THE ROLE OF VISUAL-SPATIAL ABILITY AND WORKING MEMORY IN IMAGE GUIDED SIMULATOR PERFORMANCE

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Abstract

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Numerous studies have analyzed the critical factors for training in surgical endoscopy to ensure high performance and increased patient safety. There are, however, surprisingly few studies that focus on the role of cognitive abilities, especially considering the fact that an estimated 50% of all medical errors that lead to permanent disability and death are the result of cognitive failures (Gawande, Zinner, Studdert & Biennen, 2003). This thesis provides initial outlines of two cognitive abilities that may underlie endoscopic simulator performance. In study 1 we addressed how high-level visual-spatial ability of surgical novices is related to performance of two simulator tasks with and without anatomical graphics and haptic feedback, differing in visual-spatial complexity. In study 2 we investigated whether visual and verbal working memory are related to the outcome of task performance scores in simulated laparoscopic cholecystectomy and gastroscopy training. Taken together, the results suggest that visual-spatial ability and working memory are significantly related to endoscopic simulator performance scores and that an increased cognitive workload enhances the individual differences found. These findings can be used to better implement endoscopic surgical curriculum since novice trainees can be identified early and they might benefit from supplementary education in specific surgical tasks.

This thesis for the licenciate degree is based on the following studies:

Hedman, L., Ström, P., Andersson, P., Kjellin, A., Wredmark, T., & Felländer-Tsai, L. (2006) High-level visual-spatial ability for novices correlates with performance in a visual-spatial complex surgical simulator task. *Surgical Endoscopy, 20,* 1275-1280.

Andersson, P., Hedman, L., Enochsson, L., Ström, P., Kjellin, A., Westman, B., & Felländer-Tsai, L. (submitted to Medical Teacher). Working Memory Influences the Performance of Virtual Endoscopy.

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Umeå, October, 2007

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The Role of Visual-Spatial Ability and Working Memory in Image Guided Surgical Simulator Performance

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INTRODUCTION

"We must not forget that when radium was discovered no one knew that it would prove useful in hospitals. The work was one of pure science. And this is a proof that scientific work must not be considered from the point of view of the direct usefulness of it. It must be done for itself, for the beauty of science, and then there is always the chance that a scientific discovery may become like the radium a benefit for humanity."

Marie Curie - *Lecture at Vassar College, May 14, 1921*

Within the limits of human capacity lies a potential for improving technical, clinical, and communicative skills. Simulