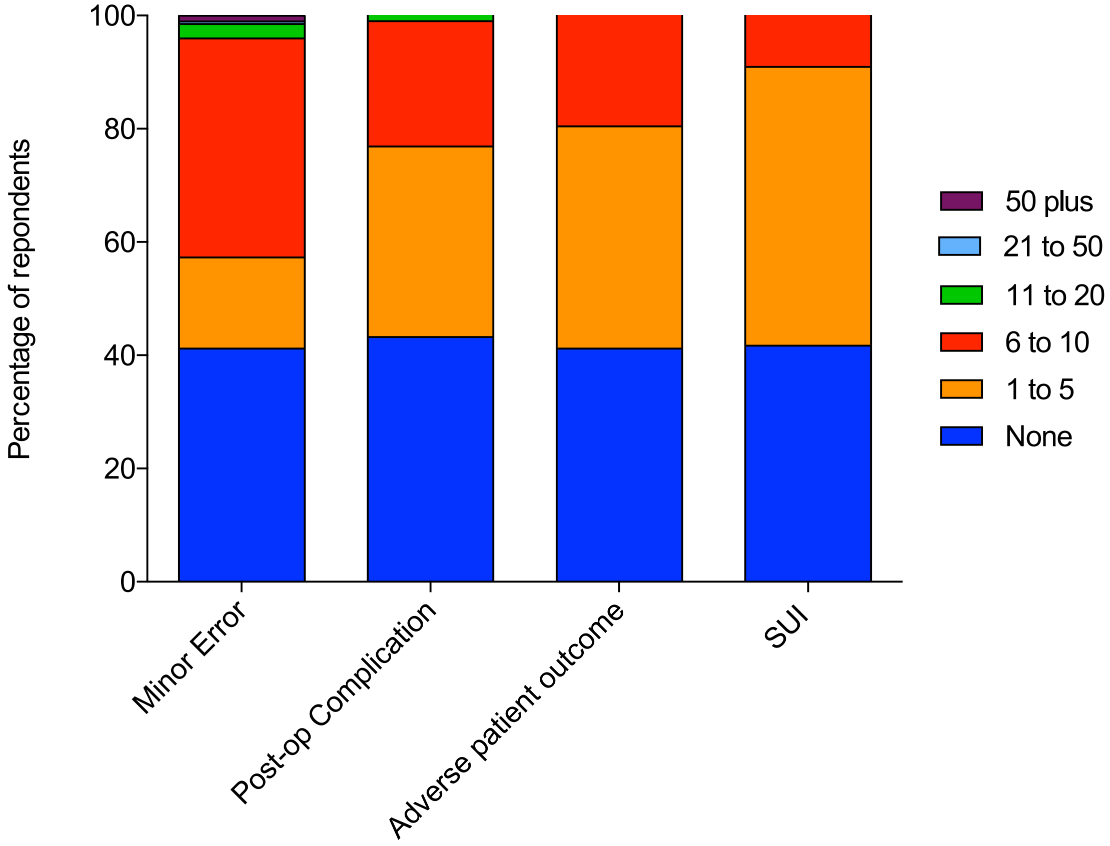


Figure 2-1: Question 3; Percentage of respondents experiencing a significant error in the past 12 months.

Survey question: “If in the past 12 months, in your opinion, you have experienced a significant error during MIS performed by yourself please estimate the number of those errors that resulted in the effects listed.”

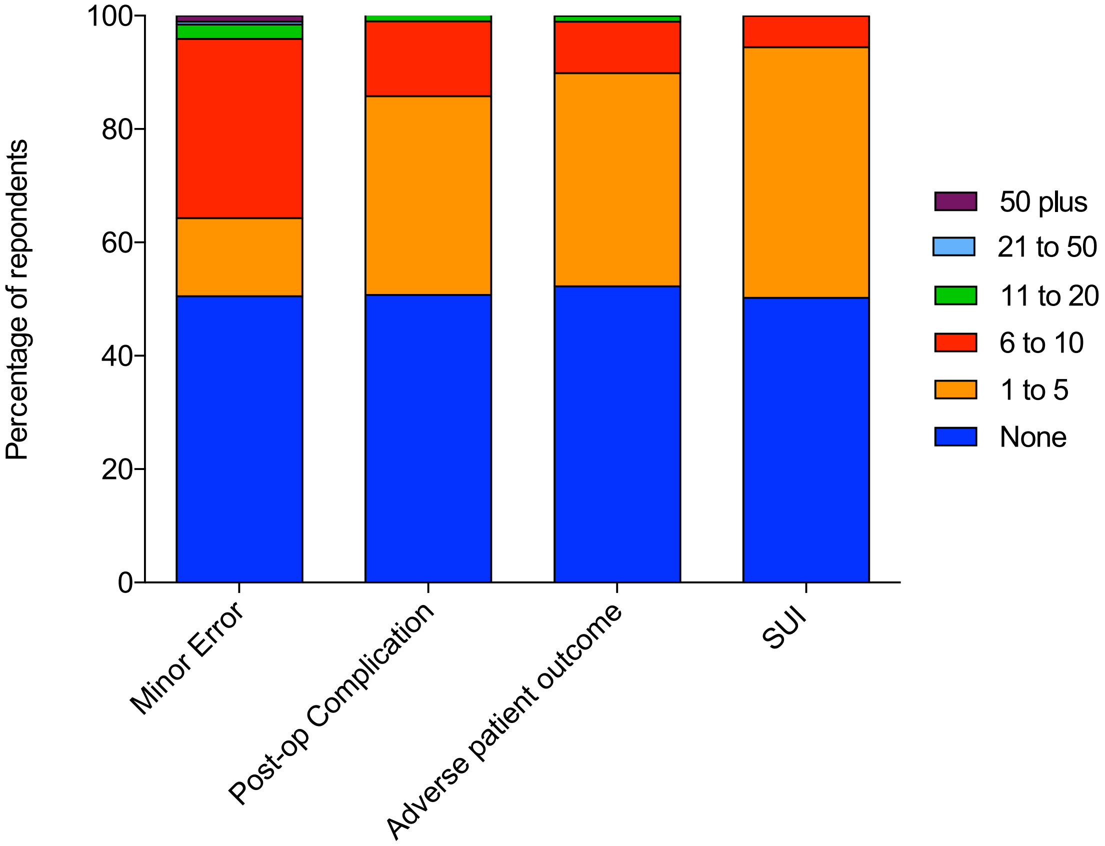


Figure 2-2: Question 4; Percentage of respondents experiencing a significant error by a trainee in the past 12 months (when present in theatre).

Survey question: “If in the past 12 months, in your opinion, you have experienced a significant error during MIS performed by a trainee whilst you were present in theatre please estimate the number of those errors that resulted in the effects listed.”

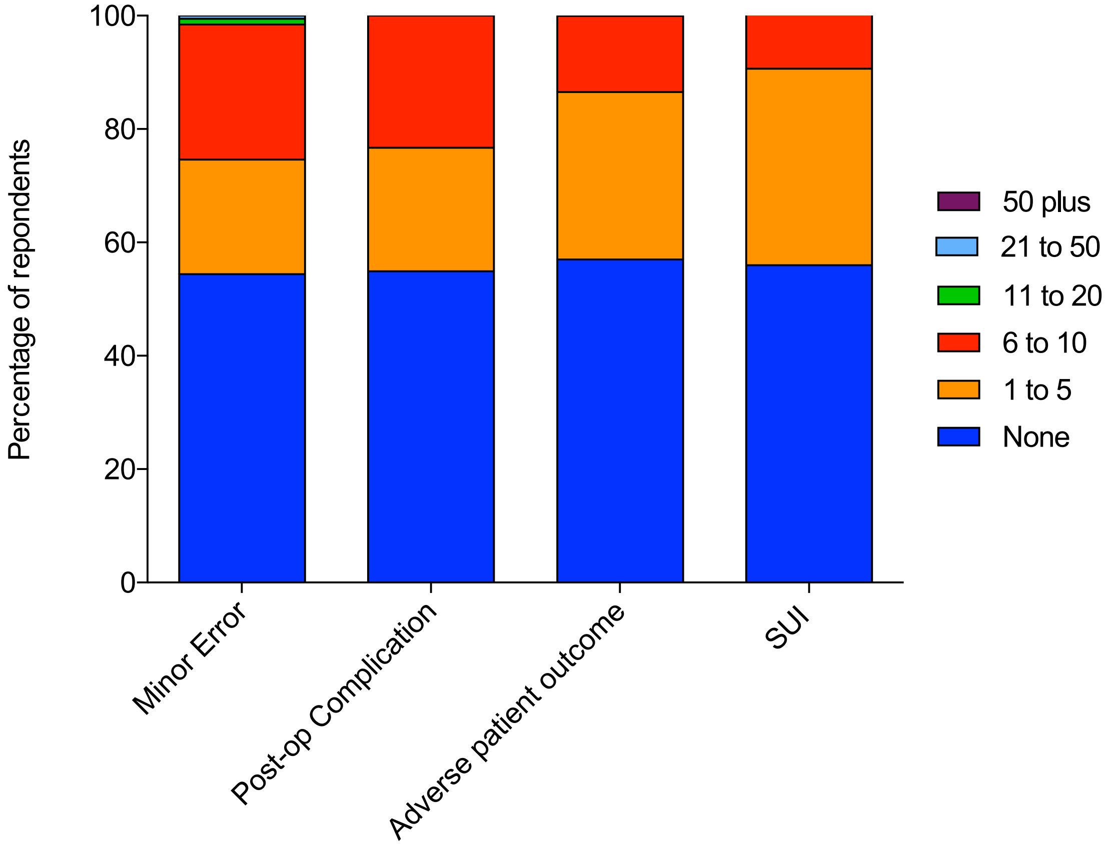


Figure 2-3: Question 5; Percentage of respondents experiencing a significant error by a trainee in the past 12 months (when not present in theatre).

Survey question: “If in the past 12 months, in your opinion, you have experienced a significant error during MIS performed by a trainee whilst you were not present in theatre please estimate the number of those errors that resulted in the effects listed.”

Among the same respondents, 75% were aware of a consultant colleague who had experienced a significant error in their practice (Figure 2-4). Interestingly, when asked to estimate how they compared to their colleagues with regard to intra-operative errors, the vast majority felt they made similar or fewer errors. (Figure 2-5)

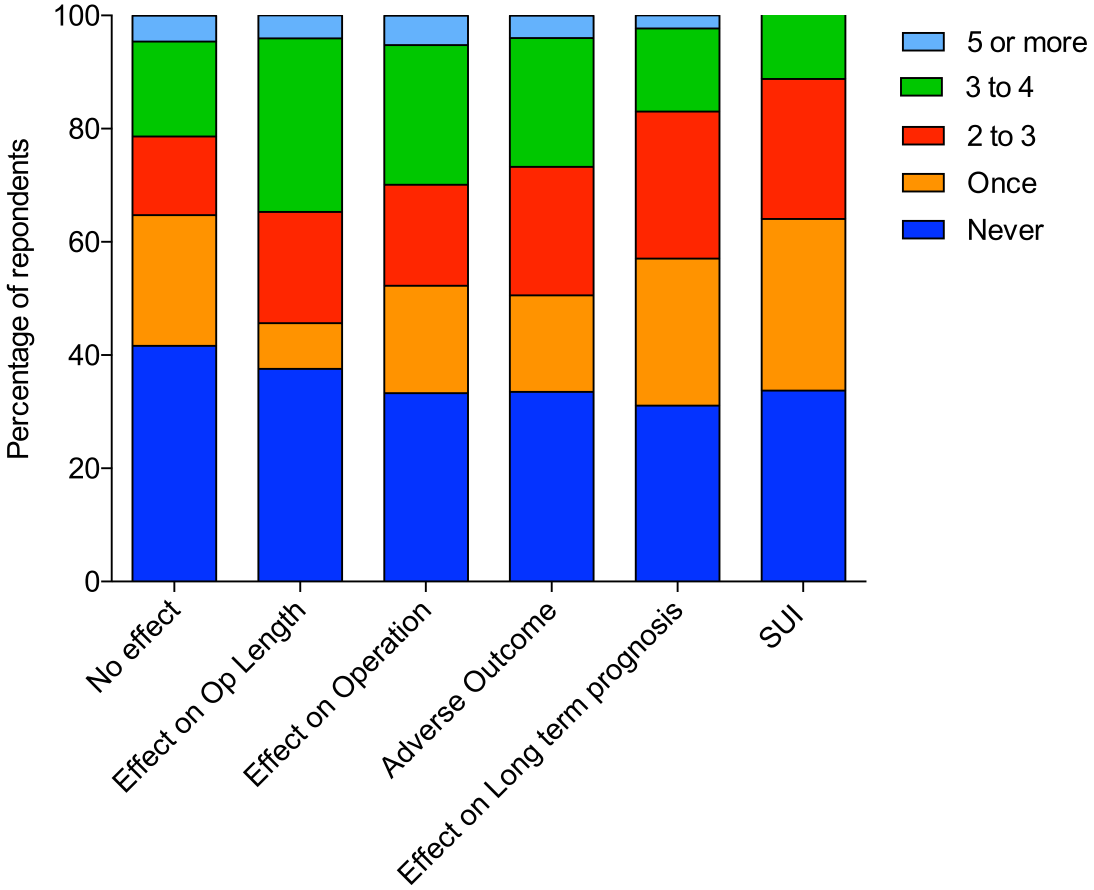


Figure 2-4: Question 6. Percentage of respondents aware of a consultant colleague who has experienced a significant error in the past 12 months.

Survey question: “If in the past 12 months are you aware of any consultant colleagues who have experienced an error during MIS? Please estimate the number of those errors that resulted in the effects listed.”

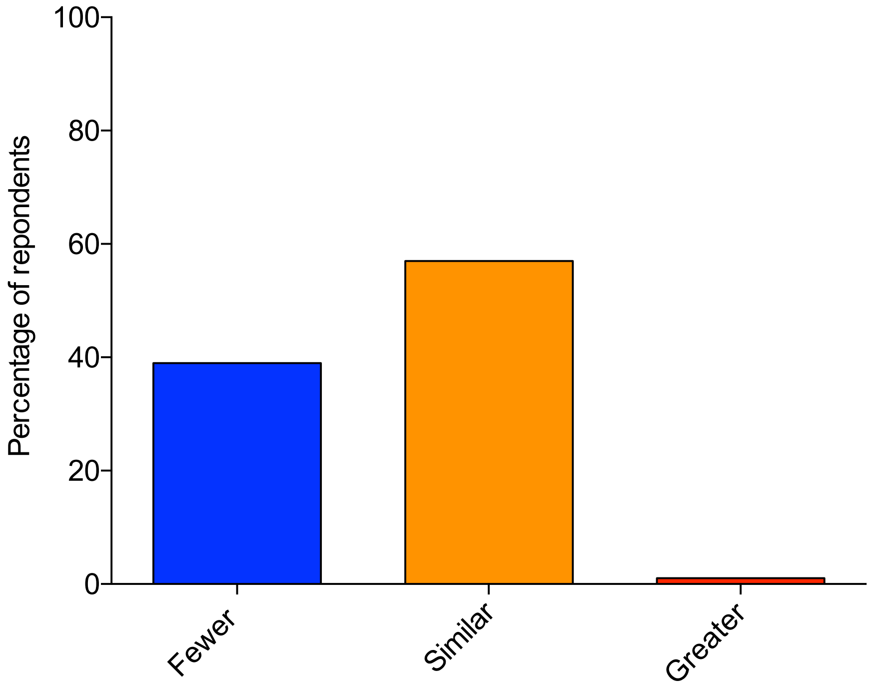


Figure 2-5: Question 7; Percentage of respondents estimation of significant errors related to their colleagues.

Survey question: “In relation to your colleagues, what proportion of significant intra-operative error do you make?”

2.3.1.1. Intra-Operative Error Reporting

Reporting of errors was variable: 85% of respondents were very likely to report an intra-operative error to a patient whilst only 50% were very likely to report an error via their institutions reporting mechanisms (Figure 2-6). Critically, 12% of respondents were not aware of the procedure for reporting an error within their institution and 59% felt error reporting guidance is needed. Overall, 40% of respondents felt that a confidential reporting system would increase the likelihood that they would report an operative error during MIS.

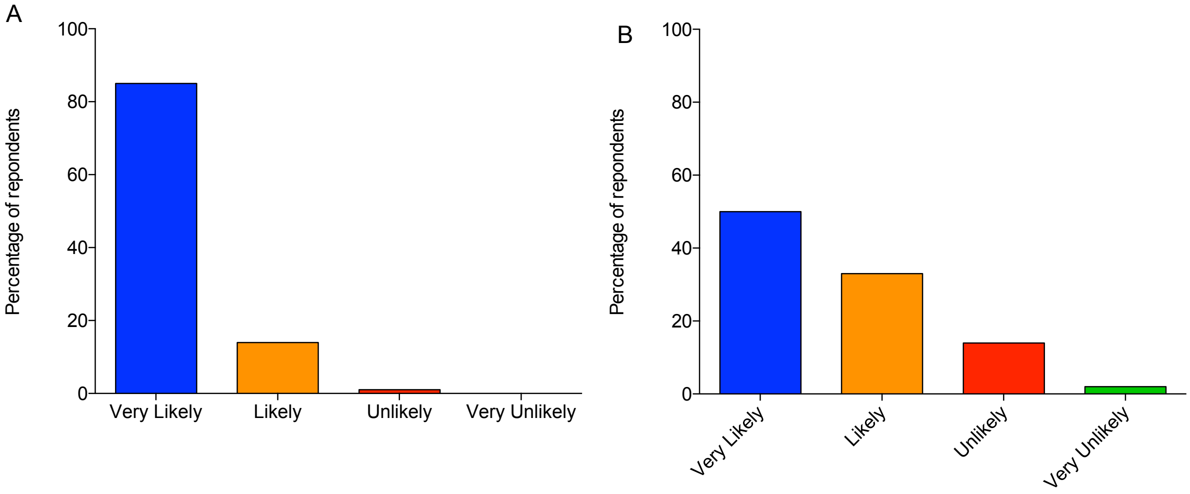


Figure 2-6: Question 9; Percentage of respondents who report errors to their patient (A) or institution (B).

Survey question: “When an intra-operative error that affected patient care/outcome has occurred how likely are you to report it (A) to the patient and (B) via your institutions reporting procedure?”

2.3.1.2. Factors Influencing Error Reporting

When asked what factors would make surgeons more likely to report an error (Question 10a), there was a variety of responses. Some respondents felt that any error should be reported, “All errors should be reported. We are in the era of transparency,” “we record and report all” and that “All errors fulfil the Duty of Candour”. The majority of respondents felt that any error that affects or is likely to affect a patient’s outcome should be reported, with many highlighting the need for a second operation or life affecting/threatening injury. Other respondents highlight that a robust reporting mechanism within “a fair blame culture and institutional maturity” with a “clear & honest indication of how the information is going to be used” along with a supportive “attitude of management and colleagues” and an environment in which “lessons could be learned”. Others mentioned that if an error was due to a system within the hospital then they would report it; “error resulting from institutional or external factors which need to be changed, e.g. equipment problems, staffing problems, lack of resources which causes increased stress or failure of equipment.”

When asked what factors would make them less likely to report an intra-operative error, surgeons cited factors such as “unauthorised discussion of these errors out with the surgical community by uninformed managers,” “blame and lack of support from colleagues and institution," "fear and intimidation" as well as "likely management hysteria and over-reaction," "crass managerial involvement" and "lack of trust and blaming natures of senior surgeons or colleagues. Non-supportive and blaming administrative culture." One respondent noted that a main barrier was "an impossible to fill in 5 page form on a computer." Many respondents state that if there is "no effect on morbidity" they may not report an error and several highlighted that it was a recognised complication of a complex procedure they may not highlight it as an intra-operative error per se. However, one respondent stated that they "always report a significant error, [as it is] dishonest and unprofessional not to."

2.3.1.3. Factors Influencing Incidence of Errors

When asked what factors had contributed to an error that had occurred in the past 12 months, many respondents highlighted a "difficult case", "technical difficulty", "distorted anatomy" and "previous surgery". Another factor to be highlighted was "fatigue" or "tiredness" along with "overwork" and "stress". Other respondents highlighted "poor equipment" or "equipment failure" with one surgeon stating "having to use substandard equipment as per trust directions". Other factors were "inexperienced staff" (theatre or surgical) and "distractions" such as "outside issues being brought into theatre and causing loss of focus".

2.3.1.4. Factors Influencing Surgical Performance

Over 50% of respondents highlighted technical skills, surgical knowledge, situational awareness and decision making as the most important factors in performing surgery (Figure 2-7).

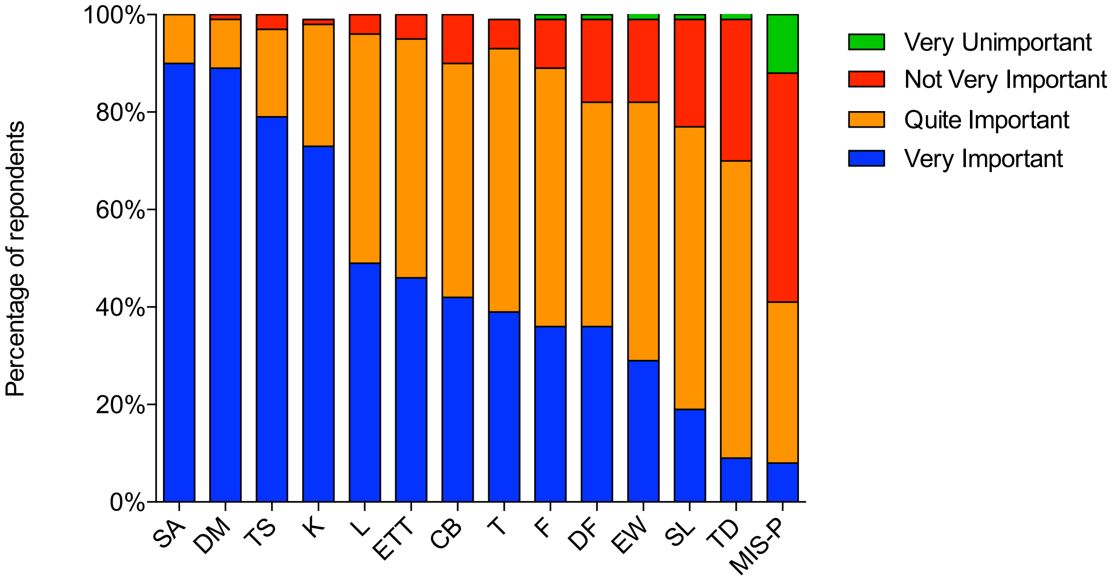


Figure 2-7: Question 2; Respondents views on factors influencing operative performance

Important factors in surgery. Arranged in order of perceived importance. Key: SA = situation awareness. DM = decision making. TS = technical skills. K = knowledge. L = leadership. ETT = experience of theatre team. CB = communication breakdown. T = teamwork. F = fatigue. DF = distracting factors. EW = excessive workload. SL = staffing levels. TD = technical demands. MIS-P = MIS procedure.

When asked to respond in free text why procedures can be prolonged, respondents highlighted factors such as “difficult cases”, “slower decision making or movements by trainees”, “poor equipment” or patient factors such as “body habitus”. One surgeon responded:

“because the surgeon is not thinking or does not have the insight when to stop or convert early to open”

Whilst others commented that:

“trainees are on the whole slow and inexperienced”

and

“I often think poor surgical skills can contribute, but that is as a result of watching some very poorly performed procedures.”

One detailed response listed several factors:

“1. technical skillset not complete (slower actions)

2. trainee not thinking ahead about the next steps of the operation (admiring the view, not progressing the surgery)

3. more actions that fail to progress the surgical task (unnecessary dissection, repeated movements to establish retraction, failure to employ team or non-dominant hand effectively)

4. late communication with scrub staff about needs for next steps”

These themes are re-iterated by several respondents:

> “with the trainees it is simply that they are inexperienced”
>
> “Surgeon experience, lap capability, decision making”
>
> “Lack of experience and confidence”

One respondent felt very strongly about this matter:

“This is a stupid question - if a lap chole is taking more than 120 minutes it should have been converted to open prior to this or the skill of the operator taken into question - especially a consultant. I carry out 3 lap choles regularly in 3.5 hours, if I am not progressing after 15 minutes I convert - hence the complication rate is low. Macho MIS is not an option. Wounds heal side to side and a few extra days in hospital for a patient who goes home without complication is better than over 2 hours on the operating table with more chance of complication. Please redress this survey!!!!”

2.4. Discussion

The advent of MIS has benefitted patients in various ways. It is associated with shorter hospital stays and decreased mortality compared with traditional open surgery. Nevertheless, MIS is a complex skill that requires surgeons to adapt to a range of novel visual-motor demands. As a result, near miss errors are likely to occur (where human error arises but does not result in patient fatality) despite the fact that catastrophic errors are rare. These errors can still have detrimental effects for both the patient and the institution so it is important to determine the incidence and cause of such errors. Information from this survey indicates that intraoperative errors during MIS occur frequently, with almost half of the respondents reporting a significant error in their own performance in the past year that had adverse effects. Several common themes were highlighted for intraoperative errors, including trainee experience/visual motor skills, difficulty of the case (e.g. patient anatomy or previous surgery) and fatigue/overwork, all of which may contribute to a prolonged operative time.

In essence, all surgical operations are at the mercy of ‘surgeon factors’ (inexperience, trainee surgeons and surgical error) and ‘patient factors’ (a difficult case). It would be expected that an operation performed by a trainee to be longer than that of a consultant with greater experience of the procedure, and we might also speculate that trainees are more likely to experience an intraoperative error. These expectations were reflected in the responses to this survey. When considering the errors that can occur, there is clearly a spectrum, spanning from the simple (such as insufficient tension on the tissues), to technical errors that are detected and rectified (e.g. tearing of the serosal layer of the bowel wall), through to errors causing post-operative complications requiring intervention (e.g. enteric leak). All of these errors would lead to longer operations and potentially to an adverse outcome such as patient mortality (74). Patient factors such as obesity, previous surgery and cause of biliary disease (e.g. biliary colic vs. acute cholecysitis) may make a LC more technically challenging and increase the likelihood of an intra-operative error. The survey confirmed the suspicion that errors are occurring, but perhaps more importantly demonstrated variation in error reporting among surgeons. Some respondents stated they reported all errors regardless, however, the majority stated it would depend on the nature of the error and whether there were consequences to the patients. A significant number highlight difficulties with reporting errors and a reluctance due to perceived attitudes of colleagues and management.

A survey such as this is subject to reporting bias, however, whilst surgeons may underestimate their own intraoperative errors and overestimate errors by others. There is no reason to suspect that false information has been supplied due to the anonymity of the survey, however, it is conceivable that respondents may have under- or over-estimated either consciously to reflect a better practise or subconsciously. This effect is illustrated in responses to question 7. Over 90% of respondents felt they made similar or fewer errors when compared to their colleagues. Responses may also be affected by recall bias. A surgeon is more likely to remember the patient who had a major complication due to an intra-operative error resulting in prolonged in-patient stay, multiple investigations/procedures and possible a complaint/litigation than they are to remember the patient who's intra-operative error had no clinical sequelae. Additionally, the number of respondents was only 10% of the stated ASGBI membership. This is likely to reflect inertia when responding to survey as there is a definite feeling of survey-overload within the medical community. It may also reflect a bias in those who responded as surgeons who have experienced a greater number of intra-operative errors may be reluctant to take part in such a survey.

2.5. Conclusion

This survey indicates inconsistent reporting of operative errors and a potential iceberg of intra-operative errors. These data highlight the need to better understand how and why technical errors occur which will in turn allow identification of factors that contribute to adverse events and improve patient outcomes.

3. Laparoscopic Motor Learning and Workspace Exploration

3.1. Introduction

Laparoscopic surgery has revolutionised medicine with greatly improved patient outcomes, yet it requires surgeons to learn complex and challenging movement patterns. As previously discussed, in contrast to open surgery, laparoscopy can introduce a variety of constraints, such as restricted movement, degradation or loss of haptic feedback, reduced visual depth perception, as well as the fulcrum effect (14). The difficulties associated with learning new motor skills when using laparoscopic instruments are exacerbated by the costs of clinical training and reduced training time: in Europe, the European Working Time Directive (EWTD) has a direct impact on training opportunities. Relatedly, the National Patient Safety Agency (NPSA) identified that surgeon factors are the most important element in patient harm (84) and commensurate with the survey of ASGBI members described in Chapter 2 identified these issues as an area of concern for most surgeons (85). Such pressures have contributed to the increased prevalence of virtual reality (VR) simulators which allow trainees to learn and practice surgical skills outside of the operating theatre (86). A growing body of evidence suggests that VR training results in performance benefits in the operating room (87–89). Training novice surgeons to automaticity leads to superior skill acquisition and transfer to the operating room, however, this requires an extensive amount of training (90,91). Development of VR systems has suffered from the assumption that only high-fidelity simulators improve operating room performance, yet research clearly demonstrates the benefits of low-fidelity training (24,92). In addition, disagreement over how best to integrate VR into training curriculums is widespread (86). Thus, current understanding of the best way to train surgeons using VR is limited.

Previous work has demonstrated methods of identifying individuals who cannot adjust to viewing a task on a separate screen/monitor and therefore cannot manipulate from such images and degradation in performance when individuals view a task on a remote screen versus direct visualisation (93,94). Hanna et al have demonstrated feasibility of evaluation of visual motor-skills and variation in performance in a virtual environment (95). The same group demonstrated no effect of 2D versus 3D imaging on performance (as measured by time taken) of trained surgeons conducting a LC (96) and also on performance on laparoscopic suturing of bowel as measured by time taken and suture quality (97).

One major problem faced within laparoscopic skill acquisition is that movements must be generated through novel force fields that create unexpected forces that perturb planned movements (98). For example, when controlling laparoscopic instruments, the interaction between the abdominal wall, laparoscopic port and the instrument results in complex disruptive forces that vary with position and time. For example this is can be particularly noticeable in bariatric surgery where the restriction of movement due to abdominal wall resistance and reduced intra-abdominal space presents additional challenges.

The relative difficulty of learning to move in novel force fields suggests that this might be a particularly important aspect for consideration in laparoscopic training. In addition, laparoscopy training requires the individual to learn new perceptual-motor maps concurrently with learning how to move in a novel force field. It seems probable that these different challenges will interact, necessitating investigations into motor learning under these concurrent task constraints. However, despite the centrality of motor skill in surgical performance, there is a fundamental lack of research into the underlying factors that influence learning the complex visual-motor skills required by laparoscopic surgeons. It is clear that without a large increase in such research, laparoscopic visual-motor training is unlikely to see significant advances in the near future.

Within the last 50 years, substantial progress has been made in understanding of visual-motor control. A recent computational theory of motor learning known as structural learning suggests that specific training regimes can allow the central nervous system to learn general rules about how task parameters co-vary, improving later performance in novel environments (e.g. operating on a new patient) (52). Whilst this approach is promising, motion capture systems required to objectively record kinematics are often expensive and unsuitable for simulation of laparoscopic tasks and VR trainers offer researchers poor experimental control.

There is evidence that training in VR simulators benefits laparoscopic skill acquisition (90). However, it is equally clear that we do not know the best way of utilising these systems for optimum training outcomes. If we are to make progress in this area, a suitable research tool is needed which can parametrically vary the factors which make laparoscopic surgery difficult, while providing detailed kinematic measures of performance. Critically, this should be achievable at a low cost to promote widespread use.

The Kinematic Assessment Tool (KAT) presents an opportunity to address the problems identified above: it is an experimentally validated, powerful and portable system capable of providing accurate and repeatable measures of kinematic performance (99). KAT is a modular system, which allows for easy integration with third party controllers, circumventing the need for bespoke software solutions. A potential controller for simulating laparoscopic style movements is the Phantom Omni: a force feedback haptic device, which allows movement across six degrees of freedom, with variable force along the x, y and z axes. The Phantom Omni has previously been successfully integrated with VR systems, demonstrating its suitability for investigating motor learning (100). The combination of a precise kinematic assessment device with an ecologically valid controller (i.e. users interact with the Phantom Omni by holding an intuitive pen-like stylus) allows hypotheses regarding the learning of surgical tasks to be experimentally investigated. In collaboration with colleagues in Engineering, such a device was developed (Omni-KAT, see below) and in this chapter, it's merits are tested by exploring whether it can provide useful data to address a relevant question: is it easier to learn planar movements when training is constrained to a plane or when training takes place in unconstrained Cartesian space? Constrained conditions make the requisite perceptual-motor map explicit, whereas unconstrained movements allow full exploration of the relationship between movement of the device and the perceptual outcomes. This tests the recent theory of structural motor learning described above that suggests full exploration of a task's 'structure' produces better learning.

3.2. Materials and Methods

The KAT system allows investigation of human motor control by recording endpoint movement data (kinematics) in response to visually presented stimuli. KAT has a modular software structure, developed using LabVIEW (National Instruments™, version 2010), permitting the use of different input devices. The key development of the KAT software to make it suitable for exploring issues relating to laparoscopic surgery involved replacing the original input device (a stylus) with a commercially available 6 degrees of freedom haptic device (SensAble Technologies Inc., PHANTOM Omni®). This provides two key features;

(i) the manipulandum has the same degrees of freedom of movement in Cartesian space as a laparoscopic device;
(ii) the haptic device can be controlled to provide a range of force fields during a task. This development will be described as the Phantom Omni - Kinematic Assessment Tool (Omni-KAT) to distinguish it from the original KAT system.

The Omni is a portable device that is compact and easy to use. It is controlled from a PC using an IEEE-1394a FireWire interface and the QuickHaptics software toolkit (SensAble Technologies Inc.) which provides device drivers and an Application

Programming Interface (API) for interaction with third party software. The KAT software was modified to integrate an interface to the QuickHaptics API, thus providing a mechanism for measurement and control of the Omni haptic device. The system used has a full six degrees of freedom and allows one to produce natural movements whilst manipulating 3D objects on screen, in the same way that a laparoscopic device allows one to move in Cartesian space and view this information on a remote monitor in the operating theatre (Figure 3-1). This device has previously been used to examine a variety of manual control tasks; from handwriting through to surgery (101,102). The system is able to deliver a force of up to 3.3 Newton's on a user's hand and has a 0.05mm positional reporting resolution. This system was controlled by a laptop running custom software. Thus, it is possible to provide a variety of different force fields (up to 3.3 Newtons) whilst participants complete motor tasks.

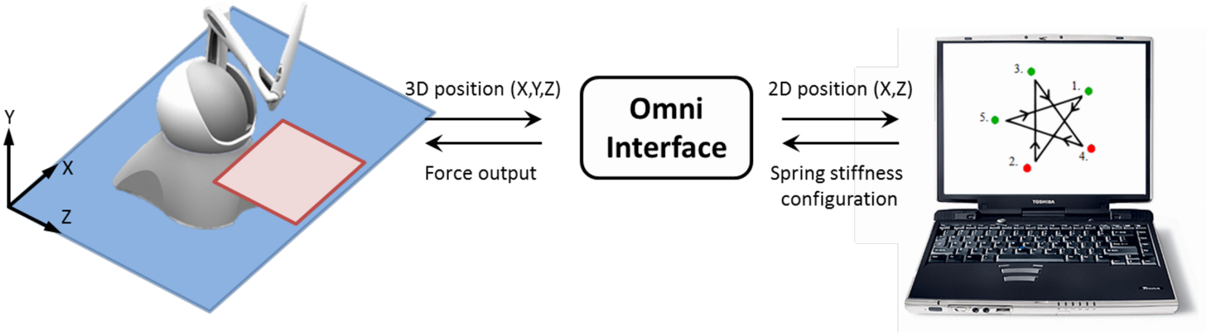


Figure 3-1: Configuration of the Omni-KAT system.

The Omni interface obtains the three-dimensional Cartesian position of the Omni stylus and two of the co-ordinates are selected to drive the task. This determines the plane in which the two-dimensional motor tasks are orientated within the Omni workspace. In addition, the Omni interface simulates a spring element (using the haptic force capabilities of the device), which acts between the stylus tip and a centre point. The spring stiffness and position of the centre point in each axis can be configured per task in order to create a customisable force field where the force varies predictably with the spring extension.

3.2.1. Participants

Participants (n=21; 17 males/ 4 females) were recruited via an opportunity sample from the University of Leeds. The ages ranged from 20 – 32 years (Mean = 23.31 years, SD = 3.45 years). The group consisted of 20 right handed individuals and 1 left handed individual. All participants reported a normal sense of touch and vision and had no history of neurological problems. Ethical approval was granted by the

University of Leeds School of Psychology Research Ethics Committee and conducted in accordance with the 1964 Declaration of Helsinki.

3.2.2. Task and Procedure

Participants sat on an adjustable seat in front of a table on which the Phantom Omni controller was placed. A Toshiba Tecra M7 (screen: 303 x 190mm, 1600 x 1200 pixels, 16bit colour, 60 HZ refresh rate) was positioned to the right of the Omni. The screen was angled vertically (90° to the table). Participants were required to use the Omni stylus to guide a cursor on the Toshiba display. Movement across the X and Z plane resulted in corresponding movement of the displayed cursor. Movement along the Y axis had no effect on the cursor. Green dots of 10mm diameter appeared sequentially on the screen in a pentagram pattern. Participants were required to move the cursor to each dot as quickly and as accurately as possible (Figure 3-2). When a dot was reached (defined as staying within its boundary for > 0.5 s) the next dot in the sequence was displayed. There were 60 dots in total within a block.

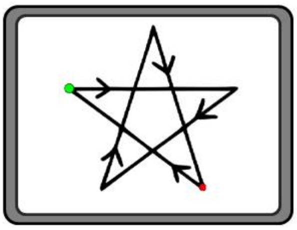


Figure 3-2: Diagrammatic representation of the Omni-KAT task performed by participants

Participants were randomly assigned to two training groups. In the ‘constrained’ group no force was applied to the X and Z plane, while a force was applied in the Y axis using a spring element (stiffness = 2 N/mm) with an origin 20 mm below the Y minimum position limit. This configuration pulled the Omni-KAT stylus toward an explicit X-Z plane along which it moves. In the unconstrained group no forces were applied in the X, Z and Y axes. Participants completed two blocks of training trials (trials 1 and 2). Subsequently, all participants immediately completed two test blocks (60 dots per block) in which movements were unconstrained in all axes (trials 3 and 4). The total movement time between dots was recorded for each block.

3.2.3. Outcome Measures

Two specific measures of performance were recorded:

(i) Mean movement time (MT), the time taken by participants to move the Omni-KAT stylus from one dot to the next

(ii) Normalised jerk (NJ) of movement. Jerk is the time derivative of acceleration. It is normalised with respect to time and distance such that trajectories of different durations and lengths can be compared giving a measure of ‘smoothness’ of the movements. Normalised jerk is given by:

$$NJ = \sqrt{\frac{MT^5}{2PL^2}\int_0^T j(t)^2 dt}$$

Skilled motor behaviour is usually quick (low MTs) and smooth (low NJ), whereas poor motor skill can be slow and involve many corrective adjustments (which can cause jerkier movements).

3.2.4. Statistical Analysis

The MT and NJ data were input into separate, mixed 2x4 (Training Group x Trial) analyses of variance (ANOVA). Greenhouse-Geisser estimates of sphericity (ε) are reported where degrees of freedom have been adjusted.

3.2.5. Study Design

This study was a between subjects design. The two main dependent variables (MT and NJ) were subjected to a 2 (training group) x 4 (trial) mixed ANOVA. Participants were randomly allocated to a training group and trial order was fixed to examine improvements over learning.

3.3. Results

3.3.1. Mean Movement Time

The MT for the two training groups for each trial are shown in Figure 3-3. Details of the ANOVA are shown in Table 3-1. Performance improved in both groups across the trials (MT decreased). There was no difference between the constrained and unconstrained groups during training (trials 1 and 2). Crucially, at test (trials 3 and 4, where movements were unconstrained for all participants) the participants that were unconstrained during training performed significantly better (shorter MTs) than participants who had been constrained.

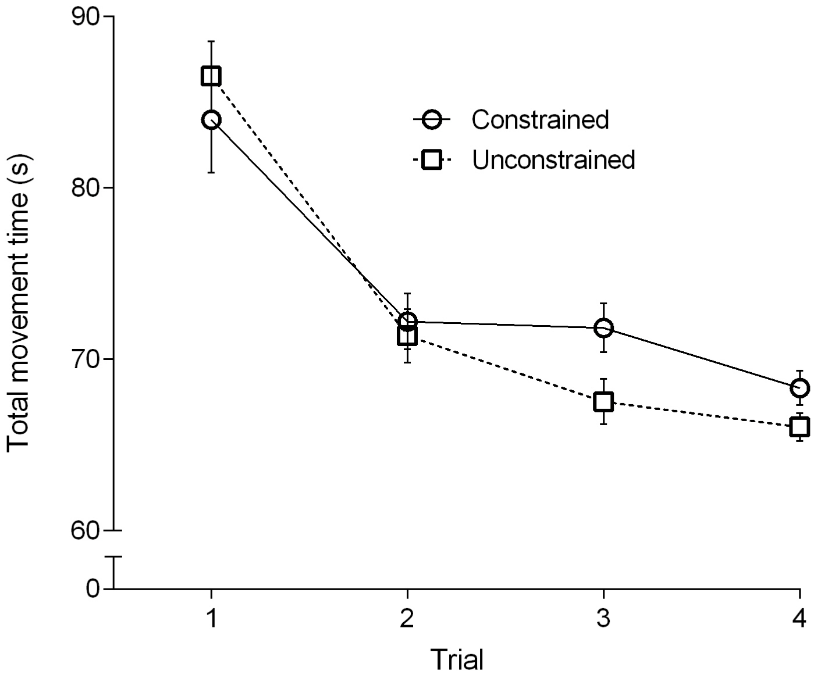


Figure 3-3: Mean Movement Time for the constrained and unconstrained groups

Table 3-1: The effects of Training Group and Trial on Movement Times

	Movement Time (MT)				
	F	df	ηp2	ε	p
Training Group (TG)	.69	1,19			>.05
Trial	72.16	3,57	.79	.55	<.001
Trial x TG	3.79	3,57	.17	.55	<.05

3.3.2. Normalised Jerk

Normalised Jerk (NJ) for the two training groups for each trial are shown in Figure 3-4. Details of the ANOVA are shown in Table 3-2. The overall pattern is similar to that seen in MT. Performance for both groups becomes better across the trials (jerk reduces reflecting smoother movements). The main difference is that the unconstrained group actually had significantly higher NJ values during training (trials 1 and 2), which presumably reflects the corrective movements required to find the correct plane of motion. When both groups performed the unconstrained test (trials 3 and 4) there was no longer a significant difference between the two groups suggesting that smoothness of performance transferred from training to test for both groups.

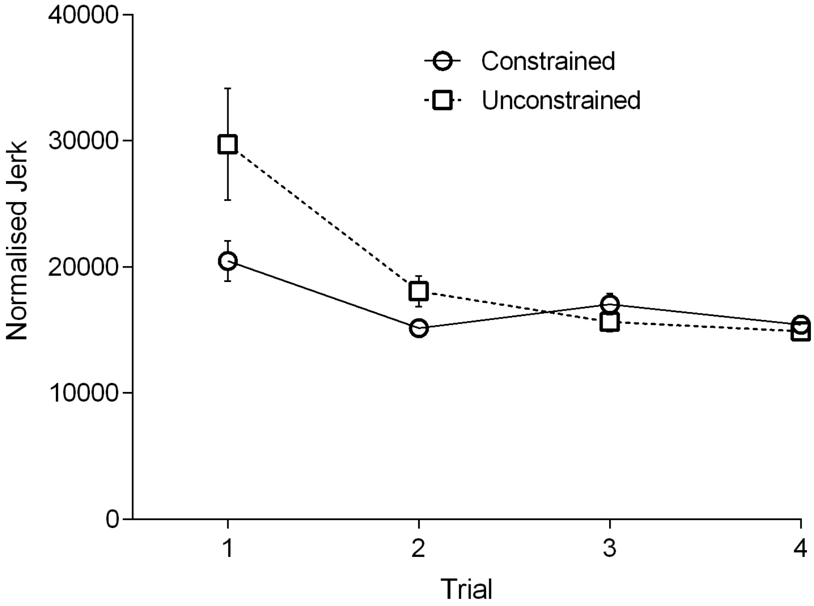


Figure 3-4: Normalised Jerk for the constrained and unconstrained groups

Table 3-2: The effects of Training Group and Trial on Smoothness (Normalised Jerk)

	Normalised Jerk (NJ)				
	F	df	ηp2	ε	p
Training Group (TG)	16.56	1,19	.47		<.001
Trial	72.16	3,57	.79	.55	<.001
Trial x TG	4.63	3,57	.20	.39	<.05

3.4. Discussion

The Omni-KAT device was designed to replicate the fundamental demands of laparoscopic surgery, specifically the manipulation of tools in 3D from 2D visual information provided on a remote monitor display. These data demonstrate that this system is able to provide a low cost (off-the-shelf equipment) method to measure and investigate motor skill learning in laparoscopy. A large range of forces, spatial restrictions and visual-motor mappings can be parametrically varied in order to manipulate and control the factors, which make laparoscopic surgery difficult. This can be achieved easily through Omni-KAT, which also automates data analysis to generate standardised kinematic performance metrics.

A recent motor learning theory suggests that general rules about a class of behaviours can be extracted to accelerate learning; a process termed ‘structural learning’ (53). In this experiment, performance at test was significantly better for participants who trained in an unconstrained condition. These findings suggest that learning the device control dynamics was more beneficial than having the requisite plane for optimum movement made explicit. This result is predicted by the theory of structural learning. The performance benefits conferred by exploring controller dynamics reflects the importance of error-based learning yet no studies have examined previously whether constraining movement to the required perceptual-motor plane improves later performance (52). These findings are consistent with recent studies that have found exposure to random or gradually varying rotation angles of displacement speeds up subsequent adaption to a novel rotation (103),(104). Within the surgical literature, there is further evidence to support this suggestion: adaption to the “fulcrum” effect is facilitated by training under randomly alternating viewing conditions (105). The practical implication of these findings is that surgical trainees should be not be subject to constraints when learning new device dynamics and that training for a specific task (e.g. using the laparoscopic diathermy tool) can benefit performance in a similar task (such as the use of the clip applicator on the cystic duct and artery).

This experiment shows that learning planar movements (such as dissecting the gall bladder from the liver bed during a laparoscopic cholecystectomy) is hindered if training is constrained to a plane despite this allowing the surgeon to develop an appropriate perceptual-motor map. In contrast, allowing the surgeon to move through unconstrained Cartesian workspace eventually leads to improved performance because of enhanced learning of the control dynamics of the surgical instrument. These findings demonstrate the usefulness of Omni-KAT in helping understand how trainee surgeons can learn to move skilfully in the presence of complex disruptive force fields – and provide insights into optimal virtual training environments. The could potentially lead to techniques that can improve the ability of surgeons to learn and adapt to the complex visual-motor challenges presented by laparoscopy. For example, structural learning is thought to improve both feed-forward learning and feedback control (greater speed and accuracy) in prism adaption and handwriting and these results indicate that structural learning may also be relevant in laparoscopy (104) (101).

It should be noted that in this experiment the quality of the end product (the pentagram shape) was not assessed and outcomes instead focused on quality of movement. Therefore it is feasible that some participants made smoother, quicker movements but did not replicate the pentagram pattern as well as others who were make slower more jerky movements. This is negated somewhat by the experimental design – the next dot in the sequence was only revealed once the preceding dot was reached (defined as staying within its boundary for > 0.5 s) meaning it is less likely participants were making quicker, smoother movements yet not following the prescribed pattern. It is also possible that the converse occurred and those making slower, jerky movements were also not following the pentagram pattern as closely as the better performing participants.

For both measures (MT and NJ) performances in unconstrained conditions for all participants (trial 3 and 4) were similar to trial 2 (the second training block) which in itself showed marked difference from trial 1 (the first training block). It is possible that these differences are due to a learning effect during trial 1 and participants have reached optimal performance (a 'ceiling effect') – therefore performance during trial 3 and 4. In order to determine this further subsequent unconstrained trails would have had to be performed.

3.5. Conclusion

The Omni-KAT system provides a novel means of investigating how to accelerate motor skill learning in an environment that simulates the task demands of laparoscopic surgery. However, it does not fully translate to MIS. It is unable to approximate some of the core restrictions placed on a surgeon such as the fulcrum effect in movements, hand grip and degradation in haptic feedback usually experienced in MIS. As such, in future studies, the possibility of integrating the system with more traditional training techniques e.g. box trainers will be explored.

4. Investigating Performance During MIS: the Operative 'Set-Up'

4.1. Introduction

The human visual-motor system is inherently mobile – our eyes rotate within our head, and our head rotates on our body. The basis of visual stability is that the central nervous system (CNS) is able to compute for and compensate for displacements (7). Humans are remarkably adept at being able to account for the change in the relationship between visual input and the movement control signals to interact with the world (the visual-motor mapping), and this capability allows us to carry out skilful actions (106–108). These visual-motor transformations have been studied using a variety of experimental paradigms aimed at revealing how the CNS adapts when the relationship between visual input and motor output is perturbed in some way. Typically, the information available at the retina is perturbed through optic prisms (109), or the relationship between an input device and cursor motion on a display are manipulated (110). When simple perturbations are applied (i.e. rotations) humans show initial errors in trajectory, which reduce over time. Once the perturbation is removed, errors often occur in the opposing direction, which is presumed to reflect changes in the inverse model (111). While studies have clearly demonstrated the capacity for humans to adapt to visual-motor transformations, and reduce subsequent error when carrying out an action, this adaptation, particularly with complex transformations takes time to occur. Even after training, motoric performance under transformed visual-spatial mapping is degraded in comparison to normal mapping (112).

Minimally invasive surgery (MIS) is particularly challenging because the natural relationship between hand and eye is disrupted and the brain must control complex movements using extremely limited sensory information obtained from a rapidly changing environment. Display of the MIS tools and the surgical site are usually via a 2D monitor positioned at the surgeon's discretion. Figure 1-2 depicts a common operating room setup for laparoscopic surgery. As discussed in section 1.2.2 the operating surgeon is stood at the patient's side and the viewing monitor is suspended over the patient at the cranial end. The surgeon performs the operation using two instruments inserted through separate incisions made in the patient's abdominal wall. The camera is inserted through a third incision (usually in the region of the umbilicus) and controlled by an assistant, allowing the surgeon to use both hands to perform the operation. Three axes are demonstrated; the surgeons head and body axes and the axis of the laparoscopic camera. The position of the camera, assistant and monitor(s) varies with each surgeons particular preference.

Monitors are typically between 21 and 26 inches in size. Current high definition cameras have 1920x1080p resolution but lower resolution cameras are often used depending upon the port size being used and equipment available. Different laparoscopic cameras with angulation at the tip (30º and 45º) can assist the surgeon to 'look round corners' i.e. around tissue or an organ that is obscuring the view. This does, however, add further distortion to the mapping between motor action and visual movement of the tools displayed on the screen. Whilst remote viewing of the laparoscopic tool may impair the absolute level of performance, it has been shown that there are some benefits to not looking at your actual hand when learning to compensate for visual distortions (102).

One possible source of variability is the degree to which the camera moves during MIS. This will depend largely on the surgery being performed. An operation such as a LC or robotic prostatectomy (removal of part/all of the prostate gland) requires a relatively static visual field and therefore there will be limited movement of the camera around the abdomen. In contrast, during a laparoscopic gastric bypass or colectomy (removal of a section of bowel) a variety of locations within the abdomen need to be visualized throughout the procedure. It would be expected that a static camera view would provide a useful frame of reference when adapting to the other visual-motor distortions present during MIS. When the image is no longer a fixed reference, continuous recalibration of the visual-motor mapping may be required. If the surgeon's visual-motor system is unable to estimate these new task parameters, the accuracy and/or speed of movement will be impaired, increasing the risk of direct harm (such as inadvertent perforation of an organ) and indirect harm (prolonged general anaesthesia) (113,114) to the patient.

A transformation in visual-spatial mapping may be particularly problematic in environments that involve motorically demanding tasks. MIS requires a high level of manual dexterity and is often conducted in high pressure situations. The processes involved in MIS procedures require the CNS to produce a congruent mapping between the workspace and hand to deliver a high degree of hand-eye co-ordination. In contrast to open surgery, where direct observation and manipulation are possible, the natural relationship between hand and eye is disrupted in MIS set-ups. Surgeons typically control tools that are inserted through the patient's abdomen wall whilst viewing a camera view of the workspace via a remote display. In this environment, visual information is decoupled from the workspace; the display can be located in a variety of positions and angles relative to the surgeon. As such, head position signals are no longer informative about target location (i.e. the surgeon is looking in the opposite direction to where the hands are moving), and experiences proprioceptive discordance (115). In other words, the viewing angle does not provide useful information about the visual-motor mapping (in contrast to normal visual-motor interactions).

Given the costs of movement errors in surgical environments, understanding how the CNS adapts in MIS is imperative (116). Several studies in the surgical literature have suggested that incomplete decoupling of head position signals during surgical tasks results in significant performance costs (115,117–121). Generally, these studies conclude that MIS monitors should be positioned in front of the surgeon and at eye level, in order to minimise the disparity between hand and eye (117,119,122). Indeed, empirical data indicate optimal performance during MIS procedures is more likely to be achieved when a straight line visual-motor alignment exists (118). This setup is not, however, always adopted in operating theatres, and the monitor is often positioned in an oblique manner relative to the surgeon.

Previous studies have demonstrated:

(i) clear performance advantages when the head and hands are pointed in the same direction during visual-motor tasks,
(ii) subjective preference of surgeons is for the visual angle to be at 0°
(iii) experienced surgeons are more adapt at dealing with increases in rotations of the visual display (118,120).

These studies have not yet precisely quantified the effects of head rotation/viewing angle on visual-motor control processes in MIS and, as such, the extent to which visual transformations modulate motoric control processes is unclear. To this end, objective, reliable and valid measures of motoric control will be used to examine manual control performance in MIS in an experimental set-up. The aim of this experiment is to investigate the effect of monitor position on visual-motor performance. By utilising the KAT system motoric performance can be investigated at a fundamental level, removing previously discussed confounding factors seen in other studies such as previous surgical experience, patient variability and vested interest bias. Predicated upon past research, the hypothesis is that increased disparity between monitor angle and torso will result in greater decrement in manual control performance.

4.2. Methods

4.2.1. Participants

Eighteen healthy adults took part (10 male). All participants were right-handed as indexed by the Edinburgh Handedness Inventory (123). The average age of participants was 24.5 years (range = 21-34 years, SD = 3.7 years). All participants had normal or corrected-to-normal vision, with no history of movement or neurological disorders. Ethical approval was granted by the University of Leeds School of Psychology Research Ethics Committee (Ethics reference: 110101) and conducted in accordance with the 1964 Declaration of Helsinki. Participants provided their full informed consent prior to their involvement.

4.2.2. Kinematic Assessment Tool

The Kinematic Assessment Tool (KAT) was discussed in section 3.2 and is a validated system capable of measuring human movement in configurable visual-spatial tasks (99). The KAT captures objective behavioural within complex tasks, and has previously been shown to reliably distinguish between poor and proficient motor performance in younger and older adults, examine compensation mechanisms for decreased motor-skill, and provided evidence for structural learning of fine motor skills (99,101,124,125).

4.2.3. Laparoscopic Box Trainer

A laparoscopic box trainer (390 mm x 265 mm x 180 mm) was positioned 700 mm above the floor and rotated 90° anticlockwise with the shorter sides orthogonal to the supporting table. The box trainer had seven entry ports (a diameter of 40 mm and had a soft rubber entry in a cross hair shape) positioned in a letter ‘H’ configuration. An ENDOPATH® XCEL™ Dilating Tip 12 mm trocar was fully inserted through each port with the gas valve facing away from the participant. A 73 mm x 60 mm x 15 mm section of soft foam was used as a collar between the port and trocar to allow free range of movement. A Toshiba Portege M700-13P tablet PC (screen 260 x 163 mm; 1,440 x 900 pixels; 32 bit colour; 60 Hz refresh rate) running the KAT was placed inside the box trainer at the distal right corner and the built-in touch screen acted as an input device (Figure 4-1). A 330 mm long laparoscopic grasper with plastic tip was then inserted through the trocar and placed on the kinematic recording device. The lowest point of the screen was positioned 580mm above the table ensuring the display is presented at eye level. The endpoint of the laparoscopic grasper was represented by an onscreen cursor and controlled by moving across the touch screen. Black markers were placed on the floor to indicate where the participants should stand in order to ensure a consistent viewing distance of approximately 800mm.

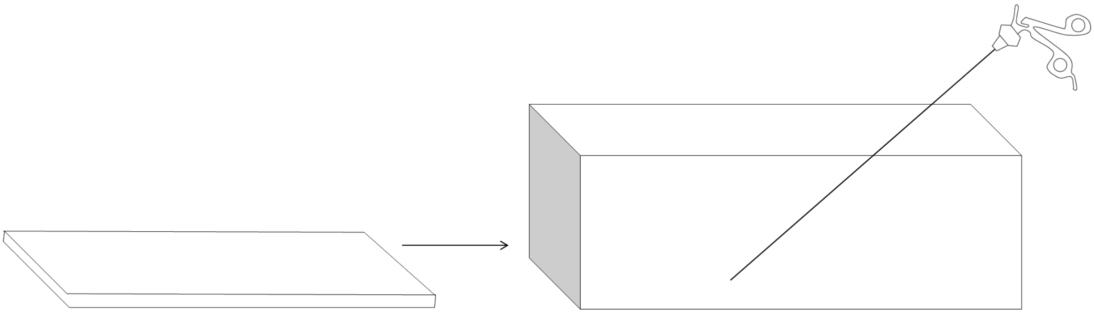


Figure 4-1: Diagrammatic representation of a laparoscopic box trainer. The touchscreen laptop seen here on the left is placed within the box trainer.

4.2.4. Visual-motor Transformation Task

Visual stimuli were presented on a Dell 1708FP monitor (screen 339 x 270 mm, 1280 x 1024 resolution, 75 Hz refresh rate) positioned at one of three angles 0°, ±45°, ±90° (Figure 4-2). These angles were defined by the angle between the central body axis of the participant in the coronal plane and the monitor screen. Participants were allocated randomly to one of six groups and performed the task 12 times at each monitor position (0°, ±45°, ±90°). There were a total of 20 movements in each trial. Allocation to these rotations were blocked and randomly ordered by participants based on a 'Latin Square' method.

Participants were required to make a series of discrete aiming movements between targets that appeared on the screen, with a 30° rotation applied. Each trial began at the start icon (the green 'S') and moved a cursor on the screen from one green dot to the next in a sequential manner (Figure 4-3). Once a green dot was reached the next green dot was displayed. Participants continued to move from one green dot to the next until they reached the finish icon. A distortion of 30° was applied to the visual feedback.

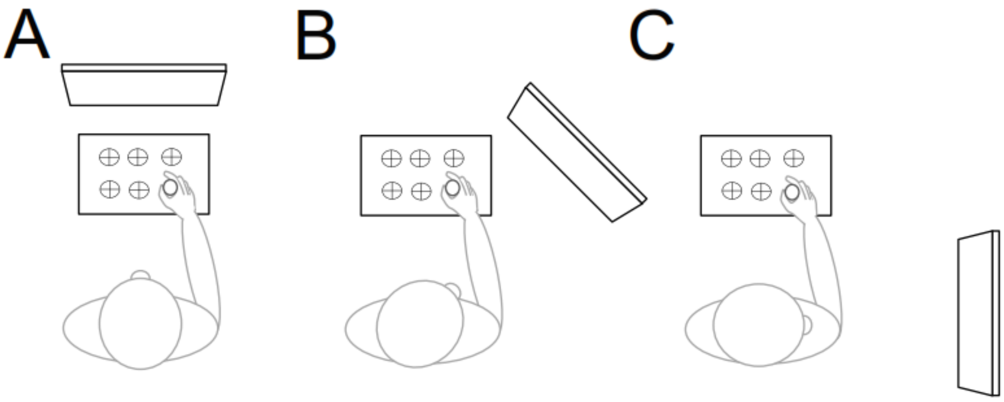


Figure 4-2: Diagrammatic representation of the experimental setup

(A) 0° Rotation: Participants held a laparoscope in their right hand and were instructed to trace a path, with visual feedback presented on a monitor directly ahead of them. The laparoscope was inserted through a trocar. **(B) 45° Rotation:** Participants engaged in the same task, however, visual feedback was presented on a monitor positioned at 45° Rotation relative to body orientation. **(C) 90° Rotation:** the monitor was oriented at 90° degrees relative to body position.

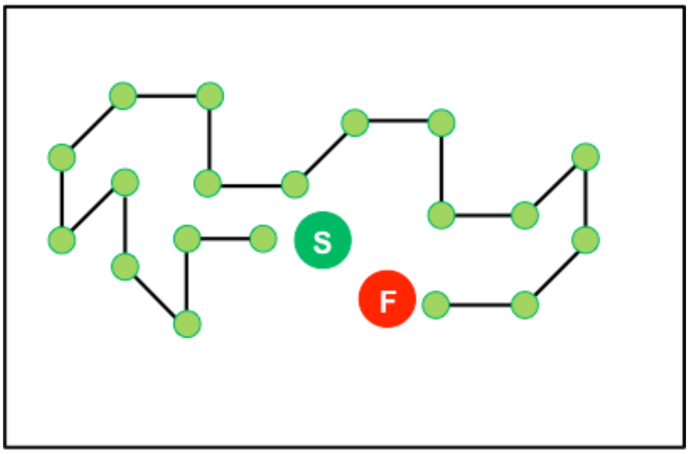


Figure 4-3: Diagrammatic representation of the task schematic

Participants, using the laparoscopic tool, moved a cursor presented on the screen from one dot to the next in a sequential manner. A distortion of 30° was applied to the visual feedback. There were a total of 20 movements in each trial. Each condition consisted of 12 trials.

4.2.5. Kinematic Outcome Measures and Data Analysis

Data analysis focused on the following standardised temporal, spatial and frequency indices some of which were introduced in the previous chapter:

(i) Mean Movement Time (MT): the duration between the start and end of the movement, as an indicator of movement speed (in sec).

(ii) Path Length (PL): the length of movement trajectories (in mm) from start to finish of an aiming task trial, and an indicator of spatial accuracy- longer trajectories indicate disruption to the path of movement, either due to increased motor variability (e.g. ‘shaky hands’) or deviation from the straight path between aiming targets.

(iii) Normalised Jerk (NJ): Jerk is the time derivative of acceleration and is minimised in smooth movements. NJ thus provides a marker of accuracy, specifically in the ‘smoothness’ of a movement.

4.2.6. Statistical Analysis

Data were subjected to a 3 (Rotation; 0° vs. 45° vs. 90°) X 2 (Time; Early [First 4 trials] vs. Late [Last 4 trials]) repeated measures ANOVA for each metric.

4.2.7. Study Design

This study was a within subjects design. The three main dependent variables (MT, PL and NJ) were subjected to a 3 (Rotation; 0° vs. 45° vs. 90°) X 2 (Time; Early [First 4 trials] vs. Late [Last 4 trials]) repeated measures ANOVA for each metric. In order to avoid order effects (e.g. practise and fatigue), allocation to conditions was counterbalanced across participants.

4.3. Results

Metrics for the first and last four trials across three screen positions: 0°, 45° and 90° for MT, PL and NJ are shown in Figure 4-4.

4.3.1. Movement Time

Analysis of MT data revealed main effects of Position ($F(2, 34) = 4.16$, $p = .024$, $\eta 2p = 0.2$, $1-\beta = .69$) and Trial ($F(1, 17) = 22.18$, $p < .001$, $\eta 2p = 0.57$, $1-\beta = .99$). Participants were significantly faster at completing the aiming task when the monitor was 0° from midline (mean PLT = 1.13 s, SE = 0.06), compared to the 45° (mean = 1.16 s, SE =0.05) and 90° (mean = 1.25 s, SE = 0.06) conditions (see Figure 4-4A and Figure 4-5A). Aiming movements also gained speed towards the end of the task, with significantly faster movements made across the L4 trial block (mean MT in F4 = 1.27 s, SE = 0.06; L4 = 1.13 s, SE = 0.05; Figs.4a and 5a). There was a significant Position x Trial interaction (F(2, 34) = 4.18, p = 0.024, η2p =0.2, 1-β = .7) whereby the effect of Position was present in the F4 trials (F(2, 34) = 5.13, p = .011, η2p = 0.23, 1-β = .79), but not in the L4 (F(2, 34) = 1.04, p = .37, η2p = 0.6, 1-β = .06). Bonferroni post-hoc comparisons subsequently showed that this effect of Position in the early trials was driven by a significant difference (p = 0.023) between the 0° (mean = 1.15; SE = 0.06) and 90° screen Positions (mean = 1.40sec; SE = 0.10) and between 45° (mean = 1.20 s, SE = 0.06) and 90° screen Positions (p = .027). There was no significant difference in MT between the 0° condition and 45° condition (p = .89). There were no differences across the L4 trials (p's > .266).

4.3.2. Path Length

Path Length provides an index of movement accuracy, whereby shorter PLs indicate better spatial accuracy because trajectories are shorter. Observations of the means showed that there was little difference in PL between the monitor Position conditions (mean PL for 0° = 47.30mm, SE = 0.97; 45° = 47.65mm, SE = 0.84; 90° = 49.47mm, SE = 1.42), hence the main effect of Position was not significant (p = .15). Participants did, however, show significant improvements in spatial accuracy as the task progressed – a main effect of Trial (F(1, 17) = 6.2, p = 0.02, η2p = 0.27, 1-β = .65; Figures 4-4B and 4-5B), revealed shorter PLs in the L4 trials (mean = 47.57; SE = 0.091) in comparison to the F4 (mean = 49.0; SE = 1.32). There was no Position x Trial interaction (p = .23).

4.3.3. Normalised Jerk

Lower NJ values indicate smoother aiming movements. The ANOVA for NJ showed that there was no main effect of Position (F(2, 34) = 1.26, p = .3, η2p = 0.07, 1-β = .26) and no Position x Trial interaction (F(2, 34) = 2.52, p = .1, η2p = 0.13, 1-β = .47). Nevertheless, there was a main effect of Trial (F(1, 17) = 11.85, p = .003, η2p = 0.41, 1-β = .9; Figures 4-4C and 4-5C), as participants produced increasingly smoother aiming movements towards the end of the task in the L4 trials (mean NJ for L4 = 611.20; SE = 83) compared to the F4 trials (mean PL for F4 = 903.44; SE = 130.92).

Figure 4-4 show metrics for first and last four trials across three screen positions: 0°, 45° and 90°. Error bars represent 95% confidence intervals after removing between-subject variability.

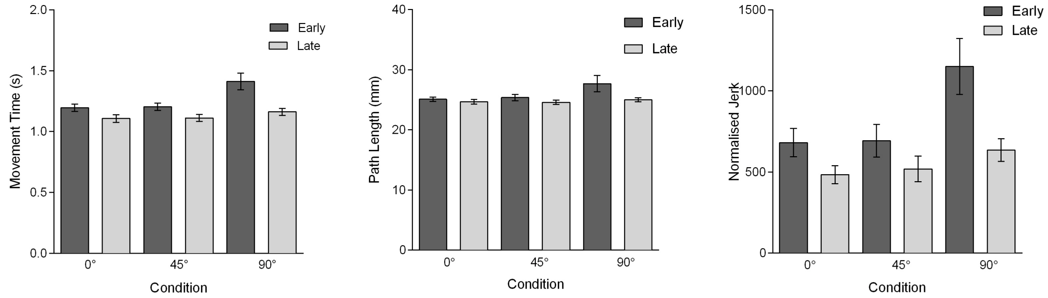


Figure 4-4: Early vs. late motor performance. Data are plotted for each metric for each trial; (A) Movement Time (MT; sec), (B) Path Length (PL; mm), (C) Normalised Jerk (NJ).

It is important to note that, whilst a comparison between the first four trials and last four trials is reported here, the same pattern of results are obtained when comparing the first and last three trials and first and last six trials (see Figure 4-5 for a trial-by-trial view of the data). To examine more precisely when the initial performance decrement for the 90° condition had been overcome by participants, we performed a post-hoc ANOVA for MT at trial 5 and found that differences were not statistically significant (p > .05).

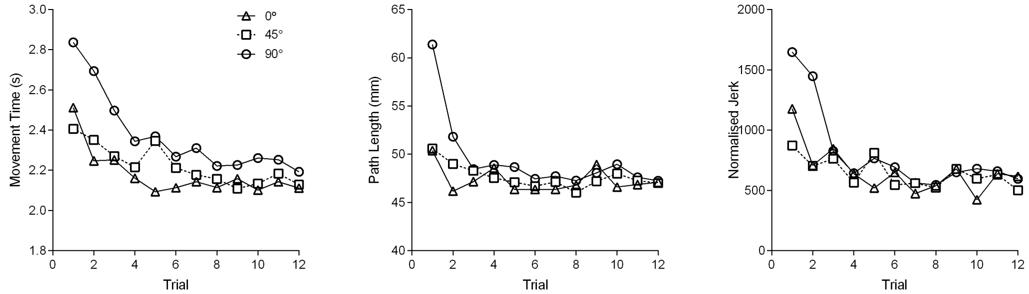


Figure 4-5: Trial-by-trial performance. Data are plotted for each metric for each trial; (A) Movement Time (MT; sec), (B) Path Length (PL; mm) and (C) Normalised Jerk (NJ).

4.4. Discussion

The human CNS displays a remarkable ability to account for changes in the relationship between visual input and the movement control signals to interact with the world in order to carry out skilled manual control. However, MIS presents a challenge to the completion of skilled manual control behaviours as the viewing angle in these environments does not provide useful information about the visual-motor mapping. The purpose of this experiment was to quantify the effects of monitor position on movement proficiency. This was achieved by varying the position of the monitor displaying visual feedback of the task from directly in front of the participant (0°), to a rotation of ±45°, and ±90°, relative to the central body axis. Participants completed a kinematic visual-motor transformation task with a laparoscopic tool, and performance metrics allowed us to assess the extent to which rotation modulated task performance. The same task was used throughout the experiment. This has potential to confound findings as effects may be due to learning. To negate this the experiment was designed so that the next dot in the pattern was not displayed until the preceding dot had been reached by the cursor, therefore, the overall pattern was not visually displayed at any point to the participant. In addition a 30° rotation was applied to negate the learning effect (101).

There was no difference in motoric performance between 0° and 45°. However, consistent with previous literature indicating optimal performance with the monitor at 0° with significant degradation in performance beyond 45° (117,121,126,127), there was an observed significant decrease in performance in MT in the initial trials in the 90° condition. Path Length (PL – an index of accuracy) and NJ (a marker of fluency/smoothness) demonstrated similar trends, but did not reach statistical significance thresholds. This may be due to a lack of sufficient power to detect a 3x2 ANOVA interaction due to the number of participants (18 in total). However, several previous similar studies have demonstrated such an effect with similar numbers (93,95,99,101,102,117,124,125,128,129).

Being able to quickly adapt to information presented in different locations and use this input for actions has clear advantages for a surgeon that has to simultaneously: (a) deal with complex environments and (b) produce skilled goal-oriented behaviour. Adaption depends on the integration of visual-to-proprioception mismatch across learning (130). In this experiment, the initial decrement in performance when the monitor was positioned at 90° had almost disappeared by the end of the task. In other words, initial performance was degraded, yet individuals were able to adapt to the new head orientation, a particularly useful process in an MIS environment, when the monitor position can vary from theatre-to-theatre.

There is a functional relationship between head position and arm movements (131). Previous research has demonstrated that neck afferents are important for accurate control of the hand in the absence or degradation of visual-motor information (131,132), and vestibular information contributes to the control of arm movements (133,134). Yet, despite these biases in the sensorimotor system, the current data add to a plethora of literature that the CNS is able to adapt to visual and mechanical distortions (135,136). However, whilst the adaption of the human sensorimotor system is clearly an impressive feat, the temporary impairment in performance during this adaptation to a change in visual-motor axis is one that may be problematic in a surgical scenario. This may have clinical implications for complex operations where it may be necessary to change the port-site through which the camera is passed; or in surgical procedures where a re-adjustment of the camera is required. For example, in gastric bypass surgery it is sometimes necessary to divide adhesions in the pelvis. This seemingly simple task is made difficult as the ‘set-up’ of the procedure is altered when operating switches to the pelvis, movements are ‘inverted’ and the surgeon needs to reverse his/her movements. Moreover, when a surgeon moves from one operating set-up to another – for example between an ‘elective’ theatre to the ‘acute’ theatre, or from a real-life scenario to a training simulator (typically a 0° set-up); the role of monitor orientation should be considered to maintain maximal operative efficiency.

These data raise an important question regarding surgical training. How can we minimise the negative effects of visual-spatial distortions and transformations in MIS? The widespread use of virtual reality simulators such as the LAP Mentor™ allow students to potentially practice their skills frequently, and in a safe environment, before entering a real-life scenario. The degree to which simulators provide useful generic training that applies to a variety of surgical tasks is not currently clear, nor are there guidelines on how to structure training time (e.g. repeatedly carrying out the same task to gain high-proficiency in an isolated skill vs. carrying out a variety of surgical tasks). Critically, a common feature within these training programs is the use of a monitor with no screen rotation (i.e. screen directly in front of the trainee). If trainee surgeons practice their skills with this set-up, it is highly likely to yield a cost when the same task must be carried out when the screen is set off at an angle in theatre. These results, and those of past studies, predict that the cost would manifest in reduced motor speed and this may be amplified in a situation where a surgeon has limited experience (120).

Structural Learning (SL) theory predicts that learning a surgical technique in a virtual context should transfer to a similar situation in real life if training allows one to learn the fundamental underlying structure of the parameter space. According to SL when learning a new skill (such as a novel MIS technique), the CNS creates a general set of rules that can later be applied and modified when encountering similar scenarios (e.g. a more rotated monitor position) (52,56). This process, often described in the cognitive literature as “learning to learn” (i.e. where common features in a cognitive task are said to facilitate learning of a new but similar task), may be a crucial part of gaining general skills and given training time constraints, surgeons must be able to adapt without significantly reducing skill in one specific set of circumstances (101). In light of these findings, surgeons might be best advised to avoid using monitor positions that deviate from the body midline where possible. In order to ensure that surgical trainees are fully prepared for work in different hospitals/theatres, future research should present trainees with varying monitor display positions in simulation. SL predicts that this approach will lead to learning that yields adaptability without loss of specificity and shall explore this in the following chapter.

4.5. Conclusion

These data suggest that the alignment of the visual display in MIS modulates task performance. While this adaptation seems to occur relatively quickly, this may still interfere with skilled actions complex surgical scenarios. These results have implications for surgical training and suggest that surgeons should avoid using unpractised monitor positions which deviate from the axis of the camera.

5. Maximising MIS performance in LAP-KAT

5.1. Introduction

Minimally invasive surgery (MIS) is challenging because the brain must control complex movements using extremely limited sensory information obtained from a rapidly changing environment. Recent advances in psychology, neuroscience and machine learning have started to explain the amazing capacity that humans show for learning to move within sparse environments (53,137).

The previous chapter explored one possible source of intra-operative variability - the degree to which the camera moves during MIS. Another potential source of variation, particularly in more complex surgery, is the switching of instruments between different port-sites in order to better access the target organ(s). These will depend largely on the surgery being performed. As previously discussed an operation such as a LC or robotic prostatectomy) requires a relatively static visual field and therefore there will be limited movement of the camera around the abdomen. In contrast, during a laparoscopic gastric bypass or colectomy (removal of a section of bowel) a variety of locations within the abdomen need to be visualized throughout the procedure. It would be expected that a static camera view would provide a useful frame of reference when adapting to the other visual-motor distortions present during MIS. When the image and the target organ is no longer a fixed reference, then continuous recalibration of the visual-motor mapping may be required.

During more complex laparoscopic surgery four to six ports are typically required to gain adequate access to the target structures and the surgeon will switch between ports throughout the surgery. The physical properties of laparoscopic tools means that switching ports changes the relationship between the surgeon’s hand movements and the movement of the tool (a relationship known as the visual-motor mapping). For example, switching to a port which is closer to a target structure means smaller movements of the laparoscopic tool handle are required to create the desired movement of the tip, the force requirements change, and disparate arm movements recruiting different joints and muscle groups are needed. Heuer and Sulzenbruck (138) studied the trajectories of the hand and of the tip of a handheld sliding lever in aiming movements. They observed that the movement of the effective part of the tool is the primary kinematic variable in motor planning and control even in the absence of continuous visual feedback. If the surgeon’s visual-motor system is unable to estimate these new task parameters, the accuracy and/or speed of movement will be impaired, increasing the risk of direct harm (such as inadvertent perforation of an organ) and indirect harm (prolonged general anaesthesia) to the patient (113,114).

5.1.1. Port Switching

As introduced in the previous chapter the structural learning theory of motor control suggests that it may be possible to minimise the deleterious consequences of switching between different ports through certain training regimes. To conceptualise this theory it is useful to consider a familiar occurrence of learning a new visual-motor mapping - driving a new car with different steering characteristics and new braking and acceleration capabilities. While a novice driver may find it difficult to switch from the car they have always driven an experienced driver who has driven many vehicles adapts to a new car quickly and easily. This phenomenon can be explained by structural learning theory, which suggests that experience can provide the human brain with exposure to a wide variety of conditions so that the underlying structure of the task can be learnt (56). A structure is a set of rules which describes how task parameters co-vary (i.e. how a set of forces applied to the brake results in different stopping times depending on the vehicle). Once the driver has discovered the structure, the problem of learning a related task (driving a new car) becomes much simpler (103).

A similar principle could apply to performing a surgical task through multiple ports. If surgeons are able to learn general rules about how port properties vary this may alleviate the negative consequences associated with port switching. Experimental findings show that training regimes in which task parameters are randomly or gradually varied provide support for the extraction of structural rules (56,103,139,140). Even when the structural rules are not extracted, motor task variation can improve future performance through other mechanisms (141–144). Despite this, current training systems offer little opportunity for variability and many focus on improving performance metrics under constant task parameters. Given that the fundamental assumption of surgical training systems is that any performance benefits will transfer to the operating room, it seems prudent to determine whether training regimes which vary task parameters (i.e. providing experience with different port conditions) would be better preparation for a novice surgeon.

The purpose of this experiment was to test whether training for MIS using varying ports would improve performance using a novel port. Traditional motor learning theory suggests that constant training conditions (i.e. using a single port) would allow participants to best improve their performance as the participants can consolidate their skill levels using feedback mechanisms on a task with stable ‘identical elements’ (145).

In contrast, structural learning theory would suggest that multiple port training should result in optimum training outcomes via the learning of general task structures.

5.2. Methods

5.2.1. Participants

Participants (N=20; 10 male, 10 female) were recruited from the University of Leeds (age range 16-31 years, mean age 23.2 years, SD 3.3 years). Given the difficulty in recruiting surgeons with a similar level of experience, only participants with no surgical background were recruited. A pilot study had previously been conducted which revealed no differences between surgeons and non-surgeons when performing novel motor tasks. Thus this sample allows reliable estimates of group differences to be extrapolated to surgical trainees.

No participants had any known neurological conditions/deficits and all had normal/corrected to normal vision. All participants completed the task with their right hand, and all were right handed as indexed by the Edinburgh Handedness Inventory (146) except for two who were classified as ambidextrous. One participant in the multiple port site group showed exceptionally poor performance at test and was identified as an outlier (Z-score on SACF = 2.37) and was subsequently excluded from further analysis. Ethical approval was granted by the University of Leeds School of Psychology Research Ethics Committee (Ethics reference: 12-0195) and conducted in accordance with the 1964 Declaration of Helsinki.

5.2.2. Apparatus

The laparoscopic box trainer (as described in previous chapters) was positioned 700 mm above the floor and rotated 90° anticlockwise with the shorter sides orthogonal to the supporting table. The box trainer has seven entry ports positioned in a ‘H’ configuration. Only the three proximal (P1, T1, P3) and a central port (P2) were used (Figure 5-1). The ports had a diameter of 40 mm and had a soft rubber entry in a cross hair shape. An ENDOPATH® XCEL™ Dilating Tip 12 mm trocar was fully inserted through each port with the gas valve facing away from the participant. A 73 mm x 60 mm x 15 mm section of soft foam was used as a collar between the port and trocar to allow free range of movement. A 330 mm long laparoscopic grasper with plastic tip was then inserted through the trocar and placed on the kinematic recording device (Figure 5-1).

A Toshiba Portege M700-13P tablet PC (screen: 257 x 160 mm, 1280 x 800 resolution, 120 Hz refresh rate) running the Kinematic Assessment Tool (KAT) was used to record endpoint position at 120 Hz (99). The tablet was placed inside the box trainer at the distal right corner and the built-in touch screen acted as an input device (Figure 5-1). Visual stimuli were presented on a Dell 1708FP monitor (screen 339 x 270 mm, 1280 x 1024 resolution, 75 Hz refresh rate) positioned behind the box trainer. The lowest point of the screen was 580 mm above the table. The rubber endpoint of the laparoscopic grasper was represented by an onscreen cursor and controlled by moving across the touch screen. Black markers were placed on the floor to indicate where the participants should stand in order to ensure a consistent viewing distance of approximately 800 mm.

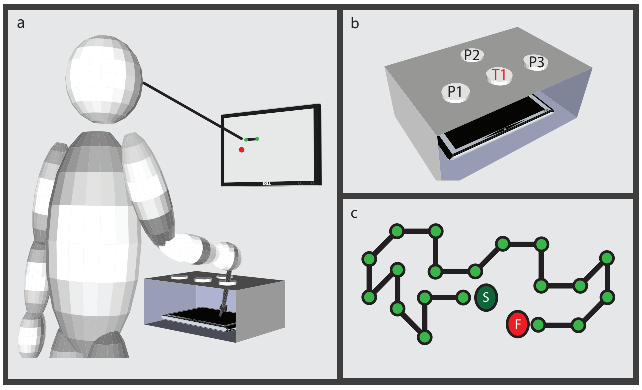


Figure 5-1: Diagrammatic representation of the experimental apparatus and set-up

(A) The experimental set up consisted of a laparoscopic training box with a touch screen laptop placed inside. Participants moved an onscreen cursor representing the tool end point to sequentially appearing targets. (B) The M group performed each training trial through ports P1, P2 or P3. The S group performed all training trials through port P2. At test both groups completed the task through port T1. (C) A total of 20 movements were made during each learning and test trial.

5.2.3. Task and Procedure

Participants were given standardised instructions at the start of each experimental block to perform the task as ‘quickly and accurately as possible’ using their right hand throughout.

The participants were randomly assigned to one of two groups: a single port-site group (S-port, N=10) or a multiple port-site group (M-group, N=10). All groups completed an identical baseline trial in which they made 60 consecutive aiming movements to sequentially appearing targets (green circles, 4 mm diameter, 115 mm apart), keeping the end of the laparoscopic grasper in contact with the touch screen at all times. All baseline trials were performed through port P2. The trial was initiated by moving the cursor over the starting position (a target labelled ‘S’), after which the next target appeared. Targets were presented in a pentagram orientation, disappearing after the next target was reached (Figure 3-2).

The M and S groups then completed a training block consisting of 30 trials. Similar to the baseline trial, participants made aiming movements to sequentially appearing targets. Each trial was made up of 20 targets (approximately between 18 – 22 mm apart) while a straight black line connected the visible targets indicating the most direct path (Figure 5-1). During all learning trials a 40° visual-motor rotation was applied with an origin at the “S” start symbol such that the cursor moved away from the origin at a 40° angle relative to the laparoscopic endpoint position. The M group performed each trial through port P1, P2 or P3 in a pseudo random, non-repeating order. The S group performed all 30 trials through port P2.

The following day the participants in both groups completed a test block, consisting of 14 trials identical to those in the training block. Both groups then completed the test trials through the novel port-site T1.

5.2.4. Measures

Performance was characterised by examining four separate measures; MT, PL, SACF and NJ as previously described (99):

Mean Movement Time (MT), the time taken to move from one target to the next in seconds.

Path Length (PL), the distance taken to move between one target to the next in millimetres.

Speed Accuracy Composite Function (SACF), is a measure that accounts for both the speed and accuracy of each movement (slower movements are usually more accurate, and vice versa). This was calculated as follows: SACF=MT × PL.

Normalised Jerk (NJ) is the time derivative of acceleration normalised over distance and time to allow for comparison between trajectories of different lengths and durations. NJ provides an index of “smoothness”.

5.2.5. Statistical Analysis

The mean scores for movements within and across all trials were calculated for each participant. This was performed on SACF, MT, PL and NJ measures of movements. Independent t-tests to compare SACF and NJ between both M and S groups were then carried out.

5.2.6. Study Design

This study was a between subjects design. Participants were randomly allocated to one of two group (M vs S). The four main dependent variables (MT, PL, SACF and NJ) were subjected to a independent t-test (M group vs S group) for each metric.

5.3. Results

5.3.1. Baseline Performance

Baseline visual-motor performance was calculated from the first 50 movements for each individual. There were no differences between the S and M groups on measures of SACF ($t(17)= -0.67$, $p > 0.05$), MT ($t(17)= -0.31$, $p > 0.05$), PL ($t(17)= -0.35$, $p > 0.05$ or NJ ($t(17)=0.37$, $p > 0.05$). Participants across groups were, therefore, considered to have similar levels of visual-motor ability at baseline.

5.3.2. Performance at Test

At test the M group showed a statistically significant performance advantage over the S group as indexed by SACF ($t(17)=2.23$, $p < 0.05$; Figure 5-2a). In order to explore the performance advantage further, the component measures (MT and PL) were examined. MT was shorter for the M group than the S group ($t(17) = 2.29$, $p < 0.05$; Figure 5-2c), however, no differences in mean PL was found between groups ($t(17)=.29$, $p > 0.05$; Figure 5-2d). This suggests that the S group were able to achieve similar accuracy to the M group but there was an added cost in terms of slower movement speed. In addition to exhibiting shorter MT, the M group also demonstrated significantly reduced NJ compared to the S group ($t(17)=2.23$, $p < 0.05$; Figure 5-2b).

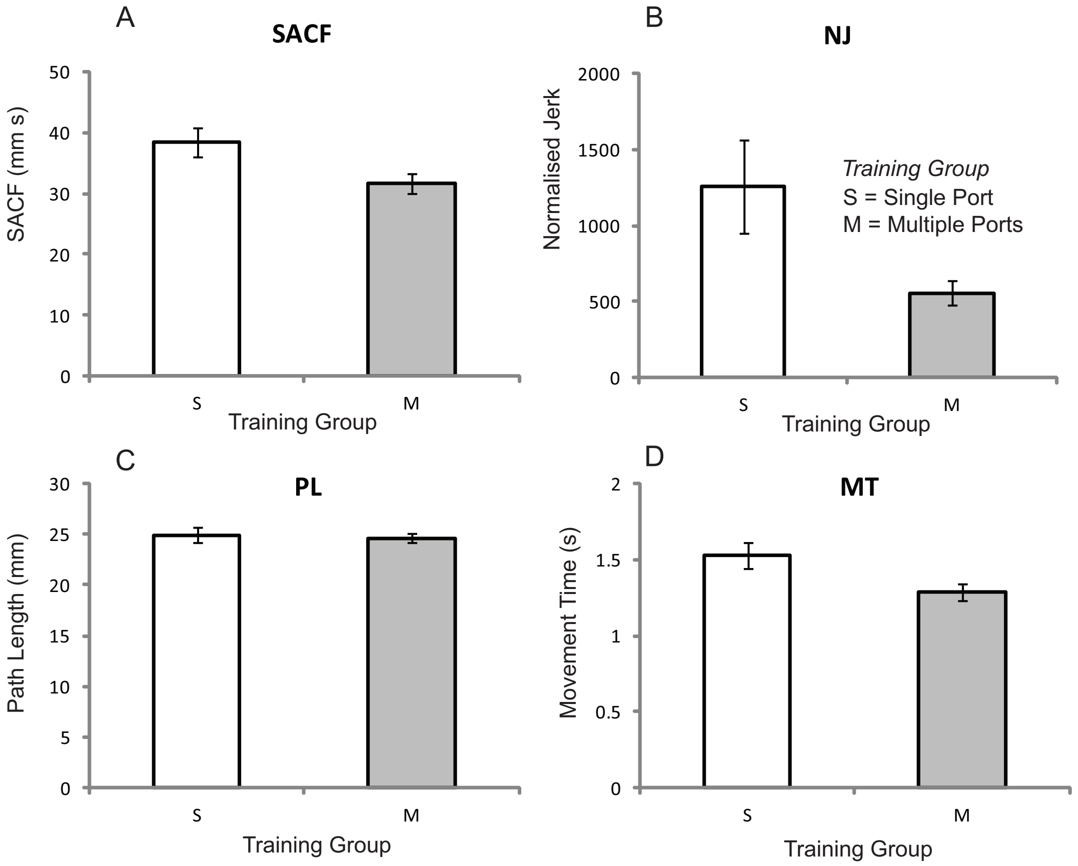


Figure 5-2: Performance of the 'S' and 'M' groups in SACF, NJ, PL and MT

Training with a Single port (S, white bars) or Multiple ports (M, grey bars). Different panels indicate performance as measured by: (A) Speed Accuracy Composite Function (SACF), (B) Normalized Jerk (NJ), (C) Path Length (PL) and (D) Movement Time (MT). All error bars = Standard Error.

5.4. Discussion

A lifetime of experience interacting with the world leads humans to develop finely tuned visual-motor maps used to help carry out skilled actions. One reason that MIS is such a challenging task is that it alters the relationship between a motor action and the outcome (as perceived visually), which requires a new mapping to be learnt (or existing mappings to be adjusted). Further complexity arises from the fact that these mappings may vary depending upon which tool and port site is being used. As such, it is not straightforward to determine the optimal training regime for learning to perform laparoscopic surgery.

This chapter examined whether theoretical understanding of how the central nervous system "learns to learn" could be used to inform laparoscopic training. The particular problem of how best to prepare an individual to use a familiar laparoscopic instrument through a completely novel port site was investigated. One group was trained with multiple port sites and compared their performance to another group which was trained using a single port site. While both groups experienced the same number of training trials, the single port site group experienced far more consistent conditions. These results show, however, that performance at the novel port site was best after training using multiple port sites. This result is predicted by structural learning theory, which states that motor task variation can allow the central nervous system to learn general rules about how task parameters co-vary (53).

Port site variability also determines angle of instrument relative to the task and thus the visual-motor map and ergonomics of the task which can in turn influence performance (71,80,128,147–150). Sub-optimal port-site placement has a detrimental effect on the task ergonomics which can degrade performance whilst the converse is also true (71,80,128,147–151) . This could have had a potential confounding effect on this experiment with the P1 and P3 ports conferring an advantage to the M group and or the P2 port a disadvantage to the S group. However, ports on the box trainer are not widely spaced as described in the above studies and the chosen ports (P1-3) are at 90^0 to the test port (T1) therefore the relative angle of change between tasks for each group was the same (Figure 5-1).

While the beneficial properties of motor task variation have been known for some time (141,152), structural learning was only recently proposed as a mechanism by which "learning to learn" could occur in the motor system (56). Several studies have now demonstrated the ability of the central nervous system to learn task structures which facilitates the acquisition of new but similar skills (101,103,104,139,140,153). These data align well with structural learning theory, indicating that surgical trainees should be encouraged to introduce variability early in their practice. Specifically, training boxes and virtual reality trainers should be designed with motor task variation in mind.

It is tempting to try to extrapolate from these findings further guidelines for training to cope with various variables present in the surgical environment. It seems reasonable to suggest that varying the relationship between body-axis and camera-axis (and/or the display-axis) during training would help attenuate any adverse effects in terms of surgical performance. What is crucial, however, is ensuring the right balance between varying task parameters and allowing consolidation and improvement (i.e. repeating similar conditions). While previous studies demonstrate that both random and gradual variation of task parameters improve future learning (104), rapid changes in the environment may result in reduced retention rates (154). In essence while variability in practice should improve the ability of a surgeon to cope with a changing surgical environment, they still need some consistent performance feedback to hone their skills.

5.5. Conclusion

This chapter demonstrates the potential to reduce the risk of human error in MIS while decreasing the time required for novice surgeons to reach proficiency. This has practical applications for trainers of junior surgeons and also for the development of surgical simulation devices that may need to incorporate greater variability into future training programs.

6. Maximising MIS Performance in VR

6.1. Introduction

MIS requires surgeons to acquire highly specific psychomotor skills enabling them to perform complex tasks while adapting to the tactile and visual sensory limitations of the operating environment. This has led to an emphasis on the importance of fundamental abilities (e.g. psychomotor skills, visual-spatial ability and depth perception) that are critical for performing MIS.

Previous chapters have explored potential factors resulting in variation of performance in MIS. This chapter investigates a possible method of ensuring maximal visual-motor performance during MIS.

In fields with large psychomotor components, such as sports, dance and music, it is commonplace for individuals to participate in a warm-up prior to engaging in their particular activity. MIS is a high-stakes, expertise driven field (76,155) and requires strenuous physical and mental activity (155,156) it therefore follows that warming-up prior performing MIS may improve intra-operative performance.

Several authors have investigated the potential benefit of a warm up prior to MIS. A variety of methodologies have been adopted to investigate this phenomenon. Some investigators have used simple balance games to warm-up (157), whereas others used bespoke tools (155), video games (158) box trainers or VR simulators (159,160). Similarly a variety of tools have been used to measure outcomes. Commonly box trainers or VR simulators have been used for a variety of reasons including availability, reproducibility and the variety of metrics they can calculate. Critically simulators do not require actual patients meaning they are more feasible to run (155,157–160). As with the modality of assessment there is also variety in particular outcome measures analysed. The majority of studies used validated global rating assessments which were scored by an expert examiner and/or outcome metrics generated by the VR simulator. These included analysis of metrics such as time taken, economy of movement (hand and tool movements and speed) and errors in performance.

Other investigators have looked at the effects of warming up on actual operative performance (161–164). The majority have adopted laparoscopic cholecystectomy as their assessment procedure (162–164), however, Lee et al investigated effect on laparoscopic renal surgery whilst Weston et al also used laparoscopic appendicectomy in addition to cholecystectomy. Whilst most studies use general surgical trainees with a range of experience levels some of the above studies use obstetrics and gynaecology, vascular and urological trainees. These papers are summarised in Table 6-1.

These studies have demonstrated:

(i) Benefit of warming up on a bench top model for performance on a bench top model
(ii) Benefit of bench-top, video game and VR warm-up on VR simulator performance
(iii) Benefit of VR warm-up (with or without bench top model) simulator on operative performance.

Interestingly Weston et al did not demonstrate any benefit of the bench top model alone or console based video games on actual operative performance. However, this study recruited a sample size smaller than the authors' power calculation deemed would be necessary.

The limited number of studies, variety of tools used to warm-up and assess outcome and measures used to assess performance means it is difficult to assess benefit of warming up across these studies. In addition the existence of only one study finding no benefit of warming up suggests the possibility of publication bias of only studies with positive results. This is reinforced in that several of the studies that contain non-significant as well as significant results (155,157–161,163,165).

It is not clear from any of these studies if the specificity of warm-up (e.g. bench top models or VR simulation) improves performance or if a generic warm-up would have equal benefit to performance (e.g. five minutes standardised, reproducible basic laparoscopic tasks). This is important as large VR simulators are expensive and relatively immobile with maintenance requirements and additional upkeep costs (e.g. upgrades such as additional procedures, computer processing etc). A relatively cheap, mobile, reproducible system with similar efficacy would help address these limitations.

Table 6-1: Summary of results of published articles investigating the benefit of warming up on surgical performance. O&G = obstetrics and gynaecology. GS = general surgery. Numbers in parentheses indicate number of procedures performed. RCT = randomised control trial. RCOS = randomised cross-over study. NRT = non-randomised trial

Authors	Number of Participants	Type of Study	Specialty of participants	Warm-up Tool	Outcome Tool	Conclusion
Kroft et al	14	RCOS	O&G	Intracorporal suturing on bench top model	Bench top model	Benefit
Kahol et al	46	NRT	O&G, GS, Trauma	Bespoke laparoscopic bench top tool	VR simulator	Benefit
Lee et al	28	RCOS	Urological	VR simulator + bench top model	Laparoscopic renal surgery	Benefit
Moldovanu et al	1 (20)	NRT	GS	VR simulator	Laparoscopic cholecystectomy	Benefit
Rosser et al	303	NRT	Not specified	Video games (console based)	Bench top model	Benefit
Weston et al	9 (109)	RCT	GS	Bench top model or video games (console based)	Laparoscopic cholecystectomy or appendicectomy	No benefit
Do et al	24	NRT	O&G (12) Medical students (12)	Bench top model	Bench top model	Benefit

Willaert et al	20	RCOS	Vascular surgery Cardiology Radiology	VR simulator	VR simulator	Benefit
Calatayud et al	8 (16)	RCOS	GS	VR simulator	Laparoscopic cholecystectomy	Benefit

There are several limitations to the studies shown in Table 6-1. Studies which have used bench top models (159,166) for tasks such as intra-corporeal suturing are not identically reproduced and standardised for each participant. For example a subject could get stuck at a particular point (e.g. mounting the needle) and hence could spend a disproportionate amount of time of this particular aspect of the task compared with another participant. Others used videos games (157,158,162) to overcome this particular issue. However, whilst these warm-up task are reproducible, video games work by rewarding progress, therefore, a participant who ‘succeeds’ in the game more than another will progress further and therefore experience a different warm-up to a participant who does not progress as well. Only Kahol et al used a bespoke tool for participants to warm-up with. The task involves correct laparoscopic placement of rings on pegs. However, the warm-up is deemed ‘complete’ once ten rings have been correctly placed meaning some participants which experience disproportionately shorter or longer warm-ups depending on their success at the task.

In addition, whilst several of these studies attempt to address the effect of the ‘learning-curve’ (for example Calatayud et al used a randomised cross-over design) it is difficult to differentiate from the effect of warming-up. None of these studies performed a post-hoc test with no warm-up. It would follow that if the improvement in performance was due to warming up and not learning that a post-hoc assessment would should performance similar to that in control conditions (ie with no warm-up)

The purpose of this experiment is to determine if the specificity of the warm-up affects operative performance. The LAP-KAT system will be used to investigate if a standardised, repeatable laparoscopic warm-up can improve performance. This experiment will compare the effects of warm-up using the LAP-KAT to the effects of warming with the LAP Mentor™ VR simulator and to assess if performance levels returned to baseline post warm-up interventions as hypothesised above.

6.2. Methods

6.2.1. Participants

Participants (N=16; 13 male, 3 female) were recruited from the General Surgical Department of St. James’ University Hospital (SJUH) in Leeds. All participants had, as a minimum, completed basic surgical training and had performed a minimum of 10 laparoscopic cholecystectomies at the point of recruitment.

No participants had any known neurological conditions/deficits and all had normal/corrected to normal vision. All participants completed the task with their right hand, and all were right handed as indexed by the Edinburgh Handedness Inventory (146). Ethical approval was granted by the University of Leeds School of Psychology Research Ethics Committee (Ethics reference: 13-0054) and conducted in accordance with the 1964 Declaration of Helsinki.

6.2.2. Apparatus

6.2.2.1. The Laparoscopic Box Trainers

As in earlier chapters the laparoscopic box trainer (previously described) was positioned 700 mm above the floor and rotated 90° anticlockwise with the shorter sides orthogonal to the supporting table. A Toshiba Portege M700-13P tablet PC (screen: 257 x 160 mm, 1280 x 800 resolution, 120 Hz refresh rate) running bespoke software (Kinematic Assessment Tool) was used to record endpoint position at 120 Hz. The tablet was placed inside the box trainer at the distal right corner and the built-in touch screen acted as an input device (Figure 5-1). Visual stimuli were presented on a Dell 1708FP monitor (screen 339 x 270 mm, 1280 x 1024 resolution, 75 Hz refresh rate) positioned behind the box trainer. The lowest point of the screen was 580 mm above the table. The rubber endpoint of the laparoscopic grasper was represented by an onscreen cursor and controlled by moving across the touch screen. Black markers were placed on the floor to indicate where the participants should stand in order to ensure a consistent viewing distance of approximately 800 mm.

6.2.2.2. The Simbionix LAP Mentor™

The Simbionix LAP Mentor™ is a laparoscopic surgical virtual reality simulator. It has a large variety of laparoscopic tasks such as basic familiarisation tasks aimed at improving orientation, eye hand coordination and manual skills; for example passing objects from hand to hand, use of electro-cautery and pattern cutting. There are set-by-step laparoscopic suturing modules with or without guidance to teach intracorporeal suturing and knotting techniques for all fields of laparoscopic surgery. Suturing basic skills include needle loading, needle insertion, knot tying, interrupted and continuous suture. Advanced tasks include practicing 'backhand' technique and suturing in difficult suture line angles. The LAP Mentor™ also has full laparoscopic procedures in general surgery (such as gastric bypass, cholecystectomy and incisional hernia repair) as well as urological procedures (e.g. nephrectomy) and gynaecological operations (e.g. salpingectomy, salpingectomy and salpingo-oophorectomy).

The LAP Mentor™ calculates a series of metrics to assess performance and progress. These can broadly be categories into metrics relating to time taken/economy of movement, those related to safety of performance and those related to errors during surgical performance. These are shown in Table 6-2.

Table 6-2: LAP Mentor™ Metrics

Metrics related to time and economy of movements	Metrics related to safety	Metrics related to errors of performance
Procedure time (min) Number of movements of right/left instrument Total path of instruments (cm) Average speed of instruments (cm/second)	Total cautery time (min) Inappropriate cautery time (min) Safe cautery (%)	Number of organ perforations Number of non-cauterised bleeding Number of possible damage to vital structures

6.2.3. Task and Procedure

Due to the involvement of the LAP Mentor™ (which is only semi-mobile) all experiments were performed at the LIMIT Suite (Leeds Institute for Minimally Invasive Therapy) at SJUH, Leeds.

Subjects participated in four different sessions each at least 24 hours apart. These are shown in Table 6-3 . In the first session (C) participants performed a 'control' laparoscopic cholecystectomy (LC). The following two sessions participants performed a warm-up prior to a 'test' LC. In one session participants warmed up using the LAP Mentor™ (W1) or by performing a LC using the LAP-KAT (W2). Participants were randomised as to which order they performed these session in. At the final session (PT) participants performed a further LC using the LAP Mentor. The LC performed on the LAP Mentor™ was the same throughout the whole experiment.

Table 6-3: Task arrangements for warm-up experiment.

Session	Task
1: Control (C)	Participants underwent a brief familiarisation session with the LAP Mentor™. Once they were satisfied they performed a laparoscopic cholecystectomy using the LAP Mentor™.
2: Warm-up 1* (Simulator) (W1)	Participants performed a warm-up by performing a laparoscopic cholecystectomy using the LAP Mentor. They then performed another laparoscopic cholecystectomy immediately afterwards using the LAP Mentor™
3: Warm-up 2* (KAT)** (W2)	Participants performed a warm-up by performing a simple task using the LAP-KAT with their dominant hand. They then performed a laparoscopic cholecystectomy immediately afterwards using the LAP Mentor™.
4: Post-hoc test (PT)	Participants performed a laparoscopic cholecystectomy using the LAP Mentor™.

* participants were randomised to either performing session this session second or third

**The LAP-KAT warm-up task performed in session 3 (KAT) is shown in Figure 6-1.

6.2.3.1. LAP-KAT Task

Participants were required to negotiate the cursor representing the end of the laparoscopic grasper from one target dot to another. They were instructed to keep the grasper in contact with the screen at all times. Once subjects placed the stylus on the 'start' button the task begins by displaying the first target dot. Participants moved the grasper to this target dot. Once it was reached, it 'disappeared' and the next target dot was displayed in a different location on the screen. Participant were instructed to move successively from one target to the next until the end of the task. This occurred when subject had made a total of 75 aiming movements. Within these 75 movements the participants moved between five target locations forming a pentagram. Dots were displayed in a random distribution.

Participants used their dominate hand to perform the task and accessed the LAP-KAT via the central port-site nearest to them (P2 in Figure 5-1). Once completed participants immediately performed a LC on the LAP Mentor™.

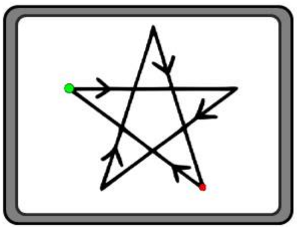


Figure 6-1: Diagrammatic representation of the LAP-KAT task used in Session 3 (KAT). Nb; this is the same task used in Chapter 3.

6.2.4. Measures

All LAP Mentor™ metrics were recorded. The following measures were analysed to assess overall performance, number of errors and quality/economy of performance.

- Overall time to extract gallbladder (GB) (min)
- Number of perforations
- Number of possible incidents of damage to vital structures
- Number of movements
    - Right hand
    - Left hand
- Total path length (cm)
    - Right hand
    - Left hand
- Average Speed of instruments (cm/s)
    - Right
    - Left

6.2.5. Statistical Analysis

A repeated measures ANOVA with session as a factor (Control vs Simulator vs KAT vs Post Test) was used to study the differences between sessions for the measures listed above. Pairwise analysis was performed to compare between sessions. Bonferroni correction was used to adjust for familywise error.

6.2.6. Study Design

This study was a between subjects design. The main dependent variables (sessions) were subjected to a 4 (sessions) X 2 (measure [e.g. time to extract gallbladder]) repeated measures ANOVA for each metric. In order to avoid order effects (e.g. practise and fatigue), allocation to warm-up condition was counterbalanced across participants.

6.3. Results

All participants completed all four sessions with the exception of two participants who was unable to attend for session 4 (PT). These individual's data was retained for the overall analysis

6.3.1. Overall Time to Extract Gallbladder

Overall there was a significant difference in time to extract the GB between sessions (F(3, 39) = 9.747, p <0.001, η2p = 0.428). There was a significant difference in total time to extract the GB between the Control and Simulator and LAP-KAT sessions (p<0.001 for both cases). This difference persisted in post-hoc testing (p=0.001). There was no significant difference between Simulator and LAP-KAT nor PT (p=0.888 and 0.589). There was also no significant difference LAP-KAT and PT (p=0.702) (Figure 6-2).

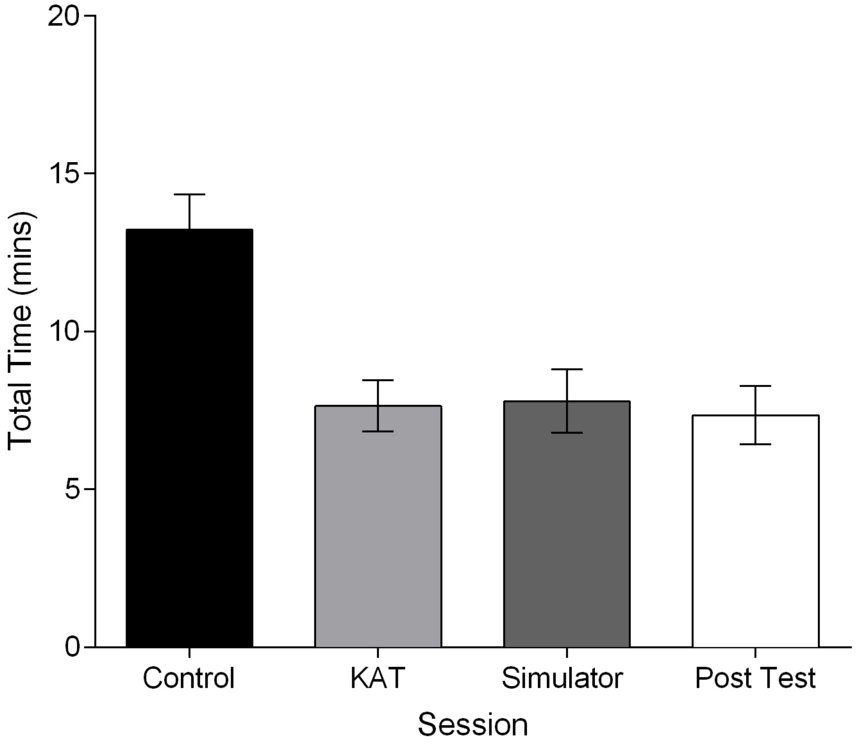


Figure 6-2: ANOVA plot of mean with standard deviation (SD) time taken to extract gallbladder. Simulator = VR performance following VR warm-up LAP-KAT= VR performance following LAP-KAT warm-up PT = post test

6.3.2. Errors in Performance

6.3.2.1. Number of Perforations

Overall there was a significant difference in number of perforations between sessions (F(3, 39) = 3.203, p = .034, η2p = 0.198). There was a significant difference in number of perforations between the Control session and Simulator (p=.033) and PT (p=.015) sessions but no significant difference between control sessions and the LAP-KAT session (p=.803). There was no difference between number of perforations in the Simulator session and LAP-KAT and PT sessions (p=.132 and 0.724 respectively). There was no significant difference between LAP-KAT and PT sessions although this relationship approached significance (p=.054) (Figure 6-3).

6.3.2.2. Possible Damage to Vital Structures

There was no significant difference in possible damage to vital structures between sessions (F(3, 39) = 1.190, p = .261, η2p = 0.097) (Figure 6-3).

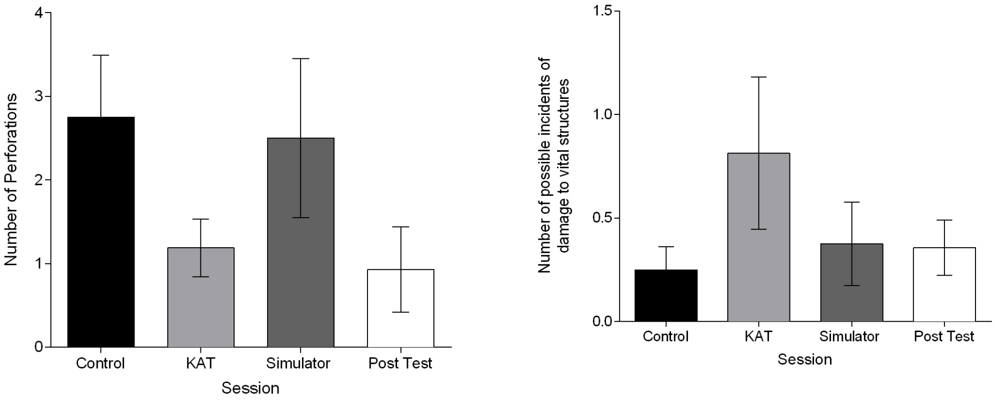


Figure 6-3: ANOVA plots of mean number with SD of errors related metrics. (A) number of solid organ perforations. (B) number of potential incidents of damage to vital structures

6.3.3. Economy of Movement

6.3.3.1. Path Length – right hand

Overall there was a significant difference in mean path length between sessions for the right hand (F(3, 39) = 16.484, p <0.001, η2p = 0.559). However, as with time taken to extract GB and perforations this was driven by differences between the control session and the other three sessions (Simulator, LAP-KAT and PT – p<0.001 for all). There was no significant difference between the remaining sessions (Figure 6-4).

6.3.3.2. Path Length – left hand

Overall there was a significant difference in mean path length between sessions for the left hand (F(3, 39) = 15.946, p <0.001, η2p = 0.551). As with path length for the right hand. this was driven by differences between the control session and the other three sessions (Simulator, LAP-KAT and PT – p<0.001 for all). There was no significant difference between the remaining sessions (Figure 6-4).

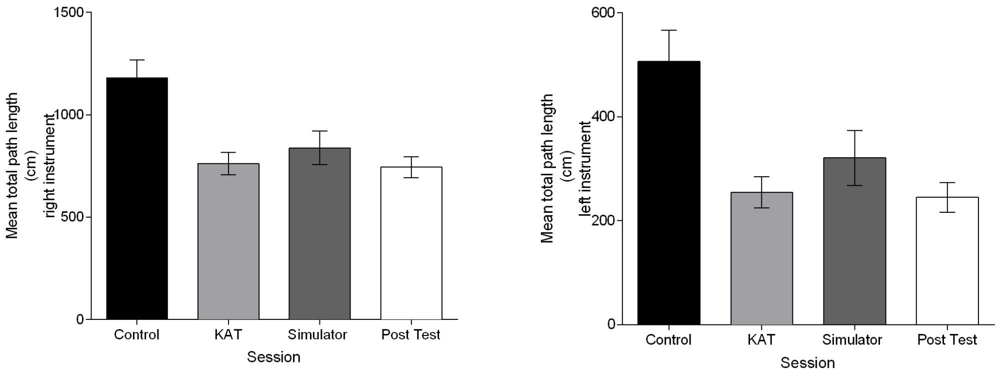


Figure 6-4: ANOVA plots of mean with SD total path length of instruments (cm). (A) Right (B) Left

6.3.3.3. Number of Movements – right hand

Overall there was a significant difference in number of movements between sessions for the right hand (F(3, 39) = 26.537, p <.001, η2p = 0.671). However, this was driven by differences between the control session and the other three sessions (Simulator, LAP-KAT and PT – p<.001 for all). There was no significant difference between the remaining sessions (Figure 6-5).

6.3.3.4. Number of Movements – left hand

Overall there was a significant difference in number of movements between sessions for the left hand (F(3, 39) = 22.508, p <0.001, η2p = 0.634). There was a significant difference between the control session and Simulator, LAP-KAT and PT (p<0.001 for all). There was no significant difference between Simulator and LAP-KAT (p=0.425) and Simulator and PT (p=0.16). There was a significant difference between the LAP-KAT and PT sessions (p=0.041) (Figure 6-5).

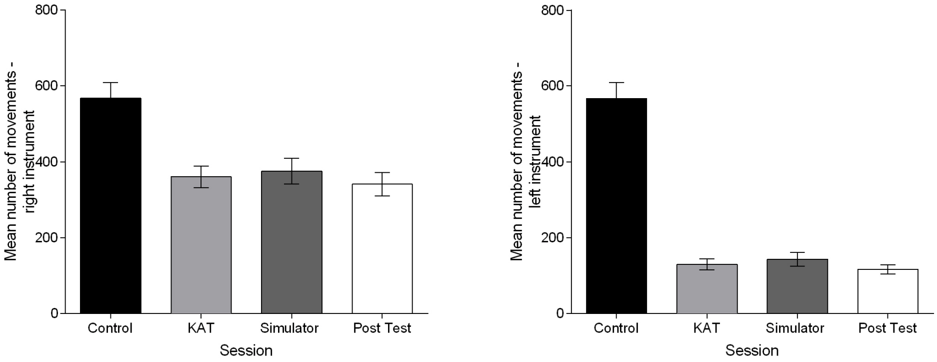


Figure 6-5: ANOVA plots of mean with SD number of instrument movements. (A) Right. (B) Left

6.3.3.5. Average Speed of Instrument

There was no significant difference in average instrument speed between sessions for either the right hand (F(3, 39) = 1.553, p = .216, η2p = 0.107) nor the left hand (F(3, 39) = 0.056, p = .982, η2p = 0.004) (Figure 6-6).

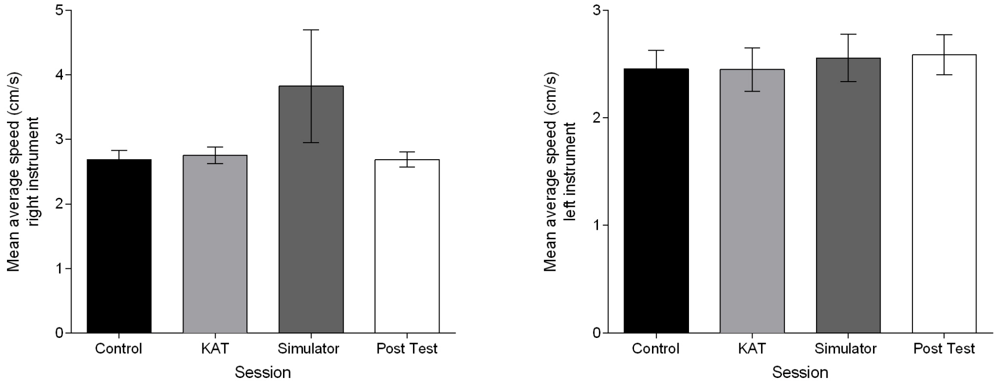


Figure 6-6: ANOVA plots of mean with SD instrument speed (cm/second) of instruments. (A) Right. (B) Left

6.4. Discussion

MIS is a high-stakes, expertise driven field (76,155). Participants in other similar, high-pressure fields perform a warm-up prior to performance. Several previous authors have investigated the effect of warming up. However, it is not clear from any of these studies if the specificity of warm-up improves performance or if a generic warm-up would have equal benefit to performance. The purpose of this experiment was to investigate if a standardised, repeatable laparoscopic warm-up can improve performance and to compare the effects of warm-up using the LAP-KAT to the effects of warming with the LAP Mentor™ VR simulator.

Results of this experiment demonstrated a significant difference in performance in time taken to extract the GB, instrument path length and number of movements (right and left hand for both) between conditions. However, pairwise analysis demonstrated that this difference was driven by differences between control performance and sessions 2, 3 and 4 (W1, W2 and PT). Given that performance in sessions 4 (PT) (when a LC with no warm-up was repeated) was similar to performance in sessions 2 and 3 (W1 and W2) this suggests that differences were due to an effect of learning as opposed to warming up. This experiment did not show any significant in average speed of instruments (left or right) nor in possible damage to vital structures. There were significant differences in number of perforations within the sessions, however, given that improvements persisted in PT and in the context of other results this is of doubtful significance.

It is worth noting some limitations. The relatively small number of participants particularly compared to studies such as Rosser et al (n=303) whilst the majority of other studies with similar designs had at least 20-plus participants. Due to the nature of the experiment it was deemed impractical not to use trained surgeons as opposed to surgically naive participants who would have required significant training in physiology, anatomy and MIS in order to perform the necessary tasks. However, this resulted in a wide variety in previous surgical experience in general and in performing LC specifically. Whilst all had performed a minimum of 10 ‘real’ LCs there was distinct variation between relatively junior and relatively senior participants, thus affecting the homogeneity of this sample. This may explain the large variation in performances across each session.

A further contributing factor may be the learning effect with regard to the LAP Mentor™ simulator. Despite all subjects having appropriate laparoscopic experience having completed at least core surgical training, the VR environment itself is unique and requires adjustment and task specific learning. This was evidenced by substantial decrease in performance after the first session and may have contaminated any tangible effect of warming up.

Another factor related to learning might be familiarisation with the VR simulator affecting surgical approach. A common surgical technique is to not completely remove the GB from the liver bed prior to controlling all bleeding points. Once haemostasis is secured the GB is removed. This is to prevent the GB becoming lodged somewhere else in the abdomen prior to removal. As such some subjects were observed in the control performing this technique. However, as they repeated the task and became familiar with it the subjects realised that once the GB had been detached the LAP Mentor™ would demonstrate the GB being removed from the abdomen and haemostasis could then be secured. Thus the incidence of this technique was noted to decrease in subsequent sessions.

In addition, the repetitive nature of the experiment may also have contributed to non-significant results most notably in the post-test session. Participants made four separate visits to the surgical simulation suite. In PT all subjects performed a LC on the VR simulator with no warm-up. The purpose of this was to assess if their performance had returned to ‘baseline’ i.e. similar to that the control session. However, it is conceivable that some subjects may have become disillusioned and they were also aware this was the final session. Thus they may have attempted to perform the task as quick as possible. However, this is not reflected in the relevant metrics such as number of movements and speed of instrument.

In order to address some of these limitation any future study examining the benefit of warm-up of LAP-KAT should compare surgeons/trainees of a similar level preferably at different levels of experience (novice, junior, senior etc.). Ideally a larger number of participants should be recruited. To tackle the learning effect participants should be taught to a pre-determined level of competence prior to the study. An alternative control condition should also be considered, one that is not directly related to the outcome being measured such as intra- or extra-corporeal knot tying. In addition to address variation in familiarisation with the VR system more prescriptive instructions particularly in reference to what constitutes a ‘completed’ LC.

Kahol et al, who’s study had some design similarities to this one (bespoke laparoscopic warm-up tool and VR assessment) and had participants warm-up for 15 minutes prior to performing their assessment task (155). The warm-up in this experiment using the LAP-KAT was standardised for each participant performing the same 75 movements whilst the simulator warm-up consisted of performing a VR LC however long that took the participant. Whilst across most metrics there was no significant difference between performance following either LAP-KAT or LAP Mentor™ it is not possible to infer whether several minutes warm-up using the LAP-KAT is equivalent to a VR LC. However, should future studies demonstrate a benefit of warming-up with either the LAP-KAT or LAP Mentor™ then further investigation into the optimal warm-up time/tool/task/condition would be warranted.

In any subsequent studies, closer examination of the effect of learning would be required. In retrospect it would be best to test participants once learning has plateaued, which would make it easier to assess the contribution (if any) of warming up to performance. This is also more likely to reflect real world practice to assess any benefit to surgeons of warming up when they are already familiar with a particular MIS procedure. In order to negate the effect of variation within subjects due to experience one option would be to use surgically naïve participants. However, this would require provisional of a large educational package to ensure participants were able to perform the required tasks (i.e.: a simulated LC). This would be very time consuming and have a significant cost. This would likely be even greater if subjects had no medical background at all. In order to negate variations in technique between subject, any future studies should provide more detailed instructions to participants, particularly if it may result in them significantly changing their technique mid-study as described above. Another potential modification to the study design could include using actual operations instead of VR assessment as Calatayud et al, Weston et al and Moldovanu et al did in their studies. However, there is not enough evidence here to justify this ethically and benefit must be shown using either LAP-KAT or LAP Mentor™ (or both) before progressing to this next step. In addition there would be further confounding factors with this sort of design, such as variation in pathology, measurement of outcomes, the need for supervising surgeons to give advice during the surgery and maintaining patient safety at all times.

6.5. Conclusion

This experiment did not show any benefit of warming up with either LAP-KAT or LAP Mentor™, however, there were several limitations and confounding factors to this study. Given work by others have demonstrated a benefit of warming up using a variety of tools then further studies which address these limitations may help to address the issue of specificity in warm-up.

7. Discussion

MIS is an ever-expanding field of surgery. Whilst LS remains the mainstay of MIS in the UK on-going technological advances are pushing boundaries and redefining MIS. RAS, NOTES, single-port laparoscopic surgery (SILS) along with advances in ‘traditional’ LS have revolutionised patient care. NICE currently recommends MIS as first-line where possible for a range of surgical procedures including colorectal and prostrate cancer resection and bariatric surgery. The range of procedures recommended to be performed by MIS is only likely to expand in the future. However, MIS has several inherent constraints which have been discussed previously but include 2D to 3D transformation, the fulcrum effect and reduced haptic feedback. Understanding how these can affect MIS and how to maximize performance is critical to maintaining high patient care in the future. There are in essence three groups of surgeons; (1) the senior consultant who learnt exclusively open surgery and is transferring his/her skills to MIS (2) the new trainee learning many procedures exclusively as minimally invasive procedures and (3) the current trainee who is somewhere in between. Given the current financial constraints in health care and reductions in training opportunities maximizing training and operative performance are imperative to continue high levels of care.

A wealth of literature has been accumulated regarding the use of simulators in MIS in order to address these issues, however, there is much debate as to the best manner in which to utilise existing resources for training. The current generation of VR simulators have more of the look and feel of MIS, however, there has been limited regard paid to the basic principles of visual-motor learning theory and how this might best be applied to maximise surgical training as well as intra-operative performance.

The purpose of this thesis was to develop an in-depth understanding of motor performance in surgery. The aim was to do this by applying current theories of visual-motor learning and developing a novel approach combining existing surgical training tools with state of the art surgical technology and adapting a rigorous experimental psychology approach within a controlled laboratory environment rooted in the principles of motor learning. However, prior to conducting laboratory based experiments a survey of expert surgical opinion with a wealth of MIS knowledge was performed. This survey was developed to better understand how and why errors may occur during MIS and to improve existing knowledge regarding the occurrence of routine errors in MIS, their relationship to patient outcomes, whether they are even reported accurately and/or consistently and to garner expert opinion concerning factors that influence error rates. The survey was distributed to all members of the

ASGBI gathering information regarding experience of MIS errors, the reporting of such errors and the important factors affecting error prevalence during MIS. Two hundred and forty-nine ASGBI members completed some of the survey from a total membership of circa 2,300, the vast majority of which were consultants. The survey indicated that intra-operative errors during MIS occur frequently, with almost half of respondents reporting a significant error in their own performance in the past year that had adverse effects. Several common themes were highlighted for intra-operative errors including trainee experience/visual-motor skills, difficulty of case (e.g. patient anatomy or previous surgery) and fatigue/overwork, all of which may contribute to prolonged length of procedure. Better understanding of why errors occur, how surgeons learn MIS and the ways in which surgical performance varies will allow development of strategies to improve training and minimise intraoperative errors with resultant improvement in patient outcomes. Furthermore, training could be focused on those factors identified as the most important for performing surgery such as technical skills. However, surveys are potentially subject to reporting bias, and it is likely this evident in the surgeons underestimating their own intraoperative errors and overestimating errors by others. Similar biases have been observed in other domains of skilled performance, such as driving, whereby most people believe they are more skill full and less risky than average (167). Given that the survey respondents were only 10% of the total stated ASGBI membership, it is also possible that there were some selection biases, with more committed/interested surgeons taking part. These data highlight the need to better understand how and why technical errors occur which will in turn allow identification of factors that contribute to adverse events and improve patient outcomes. Having identified technical performance as a potential factor for suboptimal MIS performance a novel system of assessing visual-motor performance was developed to investigate factors than may be beneficial or deleterious to MIS performance.

The Omni-KAT system is a bespoke experimental tool combining the commercially available PHANTOM Omni with the KAT software and was designed to replicate the fundamental demands of MIS - specifically, the manipulation of tools in 3D from 2D visual information provided on a remote monitor display. A large range of forces, spatial restrictions and visual-motor mappings can be parametrically varied in order to manipulate and control the factors, which make MIS difficult. Participants were given the task of generating aiming movements along a horizontal plane to move a visual cursor on a vertical screen. One group received training that constrained movements to the correct plane whilst the other group was unconstrained and could explore the entire ‘action space’. Participants were then tested in the unconstrained environment.

The results demonstrated than MT at test was significantly better for participants who trained in an unconstrained environment versus those who trained in the constrained environment. These findings suggested that learning the device control dynamics is more beneficial than having the requisite plane for optimum movement made explicit and is consistent with the theory of structural learning. The practical implication of these findings is that surgical trainees should not be subject to constraints when learning new device dynamics and that training for a specific visual-motor skill can benefit performance in a similar tasks. These findings also demonstrate the usefulness of Omni-KAT in helping us understand how trainee surgeons can learn to move precisely during MIS and provide insights into optimal virtual training environments. However, there are limitations to the Omni-KAT system including that it is a uni-manual experimental tool as opposed to MIS which is bi-manual and the interface device is a stylus which is dissimilar to a laparoscopic instrument. Initial attempts to modify the Omni-KAT so the interface device was in fact a laparoscopic grasper were unsuccessful. In order to address this the LAP-KAT was developed to allow further investigation of MIS performance using a more appropriate input device.

In MIS, the natural relationship between hand and eye is disrupted i.e. surgeons typically control tools inserted through the patient's abdomen while viewing the workspace on a remote monitor. Previous studies suggest that the visual display should be placed directly ahead of the surgeon and at eye level, in order to minimize inconsistency between the hand and eye (117,119). The purpose of the experiment regarding monitor position was to validate the LAP-KAT system as an experimental tool for investigating MIS performance and to investigate and quantify the extent of the impact of rotation on surgical performance. The results demonstrated that, in keeping with previous studies, optimal performance with the monitor at 0° and significant degradation in performance beyond 45° and that spatial accuracy was unaffected by monitor position (118,121,126). Interestingly, the effect of reduced speed in the 90° was transient - decreasing over time, suggesting rapid adaptation to the rotation. According to structural learning theory when learning a new skill (e.g. a novel laparoscopic method), the CNS creates a general set of rules that can later be applied and modified when encountering similar scenarios (e.g. a monitor position off-set from midline) (52,57). This process, often described in the cognitive literature as "learning to learn" (i.e. where common features in a cognitive task are said to facilitate learning of a new but similar task), may be a crucial part of gaining general skills (101). The LAP-KAT system was then used to determine if structural learning theory can be applied to MIS to inform training methods and performance.

Certain MIS procedures (notably bariatric surgery) require frequent switching of instruments between different abdominal port-sites to allow the most efficient access to the target organ. For example, switching to a port which is closer to a target structure means smaller movements of the tool handle are required to create the desired movement of the tip, the force requirements change, and disparate arm movements recruiting different joints and muscle groups are needed. Structural learning theory would suggest that it would be possible to minimise the deleterious consequences of port switching through certain training regimes (56). If surgeons are able to learn general rules about how port properties vary this may alleviate the negative consequences associated with port switching. Given that the fundamental assumption of surgical training systems is that performance benefits will transfer to the operating room, it seems essential to determine which task parameters would be optimal preparation for maximising performance. In this experiment one group trained with multiple port sites and their performance was compared to another group which was trained using a single port site. The results demonstrated that that performance at the novel port site was best after training using multiple port sites and is consistent with structural learning theory and suggest that variability in training should be encouraged. This shows the potential to reduce the risk of human error in MIS while decreasing the time required for novice surgeons to reach proficiency and has practical applications for trainers of surgeons and also for the development of surgical simulation devices. The next step would have been to test this hypothesis using VR simulators to investigate if results could be replicated and then progress to trails for actual MIS on real-life patients. However, the prescriptive design of the existing VR simulators renders them inadequate to vary specific parameters as would be necessary to replicate the above study satisfactorily. Unfortunately, trials on real patients were beyond the scope of this thesis. Therefore, it was decided to further investigate other parameters that could potentially improve MIS performance using the now established LAP-KAT system.

In fields with large visual-motor components, such as sports, dance and music, it is commonplace for individuals to participate in a warm-up prior to engaging in their particular activity. Several authors have investigated the potential benefit of a warm up prior to MIS using a variety of methodologies (155,157–160). The final experiment of this thesis investigated whether the LAP-KAT could be engaged as a warm-up tool to improve MIS performance. It used the LAP Mentor™ VR system LC to assess MIS performance. The results from this experiment did not show any benefit of warming up and pairwise analysis demonstrated that the demonstrated differences were most likely due to the learning curve. There were several limitations to this study including most notably the range of previous surgical experience between participants. This was due to the practicalities involved in running the experiment and may explain the large variation in performances across each session. In order to negate this effect one option would be to use surgically naïve participants. However, this would require provisional of a large educational package. In any subsequent studies, it may also be best to test participants once learning has plateaued, which would make it easier to assess the contribution of warming up to performance. Given work by others have demonstrated a benefit of warming up using a variety of tools then further studies which address these limitations may help to address the issue of specificity in warm-up.

This thesis postulated the importance of visual-motor performance in MIS. Expert opinion in the form of the survey has supported this hypothesis and the experiments described have demonstrated two novel experimental tools that can be used to investigate the visual-motor components of MIS. Using a rigorous experimental psychology approach within a controlled laboratory environment this thesis has investigated the role current motor learning theory in MIS and demonstrated that the structural learning theory can be applied to MIS training and performance.

These results should inform current thinking on MIS training and performance particularly in light of recent financial restrictions within the NHS and the on-going reduction in training hours for surgical trainees. They should also inform future development of simulators with less emphasis on the look of the simulator and more on the ability to introduce variability within tasks. This would be advantageous in training and practice but also in further experimental work as current inflexibility in the procedures offered by the VR simulators limits the ability to investigate current motor learning theory using these tools. As more surgical departments move towards simulator training to fill gaps in training and experience a greater emphasis on ‘learning-to-learn’ in visual-motor tasks should be adopted within developing curricula.

In the future further development of existing technologies in both the experimental tools described above and the existing simulators available is needed to further investigate the role of structural learning in MIS performance. The two experimental tools developed for this thesis can be used to investigate different facets of MIS and can be further developed or amalgamated into one tool to aid further investigation of visual-motor performance in MIS. An ideal system would use a laparoscopic grasper in conjunction with the PHANTOM-Omni system and the KAT software. Additionally the combination of two of these systems would closely mirror MIS. What is crucial, however, is ensuring the right balance between the ability to vary task parameters and investigate appropriate variables.

Further investigation of the role of structural learning is required in simulation and in real-life. However, the current generation VR simulators do not allow the variations in set-up necessary to investigate structural learning in a similar experimental set-up to those described above. In-vivo testing is fraught with difficulties and confounding factors such as natural variation from patient to patient and the need to simultaneously deliver a high quality service to the patient. It is also likely that a larger body of theoretical work would be required in order to gain the necessary ethical approval for such an experiment.

Whilst warm-up with either LAP-KAT of the LAP Mentor™ did not convey an improvement in performance, the limitations and confounding factors described above combined with previous findings in the literature would warrant further investigation of this phenomena before being dismissed. Such a system might even be further developed to measure surgical ‘level’ prior to performing MIS. Prior to an operating list a surgeon’s visual-motor performance for that particular day could be assessed. If he/she was performing at a sub-optimal level then they might be best served to engage in further warm-up or not to proceed with an operation.

8. Conclusion

This thesis has contributed to existing knowledge of visual-motor learning in MIS and supports the crucial role of visual-motor performance in MIS. These experiments have demonstrated two experimental tools; the OMNI-KAT and the LAP-KAT which can be used to investigate visual-motor performance in MIS and the potential role structural learning takes in MIS performance. With further development these tools may have a role in supplementing surgical training and performance in the future. Whilst the benefits of warming up prior to surgery were not demonstrated this warrants further investigation in the future.

9. Appendix 1: Literature Review Summary

Reference	Study Type	Population	Method(s) of Psychomotor Assessment	Outcome Measure	Findings	Conclusions
McClusky et al.	Prospective correlation	Medical students (n=11)		Performance on Minimally Invasive Surgical Trainer–Virtual Reality (MIST-VR)	Number of trials required to train subjects to performance goals on the MIST-VR manipulation diathermy task is significantly related to perceptual and psychomotor aptitude.	
Ritter et al.	Prospective correlation	Medical students (n=11)	Performance on Minimally Invasive Surgical Trainer–Virtual Reality (MIST-VR)	Performance on VR endoscopic simulator	Subjects with higher MIST-VR scores required significantly less trials to reach proficiency in the endoscopic task	Testing of fundamental abilities could help identify trainees who will require additional training to achieve desired performance objectives.

Van Herzeele et al.	Prospective correlation	Medical students (n=20)	Perdue and grooved pegboard (FMS) MIST-VR	Vascular Intervention Simulation Trainer (VIST) assessment by experienced interventionalist	Initial performance Perdue pegboard correlated with VIST performance Pegboard tests also correlated with subjective assessment. End performance Perdue pegboard correlated with VIST performance and subjective assessment	Visual-spatial and psychomotor abilities have been identified as good predictors of initial and end performance in a VR endovascular simulator training schedule.
Schueneman et al.	Prospective correlation	Surgical residents (n=42)				
Steele et al.	Prospective correlation	Surgical residents (n=10)	the Crawford small parts manual dexterity test (FMS)	5 consecutive anastomoses on fresh porcine jejunum scored by a single	Positive correlation between the hidden figures score test and the improvement in the cumulative error score	Visual-spatial skills are more important than pure motor ability in predicting the capacity to perform an anastomosis and tests of manual dexterity may be

			the Gibson spiral maze test (FMS) the hidden figures test' (VSP)	observer a cumulative error score	Negative correlation between two other measures and error score	misleading in this context.
Dashfield et al.	Prospective correlation	Surgical residents (n=15)	ADTRACK 2 – a joystick-controlled pursuit tracking task	Ability to tie a surgical reef knot pre- and post training session assessed by experienced observer	significant correlation between the difference in knot- tying scores and ADTRACK 2 scores	manual dexterity, eye-hand co-ordination and other motor abilities are important determinants of an individual's initial level of knot-tying skill and performance.
Schijven et al.	Prospective correlation	Surgical residents (n=33)	Xitact simulator - laparoscopic cholecystectomy clip-and-cut scenery task	Abstract Reasoning test, the Space Relations test, the Gibson Spiral Maze	Abstract Reasoning Test and Space Relation Test, correlated with laparoscopic surgical performance on the Xitact simulator.	Concurrent validity of the Xitact LS500 with the combination of the Space Relations and Abstract Reasoning test measuring individual's visual-spatial

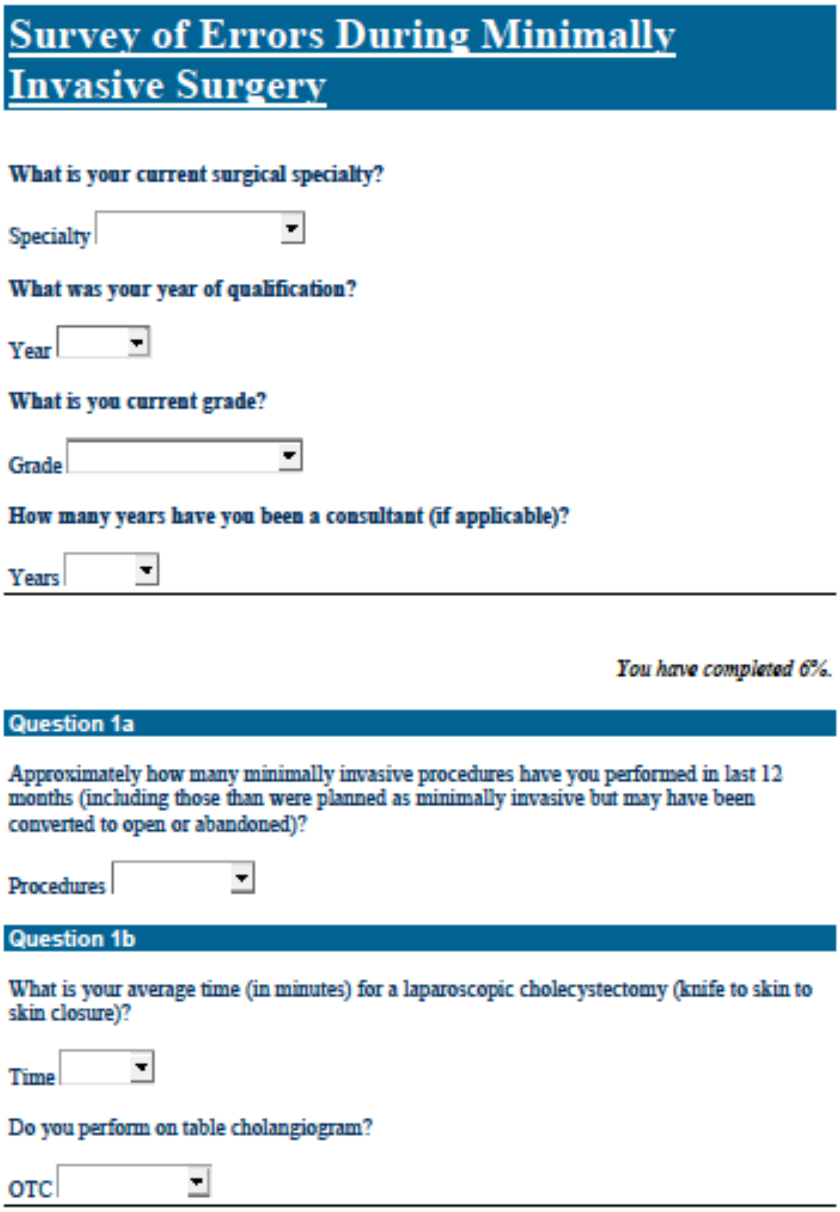
			30 repetitions	test, and the Crawford Small Parts Dexterity tester.		abilities.
Stefanidis et al.	Prospective correlation	Surgical residents (n=19)	Tremor test Reaction time Finger tapping Purdue Pegboard Grooved pegboard	Video trainer tasks MIST-VR tasks laparoscopic camera navigation tasks	Finger Tap test and grooved pegboard correlated significantly with the amount of simulator training required to achieve proficiency	psychomotor testing may be of limited value in the prediction of baseline laparoscopic performance, its importance may lie in the prediction of the rapidity of skill acquisition.
Wanzel et al.	Prospective correlation	Dental students (n=27) Craniofacial residents (n=12) Craniofacial attending surgeons	Crawford Small Parts Dexterity test	rigid fixation of an anterior mandible on bench model simulations. Assessed using ISOTRAK II System (motion	A sole significant correlation was seen between manual dexterity and total global rating score.	

		(n=8)		detector) measuring number of hand movements and path length OSATS – including global ratings score		

FMS = fine motor skill

VSP =visual-spatial ability

10. Appendix 2: Survey of Errors During MIS



Survey of Errors During Minimally Invasive Surgery

What is your current surgical specialty?

Specialty

What was your year of qualification?

Year

What is you current grade?

Grade

How many years have you been a consultant (if applicable)?

Years

You have completed 6%.

Question 1a

Approximately how many minimally invasive procedures have you performed in last 12 months (including those than were planned as minimally invasive but may have been converted to open or abandoned)?

Procedures

Question 1b

What is your average time (in minutes) for a laparoscopic cholecystectomy (knife to skin to skin closure)?

Time

Do you perform on table cholangiogram?

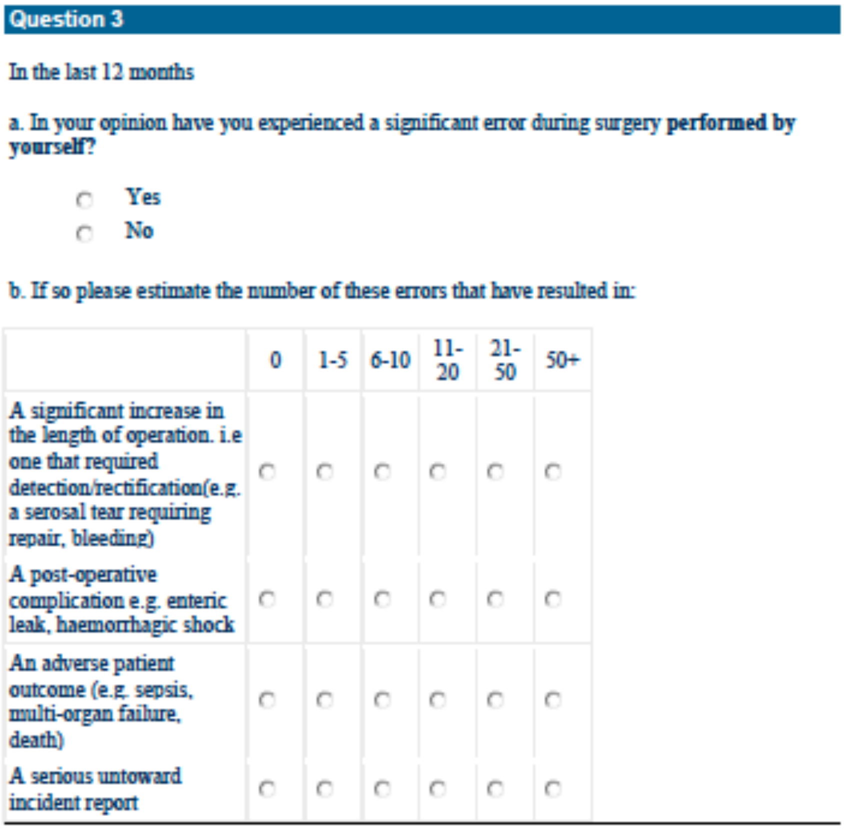
OTC

Question 2

Please rate the following factors on the degree to which they influence the likelihood of a surgical error occurring:

	Very important	Quite important	Not that important	Not at all important
Technical skill of operating surgeon	○	○	○	○
Technical demands of the operation	○	○	○	○
Technical skill of assistant	○	○	○	○
MIS procedure (as opposed to open)	○	○	○	○
Level of knowledge of surgeon (e.g. anatomical knowledge or knowledge of operative steps)	○	○	○	○
Intra-operative situational awareness e.g. awareness of hazards/potential hazards within the operation	○	○	○	○
Decision-making. i.e. ability to perform and progress operation safety	○	○	○	○
Communication breakdown within theatre team	○	○	○	○
Teamwork. i.e. with assistant, scrub nurse, greater surgical team	○	○	○	○
Leadership. i.e. ability of operating surgeon to direct surgical team effectively towards successful operation, deal with problems within team etc	○	○	○	○
Fatigue	○	○	○	○
Staffing levels	○	○	○	○
Excessive workload	○	○	○	○
Outside distracting factors	○	○	○	○
Regular and experienced theatre team	○	○	○	○

Are there any other important factors in surgical error you wish to mention that were not listed above?



Question 3

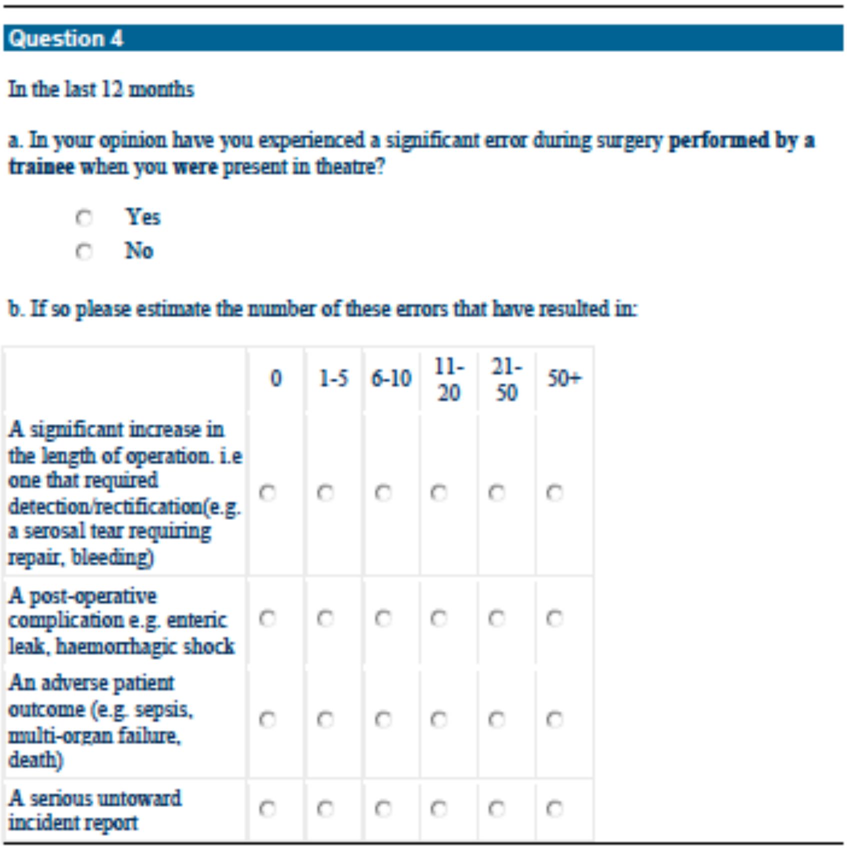
In the last 12 months

a. In your opinion have you experienced a significant error during surgery **performed by yourself?**

○ Yes
○ No

b. If so please estimate the number of these errors that have resulted in:

	0	1-5	6-10	11-20	21-50	50+
A significant increase in the length of operation. i.e one that required detection/rectification(e.g. a serosal tear requiring repair, bleeding)	○	○	○	○	○	○
A post-operative complication e.g. enteric leak, haemorrhagic shock	○	○	○	○	○	○
An adverse patient outcome (e.g. sepsis, multi-organ failure, death)	○	○	○	○	○	○
A serious untoward incident report	○	○	○	○	○	○



Question 4

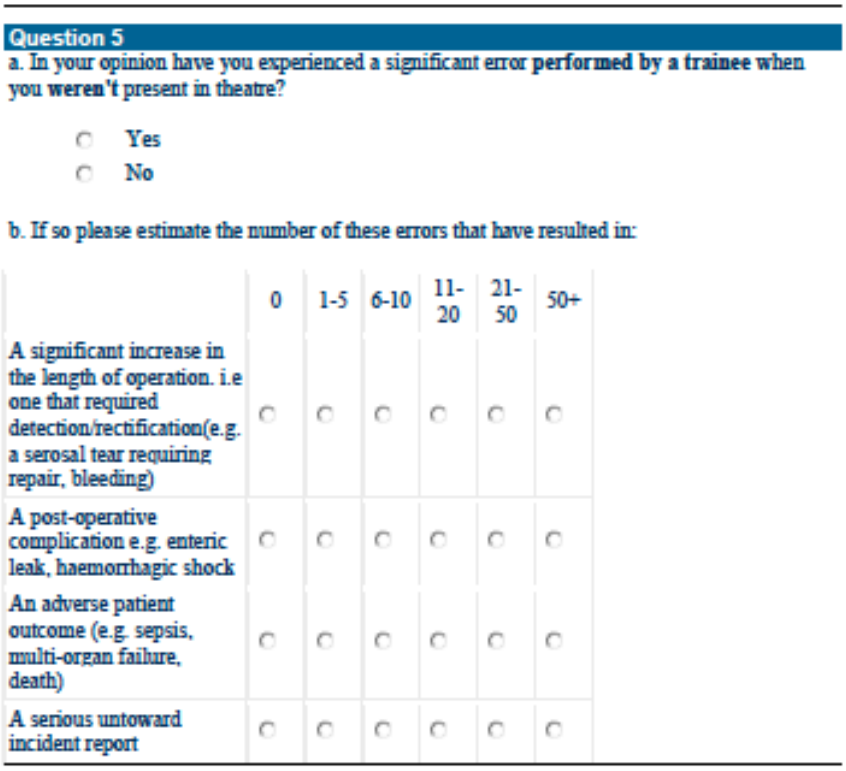
In the last 12 months

a. In your opinion have you experienced a significant error during surgery **performed by a trainee** when you were present in theatre?

○ Yes
○ No

b. If so please estimate the number of these errors that have resulted in:

	0	1-5	6-10	11-20	21-50	50+
A significant increase in the length of operation. i.e one that required detection/rectification(e.g. a serosal tear requiring repair, bleeding)	○	○	○	○	○	○
A post-operative complication e.g. enteric leak, haemorrhagic shock	○	○	○	○	○	○
An adverse patient outcome (e.g. sepsis, multi-organ failure, death)	○	○	○	○	○	○
A serious untoward incident report	○	○	○	○	○	○



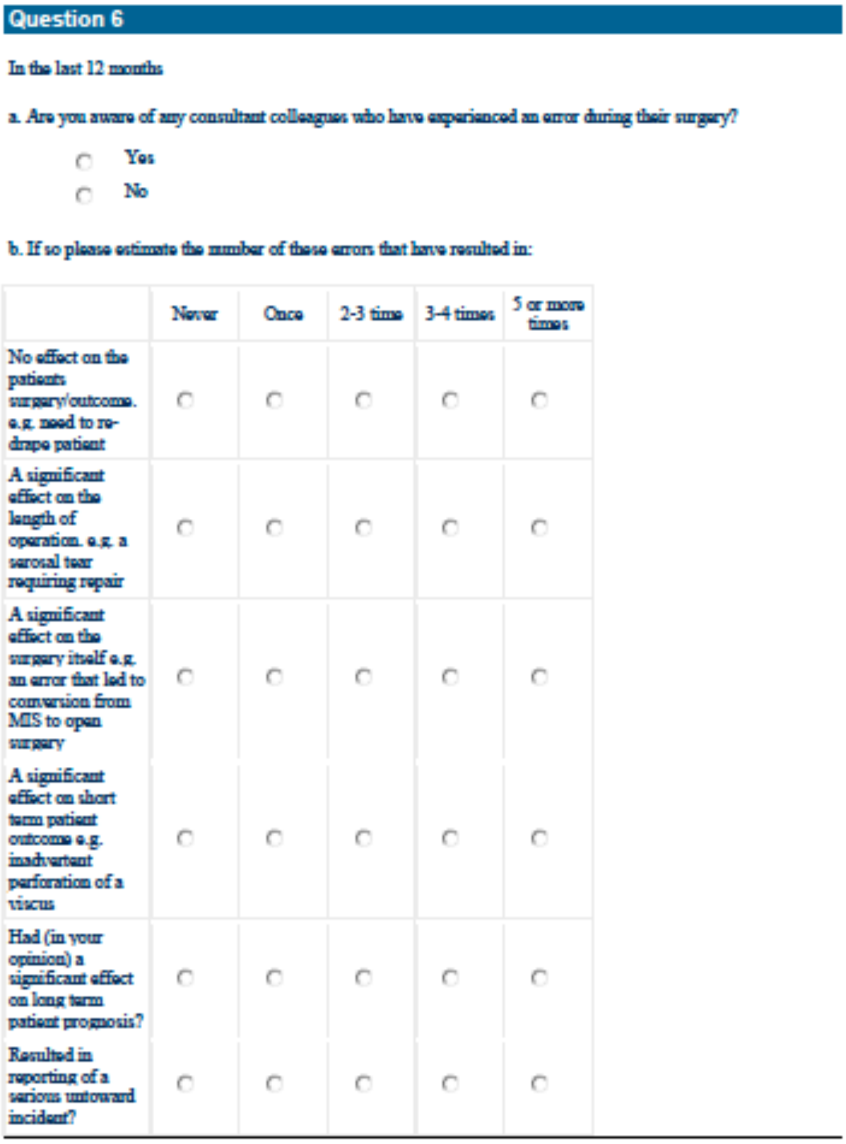
Question 5

a. In your opinion have you experienced a significant error **performed by a trainee** when you **weren't** present in theatre?

○ Yes
○ No

b. If so please estimate the number of these errors that have resulted in:

	0	1-5	6-10	11-20	21-50	50+
A significant increase in the length of operation. i.e one that required detection/rectification(e.g. a serosal tear requiring repair, bleeding)	○	○	○	○	○	○
A post-operative complication e.g. enteric leak, haemorrhagic shock	○	○	○	○	○	○
An adverse patient outcome (e.g. sepsis, multi-organ failure, death)	○	○	○	○	○	○
A serious untoward incident report	○	○	○	○	○	○



Question 6

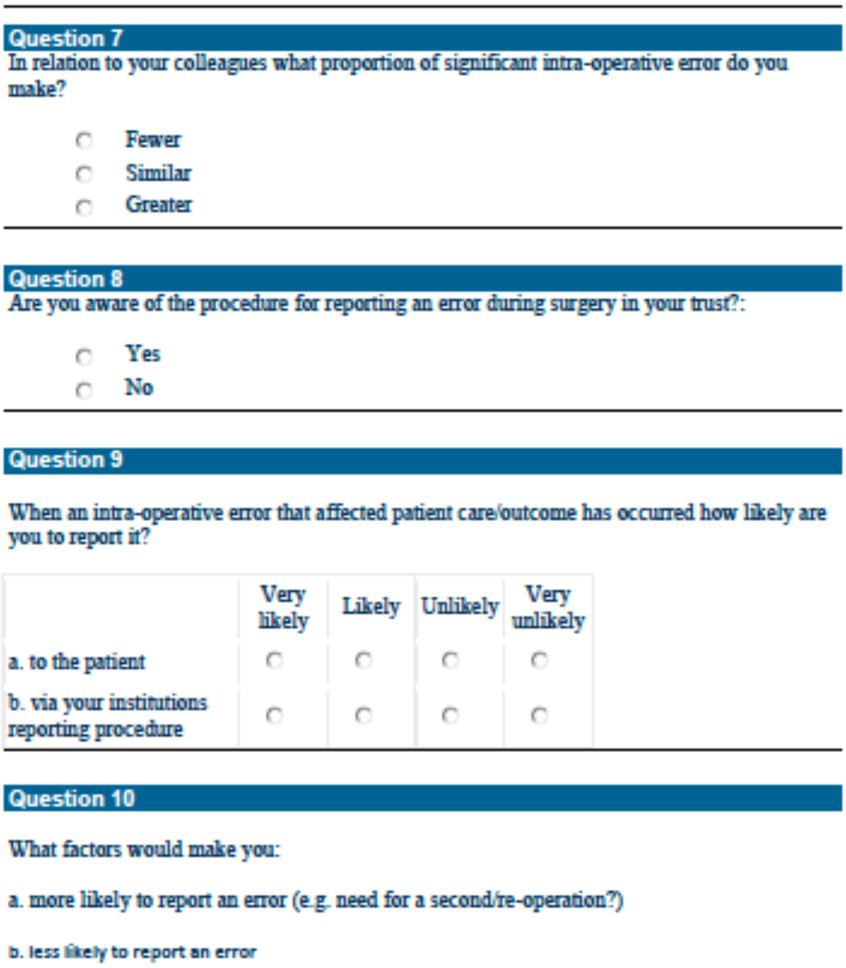
In the last 12 months

a. Are you aware of any consultant colleagues who have experienced an error during their surgery?

○ Yes
○ No

b. If so please estimate the number of these errors that have resulted in:

	Never	Once	2-3 time	3-4 times	5 or more times
No effect on the patients surgery/outcome. e.g. need to re-drape patient	○	○	○	○	○
A significant effect on the length of operation. e.g. a serosal tear requiring repair	○	○	○	○	○
A significant effect on the surgery itself e.g. an error that led to conversion from MIS to open surgery	○	○	○	○	○
A significant effect on short term patient outcome e.g. inadvertent perforation of a viscus	○	○	○	○	○
Had (in your opinion) a significant effect on long term patient prognosis?	○	○	○	○	○
Resulted in reporting of a serious untoward incident?	○	○	○	○	○



Question 7

In relation to your colleagues what proportion of significant intra-operative error do you make?

- ○ Fewer
- ○ Similar
- ○ Greater

Question 8

Are you aware of the procedure for reporting an error during surgery in your trust?:

- ○ Yes
- ○ No

Question 9

When an intra-operative error that affected patient care/outcome has occurred how likely are you to report it?

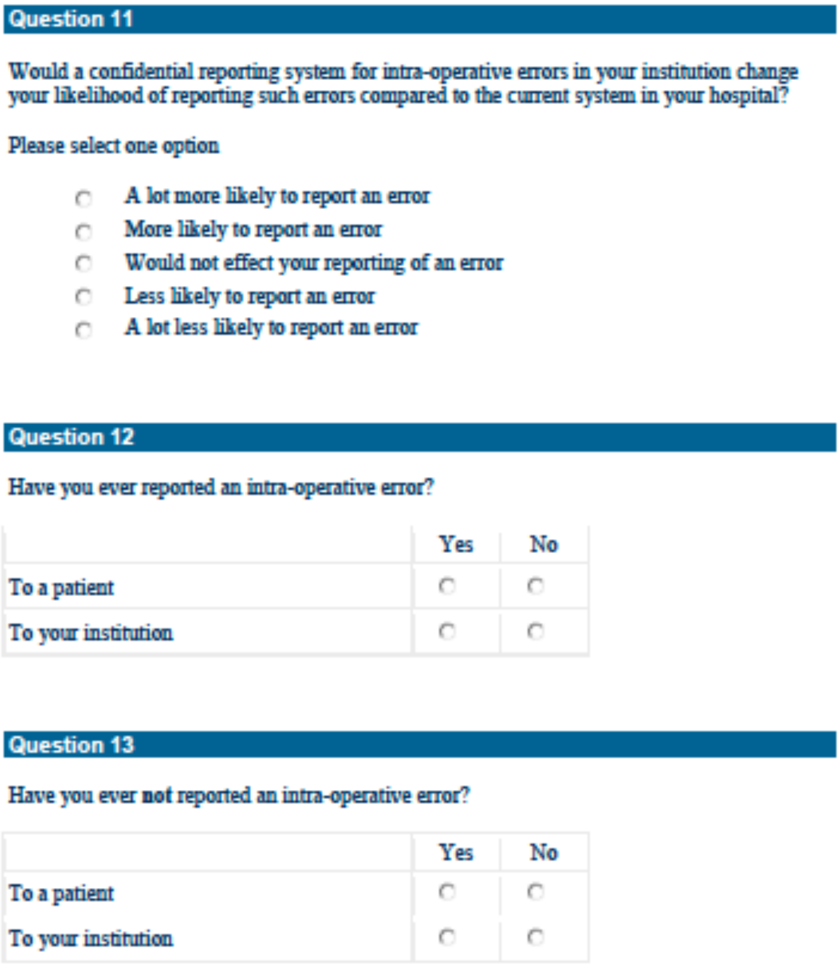
	Very likely	Likely	Unlikely	Very unlikely
a. to the patient	○	○	○	○
b. via your institutions reporting procedure	○	○	○	○

Question 10

What factors would make you:

a. more likely to report an error (e.g. need for a second/re-operation?)

b. less likely to report an error



Question 11

Would a confidential reporting system for intra-operative errors in your institution change your likelihood of reporting such errors compared to the current system in your hospital?

Please select one option

- ○ A lot more likely to report an error
- ○ More likely to report an error
- ○ Would not effect your reporting of an error
- ○ Less likely to report an error
- ○ A lot less likely to report an error

Question 12

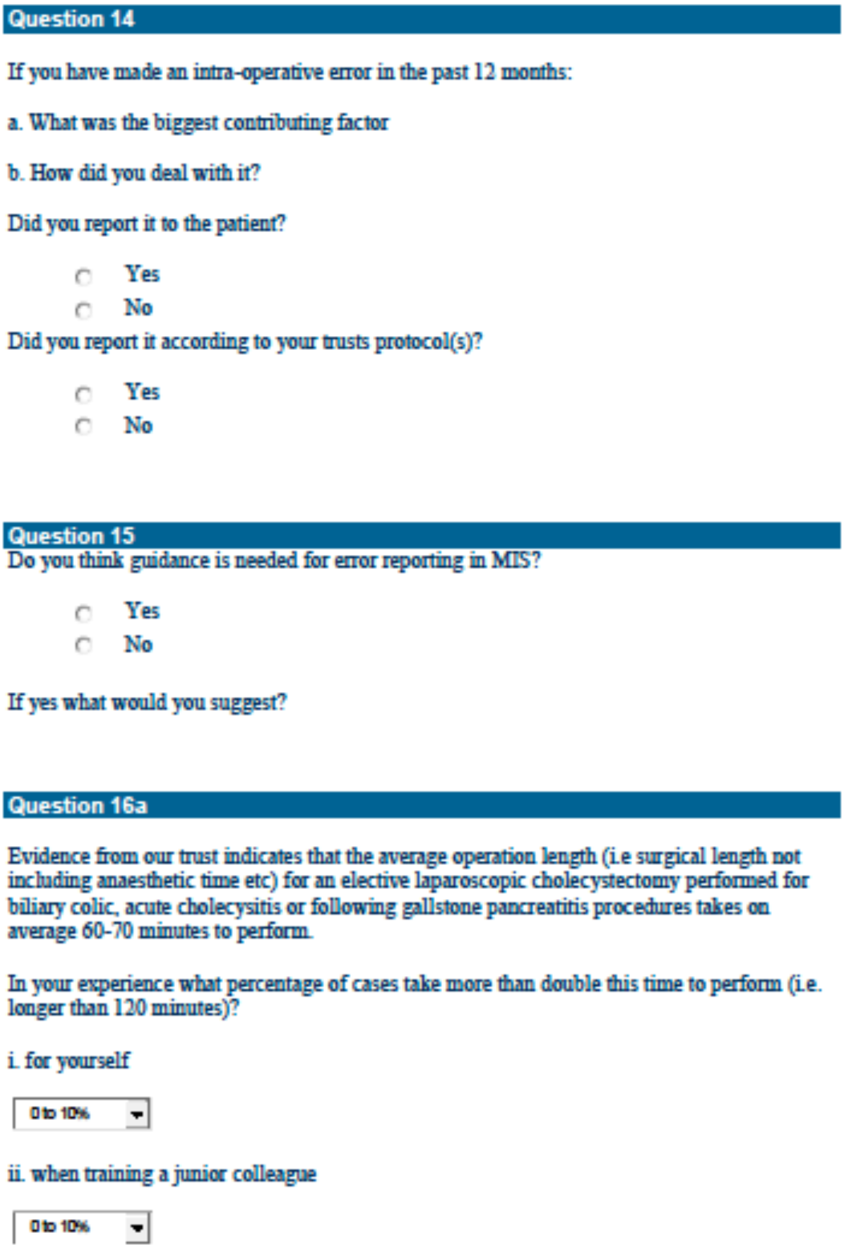
Have you ever reported an intra-operative error?

	Yes	No
To a patient	○	○
To your institution	○	○

Question 13

Have you ever **not** reported an intra-operative error?

	Yes	No
To a patient	○	○
To your institution	○	○



Question 14

If you have made an intra-operative error in the past 12 months:

a. What was the biggest contributing factor

b. How did you deal with it?

Did you report it to the patient?

○ Yes
○ No

Did you report it according to your trusts protocol(s)?

○ Yes
○ No

Question 15

Do you think guidance is needed for error reporting in MIS?

○ Yes
○ No

If yes what would you suggest?

Question 16a

Evidence from our trust indicates that the average operation length (i.e surgical length not including anaesthetic time etc) for an elective laparoscopic cholecystectomy performed for biliary colic, acute cholecysitis or following gallstone pancreatitis procedures takes on average 60-70 minutes to perform.

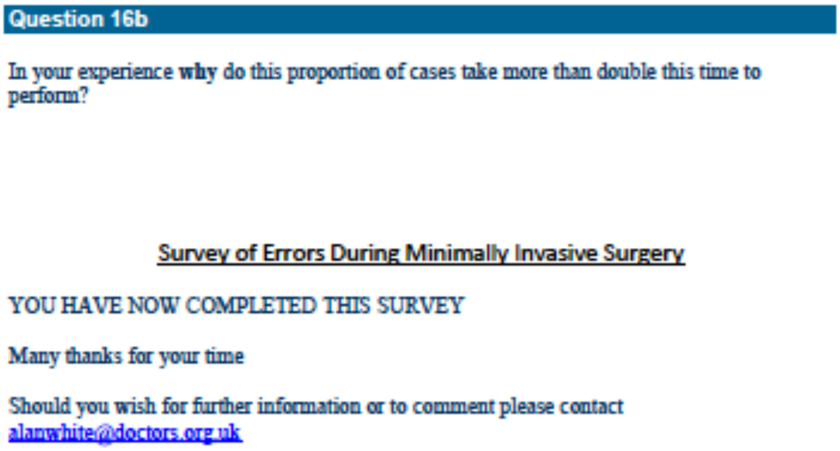
In your experience what percentage of cases take more than double this time to perform (i.e. longer than 120 minutes)?

i. for yourself

0 to 10%

ii. when training a junior colleague

0 to 10%



Question 16b

In your experience **why** do this proportion of cases take more than double this time to perform?

Survey of Errors During Minimally Invasive Surgery

YOU HAVE NOW COMPLETED THIS SURVEY

Many thanks for your time

Should you wish for further information or to comment please contact alanwhite@doctors.org.uk

11. References

1. Vincent C. Patient Safety. 2010.
2. Richardson WC, Berwick DM, Bisgard C, Bristow L, Buck CR, Coye J, et al. To Err is Human: Building A Safer Health System - Institute of Medicine [Internet]. Medscape. 2000. Available from: http://www.iom.edu/Reports/1999/To-Err-is-Human-Building-A-Safer-Health-System.aspx
3. Brennan TA, Leape LL, Laird NM, Hebert L, Localio AR, Lawthers AG, et al. Incidence of adverse events and negligence in hospitalized patients. Results of the Harvard Medical Practice Study I. N Engl J Med. 1991;324:370–6.
4. Vincent C, Neale G, Woloshynowych M. Adverse events in British hospitals: preliminary retrospective record review. BMJ. 2001;322:517–9.
5. Regenbogen SE, Greenberg CC, Studdert DM, Lipsitz SR, Zinner MJ, Gawande AA. Patterns of technical error among surgical malpractice claims: an analysis of strategies to prevent injury to surgical patients. Ann Surg. 2007;246:705–11.
6. AUGIS. AUGIS/RCS Commissioning guide: Gallstone disease. 2013.
7. Cuschieri a. Visual Displays and Visual Perception in Minimal Access Surgery. Surg Innov. 1995 Sep;2(3):209–14.
8. Tang B, Hanna GB, Joice P AC. Identification and Categorization of Technical Errors by Observational Clinical Human Reliability Assessment (OCHRA) During Laparoscopic Cholecystectomy. Arch Surg. 2004;139(11):1215–20.
9. Crosby G, Culley DJ. Surgery and Anesthesia: Healing The Body But Harming The Brain? Anesth Analg. 2012;112(5):999–1001.
10. Reynolds W. The First Laparoscopic Cholecystectomy. JSLS J Soc Laparoendosc Surg. 2001;5(1):89–94.
11. Singh P, Darzi A. Surgical training. Br J Surg. John Wiley & Sons, Ltd.; 2013 Feb 1;100(3):307–9.
12. RCS. From Theory to Theatre: Overcoming barriers ot innovation in surgery. 2011.
13. Williams NS BC and OP. Bailey & Love's Short Practice of Surgery. 25th Edn N. S. Williams, C. J. K. Bulstrode and P. R. O'Connell (eds) 283 × 225 mm. Pp. 1514. Illustrated. 2008. Hodder Arnold: London. Br J Surg. John Wiley & Sons,

Ltd.; 2008 Oct 1;95(10):1311.

14. Stefanidis D, Korndorffer JR, Markley S, Sierra R, Scott DJ. Proficiency Maintenance: Impact of Ongoing Simulator Training on Laparoscopic Skill Retention. Vol. 202, Journal of the American College of Surgeons. Elsevier; 2006. p. 599–603.

15. Bazou D, Behan G, Reid C, Boland JJ, Zhang HZ. Imaging of human colon cancer cells using He-Ion scanning microscopy. J Microsc. 2011;242(3):290–4.

16. Desai JP, Kresh JY, Wechsler AS, Castellanos AE, Meyers WC. Robotic Surgery. Wiley Encycl Biomed Eng. 2006;5:3099–106.

17. Birkmeyer JD, Siewers AE, Finlayson EVA, Stukel TA, Lucas FL, Batista I, et al. Hospital Volume and Surgical Mortality in the United States. N Engl J Med. Massachusetts Medical Society; 2002 Apr 11;346(15):1128–37.

18. Phillip H, Fleet Z BK. The European Working Time Directive—interim report and guidance from The Royal College of Surgeons of England Working Party. 2007.

19. Bann SD, Datta VK, Khan MS, Ridgway PF, Darzi AW. Attitudes towards skills examinations for basic surgical trainees. Int J Clin Pract. Blackwell Science Ltd; 2005 Jan 1;59(1):107–13.

20. Mason JD, Ansell J, Warren N, Torkington J. Is motion analysis a valid tool for assessing laparoscopic skill? Surg Endosc. 2012 Dec 12;

21. Catchpole K, Panesar S R, V T, Hibbert P CK. Surgical safety can be improved through better understanding of incidents reported to a national database. 2009.

22. Roberts KE, Bell RL DA. Evolution of surgical skills training. World J Gastroenterol. 2006;28(12(20)):3219–24.

23. Gallagher a G, Satava RM. Virtual reality as a metric for the assessment of laparoscopic psychomotor skills. Learning curves and reliability measures. Surg Endosc. 2002 Dec;16(12):1746–52.

24. Gallagher AG, Ritter EM, Champion H, Higgins G, Fried MP, Moses G, et al. Virtual Reality Simulation for the Operating Room: Proficiency-Based Training as a Paradigm Shift in Surgical Skills Training. Ann Surg. 2005;241(2).

25. Orzech N, Palter VN, Reznick RK, Aggarwal R, Teodor P. R ANDOMIZED C LINICAL T RIAL A Comparison of 2 Ex Vivo Training Curricula for Advanced Laparoscopic Skills. 2012;255(5).

26. Botden SM, Torab F, Buzink SN JJ. The importance of haptic feedback in

laparoscopic suturing training and the additive value of virtual reality simulation. Surg Endosc. 2008;22(5):1214–22.

27. Nagendran M, Gurusamy KS, Aggarwal R, Loizidou M, Davidson BR. Virtual reality training for surgical trainees in laparoscopic surgery (Review) Virtual reality training for surgical trainees in laparoscopic surgery. Cochrane database Syst Rev. 2013;(8).

28. Seymour NE, Gallagher AG, Roman S a, O'Brien MK, Bansal VK, Andersen DK, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. Ann Surg. 2002 Oct;236(4):458-63-4.

29. Andreatta PB, Woodrum DT, Birkmeyer JD, Yellamanchilli RK, Doherty GM, Gauger PG, et al. Laparoscopic Skills Are Improved With LapMentor??? Training. Ann Surg. 2006;243(6):854–63.

30. Hamilton EC, Scott DJ, Fleming JB, Rege R V., Laycock R, Bergen PC, et al. Comparison of video trainer and virtual reality training systems on acquisition of laparoscopic skills. Surg Endosc Other Interv Tech. 2002;16(3):406–11.

31. Akdemir A, Şendağ F, Öztekin MK. Laparoscopic virtual reality simulator and box trainer in gynecology. Int J Gynecol Obstet. Elsevier; 2016 Mar 21;125(2):181–5.

32. Diesen DL, Erhunmwunsee L, Bennett KM, Ben-David K, Yurcisin B, Ceppa EP, et al. Effectiveness of Laparoscopic Computer Simulator Versus Usage of Box Trainer for Endoscopic Surgery Training of Novices. J Surg Educ. Elsevier; 2016 Mar 21;68(4):282–9.

33. Korndorffer Jr JR, Bellows CF, Tekian A, Harris IB, Downing SM. Effective home laparoscopic simulation training: a preliminary evaluation of an improved training paradigm. Am J Surg. Elsevier; 2016 Mar 21;203(1):1–7.

34. Maan ZN, Maan IN, Darzi a W, Aggarwal R. Systematic review of predictors of surgical performance. Br J Surg. 2012 Dec;99(12):1610–21.

35. Van Herzeele I, O'Donoghue KGL, Aggarwal R, Vermassen F, Darzi A, Cheshire NJW. Visuospatial and psychomotor aptitude predicts endovascular performance of inexperienced individuals on a virtual reality simulator. J Vasc Surg. Elsevier Inc.; 2010 Apr;51(4):1035–42.

36. Dashfield AK, Lambert AW, Campbell JK, Wilkins DC. Original article Correlation between psychometric test scores and learning tying of surgical reef knots. 2001;139–43.

37. Stefanidis D, Korndorffer JR, Black FW, Dunne JB, Sierra R, Touchard CL, et al. Psychomotor testing predicts rate of skill acquisition for proficiency-based laparoscopic skills training. Surgery. 2006 Aug;140(2):252–62.

38. Ritter EM, McClusky D a, Gallagher AG, Enochsson L, Smith CD. Perceptual, visuospatial, and psychomotor abilities correlate with duration of training required on a virtual-reality flexible endoscopy simulator. Am J Surg. 2006 Sep;192(3):379–84.

39. McClusky D, Ritter E. Correlation between perceptual, visuo-spatial, and psychomotor aptitude to duration of training required to reach performance goals on the MIST-VR surgical. Am …. 2005;

40. Steele R, Walder C, Herbert M. Psychomotor testing and the ability to perform an anastomosis in junior surgical trainees. Br J Surg. 1992;79:1065–7.

41. Schijven MP, Jakimowicz JJ, Carter FJ. How to select aspirant laparoscopic surgical trainees: establishing concurrent validity comparing Xitact LS500 index performance scores with standardized psychomotor aptitude test battery scores. J Surg Res. 2004 Sep;121(1):112–9.

42. Wanzel KR, Hamstra SJ, Caminiti MF, Anastakis DJ, Grober ED, Reznick RK. Visual-spatial ability correlates with efficiency of hand motion and successful surgical performance. Surgery. 2003 Nov;134(5):750–7.

43. Gallagher AG, Smith CD, Bowers SP, Seymour NE, Pearson A, McNatt S, et al. Psychomotor skills assessment in practicing surgeons experienced in performing advanced laparoscopic procedures. J Am Coll Surg. 2003 Sep;197(3):479–88.

44. Jordan J a, Gallagher a G, McGuigan J, McClure N. Virtual reality training leads to faster adaptation to the novel psychomotor restrictions encountered by laparoscopic surgeons. Surg Endosc. 2001 Oct;15(10):1080–4.

45. Pearson a M, Gallagher a G, Rosser JC, Satava RM. Evaluation of structured and quantitative training methods for teaching intracorporeal knot tying. Surg Endosc. 2002 Jan;16(1):130–7.

46. Sturm LP, Windsor J a, Cosman PH, Cregan P, Hewett PJ, Maddern GJ. A systematic review of skills transfer after surgical simulation training. Ann Surg. 2008 Aug;248(2):166–79.

47. Zendejas B, Brydges R, Hamstra SJ, Cook D a. State of the Evidence on Simulation-Based Training for Laparoscopic Surgery: A Systematic Review. Ann

Surg. 2013 Feb 12;257(4).

48. Palter VN, Orzech N, Reznick RK, Grantcharov TP. Validation of a structured training and assessment curriculum for technical skill acquisition in minimally invasive surgery: a randomized controlled trial. Ann Surg. 2013 Feb;257(2):224–30.

49. Aggarwal R, Ward J, Balasundaram I, Sains P, Athanasiou T, Darzi A. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. Ann Surg. 2007 Nov;246(5):771–9.

50. Calatayud D, Arora S, Aggarwal R, Kruglikova I, Schulze S, Funch-Jensen P, et al. Warm-up in a virtual reality environment improves performance in the operating room. Ann Surg. 2010 Jun;251(6):1181–5.

51. Gallagher AG, Satava RM, Shorten GD. Measuring surgical skill: a rapidly evolving scientific methodology. Surg Endosc. 2013 Feb 1;

52. Wolpert DM, Diedrichsen J, Flanagan JR. Principles of sensorimotor learning. Nat Rev Neurosci. Nature Publishing Group; 2011 Dec;12(12):739–51.

53. Braun DA, Mehring C, Wolpert DM. Structure learning in action. 2010;206:157–65.

54. Takahashi C, Diedrichsen J, Watt SJ. Integration of vision and haptics during tool use. J Vis. ; 2009;9:3.

55. Way LW, Stewart L, Gantert W, Liu K, Lee CM, Whang K, et al. Causes and prevention of laparoscopic bile duct injuries: analysis of 252 cases from a human factors and cognitive psychology perspective. Ann Surg. 2003;237(4):460–9.

56. Braun D, Mehring C, Wolpert D. Structure learning in action. Behav Brain Res. 2010;206:157–65.

57. Braun DA, Waldert S, Aertsen A, Wolpert DM, Mehring C. Structure Learning in a Sensorimotor Association Task. PLoS One. 2010;5(1).

58. Sailer U, Flanagan JR, Johansson RS. Eye-hand coordination during learning of a novel visuomotor task. J Neurosci. 2005 Sep 28;25(39):8833–42.

59. Qiu Z, Sun J, Pu Y, Jiang T, Cao J, Wu W. Learning curve of transumbilical single incision laparoscopic cholecystectomy (SILS): a preliminary study of 80 selected patients with benign gallbladder diseases. World J Surg. 2011 Sep;35(9):2092–101.

60. Akiyoshi T, Kuroyanagi H, Ueno M, Oya M, Fujimoto Y, Konishi T, et al. Learning curve for standardized laparoscopic surgery for colorectal cancer under supervision: a single-center experience. Surg Endosc. 2011 May;25(5):1409–14.

61. Park S-S, Kim M-C, Park MS, Hyung WJ. Rapid adaptation of robotic gastrectomy for gastric cancer by experienced laparoscopic surgeons. Surg Endosc. 2012 Jan;26(1):60–7.

62. Gurusamy KS, Aggarwal R, Palanivelu L, Davidson BR. Virtual reality training for surgical trainees in laparoscopic surgery. Cochrane database Syst Rev. 2009 Jan;(1):CD006575.

63. Gurusamy K, Aggarwal R, Palanivelu L, Davidson BR. Systematic review of randomized controlled trials on the effectiveness of virtual reality training for laparoscopic surgery. Br J Surg. 2008 Sep;95(9):1088–97.

64. Wagner MJ, Smith MA. Shared internal models for feedforward and feedback control. J Neurosci. 2008 Oct;28(42):10663–73.

65. Pruszynski JA, Kurtzer I, Scott SH. Rapid motor responses are appropriately tuned to the metrics of a visuospatial task. J Neurophysiol. 2008 Jul;100(1):224–38.

66. Kahneman D, Tversky A. Choices, Values, and Frames. ; 2000.

67. Buckingham G, Ranger NS, Goodale MA. Handedness, laterality and the size-weight illusion. Cortex. Elsevier Srl; 2012;48(10):1342–50.

68. Cuscheri A. Whither Minimal Access Surgery: Tribulations and Expectations. Am J Surg. 1995;169(January):9–19.

69. Keele SW. Psychological Bulletin. 1969;70(6).

70. O'Connor T, Papanikolaou V, Keogh I. Safe surgery, the human factors approach. Surgeon. 2010;8:93–5.

71. Karwowski W. Advances in Human facton and Ergonomics in Healthcare. 2010;(August 2016).

72. Toff NJ. Human factors in anaesthesia: Lessons from aviation. Br J Anaesth. 2010;105(1):21–5.

73. Allnutt M. Human factors in accidents. Br J Anaesth. 1987;856–64.

74. Bonrath EM, Zevin B, Dedy NJ, Grantcharov TP. Error rating tool to identify and analyse technical errors and events in laparoscopic surgery. Br J Surg. 2013

Jul;100(8):1080–8.

75. Mishra A, Catchpole K, Dale T, McCulloch P. The influence of non-technical performance on technical outcome in laparoscopic cholecystectomy. Surg Endosc Other Interv Tech. 2008;22(1):68–73.

76. Aggarwal R, Moorthy K, Darzi a. Laparoscopic skills training and assessment. Br J Surg. 2004 Dec;91(12):1549–58.

77. Moorthy K, Munz Y, Sarker SK, Darzi A. Clinical review Objective assessment of technical skills in surgery. 2003;1032–7.

78. Flin R, Yule S, McKenzie L, Paterson-Brown S, Maran N. Attitudes to teamwork and safety in the operating theatre. Surg. 2006 Jun;4(3):145–51.

79. Yule S, Flin R, Paterson-Brown S, Maran N. Non-technical skills for surgeons in the operating room: A review of the literature. Surgery. 2006;139(2):140–9.

80. Joice P, Hanna G., Cuschieri A. Errors enacted during endoscopic surgery—a human reliability analysis. Appl Ergon. 1998;29(6):409–14.

81. Makary MA, Daniel M. Medical error — the third leading cause of death in the US. Bmj. 2016;2139(May):1–5.

82. Reason JT. Understanding adverse events: human factors. Qual Saf Heal Care. 1995;4(2):80–9.

83. Leape LL. Error in medicine. JAMA. 1994;272(23):1851–7.

84. Catchpole K, Panesar SS, Russell J, Tang V, Hibbert P, Cleary K. Surgical safety can be improved through better understanding of incidents reported to a national database.

85. White A, Skelton M, Mushtaq F, Pike T, Mon-Williams M, Lodge J, et al. Inconsistent reporting of minimally invasive surgery errors. Ann R Coll Surg Engl. 2015 Nov;97(8):608–12.

86. Bashir G. Technology and medicine: the evolution of virtual reality simulation in laparoscopic training. Med Teach. 2010;32(7):558–61.

87. Haque S, Srinivasan S. A Meta-Analysis of the Training Effectiveness of Virtual Reality Surgical Simulators. IEEE Trans Inf Technol Biomed. 2006;10(1).

88. Seymour NE. VR to OR: a review of the evidence that virtual reality simulation improves operating room performance. World J Surg. 2008 Feb;32(2):182–8.

89. Orzech N, Palter VN, Reznick RK, Aggarwal R, Grantcharov TP. A comparison of 2 ex vivo training curricula for advanced laparoscopic skills: a randomized

controlled trial. Ann Surg. 2012 May;255(5):833–9.

90. Stefanidis D, Scerbo MW, Sechrist C, Mostafavi A, Heniford BT. Do novices display automaticity during simulator training? Am J Surg. 2008 Feb;195(2):210–3.

91. Stefanidis D, Scerbo MW, Montero PN, Acker CE, Smith WD. Simulator training to automaticity leads to improved skill transfer compared with traditional proficiency-based training: a randomized controlled trial. Ann Surg. 2012 Jan;255(1):30–7.

92. Aggarwal R, Grantcharov T, Moorthy K, Hance J, Darzi A. A competency-based virtual reality training curriculum for the acquisition of laparoscopic psychomotor skill. Vol. 191, American journal of surgery. Excerpta Medica; 2006. p. 128–33.

93. Frizelle FA, Hanna GB, Tan L, Gardiner Q, Cuschieri A, White PS. Comparison of direct monocular endoscopic, two- and three-dimensional display systems on surgical task performance in functional endoscopic sinus surgery. Clin Otolaryngol Allied Sci. 1998;23(3):268.

94. Hanna GB, Drew T, Clinch P, Hunter B, Shimi S, Dunkley MP, et al. A microprocessor-controlled psychomotor tester for minimal access surgery. Surg Endosc. 1996;10(10):965–9.

95. Hanna, G B, Drew T, Cuschieri A. Technology for Psychomotor Skills Testing in Endoscopic Surgery. Semin Laparosc Surg. 1997;4(2):120–4.

96. Hanna GB, Shimi SM, Cuschieri a. Randomised study of influence of two-dimensional versus three-dimensional imaging on performance of laparoscopic cholecystectomy. Lancet. 1998;351(9098):248–51.

97. Hanna GB, Cuschieri A. Influence of two-dimensional and three-dimensional imaging on endoscopic bowel suturing. World J Surg. 2000;24(4):444–9.

98. Gandolfo F, Mussa-Ivaldi FA, Bizzi E. Motor learning by field approximation (arm trajectories/adaptation/generalization of learning/regularization/intrinsic coordinates). Neurobiology. 1996;93:3843–6.

99. Culmer PR, Levesley MC, Mon-Williams M, Williams JHG. A new tool for assessing human movement: The Kinematic Assessment Tool. J Neurosci Methods. 2009 Oct;184(1):184–92.

100. Maciel A, Liu Y, Ahn W, Singh TP, Dunnican W, De S. Development of the VBLaST: a virtual basic laparoscopic skill trainer. Int J Med Robot. 2008 Jun;4(2):131–8.

101. Johnson RL, Culmer PR, Burke MR, Mon-Williams M, Wilkie RM. Exploring structural learning in handwriting. Exp Brain Res. 2010 Dec;207(3–4):291–5.

102. Wilkie RM, Johnson RL, Culmer PR, Allen R, Mon-Williams M. Looking at the task in hand impairs motor learning. J Neurophysiol. 2012 Dec;108(11):3043–8.

103. Braun DA, Aertsen A, Wolpert DM, Mehring C. Motor task variation induces structural learning. Curr Biol. Elsevier Ltd; 2009 Mar;19(4):352–7.

104. Turnham EJA, Braun DA, Wolpert DM. Facilitation of learning induced by both random and gradual visuomotor task variation. J Neurophysiol. 2012 Feb;107(4):1111–22.

105. Jordan JA, Gallagher AG, McGuigan J, McGlade K, McClure N. A comparison between randomly alternating imaging, normal laparoscopic imaging, and virtual reality training in laparoscopic psychomotor skill acquisition. Am J Surg. 2000 Sep;180(3):208–11.

106. Harris CS. Perceptual adaptation to inverted, reversed, and displaced vision. Psychol Rev. US: American Psychological Association; 1965;72(6):419–44.

107. Kim WS, Ellis SR, Tyler ME, Hannaford B, Stark LW. Quantitative Evaluation of Perspective and Stereoscopic Displays in Three-Axis Manual Tracking Tasks. Vol. 17, Systems, Man and Cybernetics, IEEE Transactions on. 1987. p. 61–72.

108. Mistry S, Contreras-Vidal JL. Learning multiple visuomotor transformations: adaptation and context-dependent recall. Motor Control. 2004 Oct;8(4):534–46.

109. Mon-Williams M, Wann JP, Jenkinson M, Rushton K. Synaesthesia in the normal limb. Proc Biol Sci. 1997 Jul;264(1384):1007–10.

110. de Oliveira RF, Wann JP. Integration of dynamic information for visuomotor control in young adults with developmental coordination disorder. Exp Brain Res. 2010 Sep;205(3):387–94.

111. Miall RC, Wolpert DM. Forward models for physiological motor control. Neural Networks. 1996;9(8):1265–79.

112. Cunningham HA. Aiming error under transformed spatial mappings suggests a structure for visual-motor maps. J Exp Psychol Hum Percept Perform. 1989 Aug;15(3):493–506.

113. Reich DL, Bennett-guerrero E, Bodian CA, Hossain S, Winfree W, Krol M. Intraoperative Tachycardia and Hypertension Are Independently Associated with Adverse Outcome in Noncardiac Surgery of Long Duration. Anesth Analg. 2002;95:273–7.

114. Bandrinath SS, Bhaskaran S, Sundararaj I, Rao BS, Mukesh BN. Mortality and morbidity associated with opthalamic surgery. Opthalamic Surg Lasers. 1995;26:535–41.

115. Cresswell a B, Macmillan a I, Hanna GB, Cuschieri a. Methods for improving performance under reverse alignment conditions during endoscopic surgery. Surg Endosc. 1999 Jun;13(6):591–4.

116. Wann JP, Rushton S, Mon-Williams M. Natural problems for stereoscopic depth perception in virtual environments. Vis Res. 1995/10/01. 1995;35(19):2731–6.

117. Hanna GB, Shimi SM, Cuschieri a. Task performance in endoscopic surgery is influenced by location of the image display. Ann Surg. 1998 Apr;227(4):481–4.

118. Haveran L, Novitsky Y, Czerniach D. Optimizing laparoscopic task efficiency: the role of camera and monitor positions. Surg …. 2007 Jun;21(6):980–4.

119. Zhang L, Cao CGL. Effect of automatic image realignment on visuomotor coordination in simulated laparoscopic surgery. Appl Erg. 2012/03/01. 2012 Nov;43(6):993–1001.

120. Gould JC, Frydman J. Reverse-alignment surgical skills assessment. Surg Endosc. 2007 Apr;21(4):669–71.

121. Matern U, Faist M, Kehl K, Giebmeyer C, Buess G. Monitor position in laparoscopic surgery. Surg Endosc. 2005 Mar;19(3):436–40.

122. Zehetner J, Kaltenbacher A, Wayand W, Shamiyeh A. Screen height as an ergonomic factor in laparoscopic surgery. Surg Endosc. 2006 Jan;20(1):139–41.

123. Oldfield RC. The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia. 1971;9(1):97–113.

124. Raw RRK, Kountouriotis GK, Mon-Williams M, Wilkie RM. Movement control in older adults: does old age mean middle of the road? J Exp Psychol Hum Percept Perform. 2012 Jun;38(3):735–45.

125. Raw RK, Wilkie RM, Culmer PR, Mon-Williams M. Reduced motor asymmetry in older adults when manually tracing paths. Exp Brain Res. 2012 Mar;217(1):35–41.

126. Emam TA, Hanna G, Cuschieri A. Comparison of orthodox versus off-optical axis endoscopic manipulations. Surg Endosc Other Interv Tech. Springer-Verlag; 2002;16(3):401–5.

127. Haveran L a, Novitsky YW, Czerniach DR, Kaban GK, Taylor M, Gallagher-

Dorval K, et al. Optimizing laparoscopic task efficiency: the role of camera and monitor positions. Surg Endosc. 2007 Jun;21(6):980–4.

128. Hanna GB, Cuschieri A. Influence of the optical axis-to-target view angle on endoscopic task performance. Surg Endosc. 1999;13(4):371–5.

129. George H, Cresswell AB, Cuschieri A. Shadow depth cues and endoscopic task performance. Arch Surg. 2002;137(10):1166–9.

130. Seidler RD, Bloomberg JJ, Stelmach GE. Context-dependent arm pointing adaptation. Behav Brain Res. 2001 Mar;119(2):155–66.

131. Berger M, Lechner-Steinleitner S, Kozlovskaya I, Holzmüller G, Mescheriakov S, Sokolov A, et al. The effect of head-to-trunk position on the direction of arm movements before, during, and after space flight. J Vestib Res. 1998;8(5):341–54.

132. Guerraz M, Blouin J, Vercher J-L. From head orientation to hand control: evidence of both neck and vestibular involvement in hand drawing. Exp Brain Res. 2003 May;150(1):40–9.

133. Bresciani J-P, Blouin J, Sarlegna F, Bourdin C, Vercher J-L, Gauthier GM. On-line versus off-line vestibular-evoked control of goal-directed arm movements. Neuroreport. 2002 Aug;13(12):1563–6.

134. Bresciani J-P, Blouin J, Popov K, Bourdin C, Sarlegna F, Vercher JL, et al. Galvanic vestibular stimulation in humans produces online arm movement deviations when reaching towards memorized visual targets. Neurosci Lett. 2002 Jan;318(1):34–8.

135. Shadmehr R, Brashers-Krug T. Functional Stages in the Formation of Human Long-Term Motor Memory. J Neurosci. 1997 Jan;17(1):409–19.

136. Stratton GM. Vision without inversion of the retinal image. Psychol Rev. 1897;4(5):463–81.

137. Tenenbaum JB, Kemp C, Griffiths TL, Goodman ND. How to grow a mind: statistics, structure, and abstraction. Science (80-). 2011 Mar;331(6022):1279–2385.

138. Heuer H, Sülzenbrück S. Trajectories in operating a handheld tool. J Exp Psychol Hum Percept Perform. 2009 Apr;35(2):375–89.

139. Kobak D, Mehring C. Adaptation paths to novel motor tasks are shaped by prior structure learning. J Neurosci. 2012 Jul;32(29):9898–908.

140. Yousif N, Diedrichsen J. Structural learning in feedforward and feedback control. J Neurophysiol. 2012 Nov;108(9):2373–82.

141. Seidler RD. Multiple motor learning experiences enhance motor adaptability. J Cogn Neurosci. 2001;16(1):65–73.

142. Abeele S, Bock O. Mechanisms for sensorimotor adaptation to rotated visual input. Exp Brain Res. 2001 Jul;139(2):248–53.

143. Cunningham H, Welch R. Multiple concurrent visual-motor mappings: implications for models of adaptation. J Exp Psychol Hum Percept Perform. 1994;20(5):987–99.

144. Roller CA, Cohen HS, Kimball KT, Bloomberg JJ. Variable practice with lenses improves visuo-motor plasticity. Brain Res Cogn Brain Res. 2001 Oct;12(2):341–52.

145. Fitts PM, Posner MI. Human performance. Oxford, England: Brooks/COles; 1967.

146. Oldfield R. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia. 1971;9:97–113.

147. Hanna GB, Shimi S, Cuschieri A. Influence of direction of view, target-to-endoscope distance and manipulation angle on endoscopic knot tying. Br J Surg. 1997;84(10):1460–4.

148. Hanna GB, Shimi S, Cuschieri a. Optimal port locations for endoscopic intracorporeal knotting. Surg Endosc. 1997;11(4):397–401.

149. van Det MJ, Meijerink WJHJ, Hoff C, Totté ER, Pierie JPEN. Optimal ergonomics for laparoscopic surgery in minimally invasive surgery suites: a review and guidelines. Surg Endosc. 2009 Jun;23(6):1279–85.

150. Hanna GB, Elamass M, Cuschieri A. Ergonomics of hand-assisted laparoscopic surgery. Semin Laparosc Surg. 2001;8(2):92–5.

151. Ahmed S, Hanna GB, Cuschieri A. Optimal angle between instrument shaft and handle for laparoscopic bowel suturing. Arch Surg. 2004;139(1):89–92.

152. Welch RB, Bridgeman B, Anand S, Browman KE. Alternating prism exposure causes dual adaptation and generalization to a novel displacement. Percept Psychophys. 1993 Aug;54(2):195–204.

153. Braun DA, Aertsen A, Wolpert DM, Mehring C. Learning optimal adaptation strategies in unpredictable motor tasks. J Neurosci. 2009 May;29(20):6472–8.

154. Huang VS, Shadmehr R. Persistence of motor memories reflects statistics of the learning event. J Neurophysiol. 2009 Aug;102(2):931–40.

155. Kahol K, Satava RM, Ferrara J, Smith ML. Effect of short-term pretrial practice on surgical proficiency in simulated environments: a randomized trial of the "preoperative warm-up" effect. J Am Coll Surg. American College of Surgeons; 2009 Feb;208(2):255–68.

156. Hall JC, Ellis C, Hamdorf J. Surgeons and cognitive processes. Br J Surg. 2003 Jan;90(1):10–6.

157. Plerhoples T a, Zak Y, Hernandez-Boussard T, Lau J. Another use of the mobile device: warm-up for laparoscopic surgery. J Surg Res. Elsevier Inc; 2011 Oct;170(2):185–8.

158. Rosser JC, Gentile D a, Hanigan K, Danner OK. The effect of video game "warm-up" on performance of laparoscopic surgery tasks. JSLS. 2012;16(1):3–9.

159. Kroft J, Ordon M, Arthur R, Pittini R. Does surgical "warming up" improve laparoscopic simulator performance? Simul Healthc. 2012 Dec;7(6):339–42.

160. Lendvay T, Brand T, White L. Virtual Reality Robotic Surgery Warm-Up Improves Task Performance in a Dry Lab Environment: A Prospective Randomized Controlled Study. … Coll Surg. 2013;216(October 2012):1181–92.

161. Lee JY, Mucksavage P, Kerbl DC, Osann KE, Winfield HN, Kahol K, et al. Laparoscopic warm-up exercises improve performance of senior-level trainees during laparoscopic renal surgery. J Endourol. 2012 May;26(5):545–50.

162. Weston MK, Stephens JH, Schafer A, Hewett PJ. Warm-up before laparoscopic surgery is not essential. ANZ J Surg. 2014 Mar;84(3):143–7.

163. Moldovanu R, Târcoveanu E, Dimofte G, Lupaşcu C, Bradea C. Preoperative warm-up using a virtual reality simulator. JSLS. 2011;15(4):533–8.

164. Calatayud D, Arora S, Aggarwal R, Kruglikova I, Schulze S, Funch-Jensen P, et al. Warm-up in a virtual reality environment improves performance in the operating room. Ann Surg. 2010 Jun;251(6):1181–5.

165. Willaert WIM, Aggarwal R, Daruwalla F, Van Herzeele I, Darzi AW, Vermassen FE, et al. Simulated procedure rehearsal is more effective than a preoperative generic warm-up for endovascular procedures. Ann Surg. 2012 Jun;255(6):1184–9.

166. Do AT, Cabbad MF, Kerr A, Serur E, Robertazzi RR, Stankovic MR. Scientific

paper A Warm-up Laparoscopic Exercise Improves the Subsequent Laparoscopic Performance of Ob-Gyn Residents : a Low-Cost Laparoscopic Trainer. 2006;297–301.

167. Svenson O. Are we all less risky and more skillful fellow drivers ? * Do people engaged in a risky activity where skill plays some role , have an unbiased view of their own skill and risk taking ? More specifically, do they have a correct conception of their own sk. 1981;47:143–8.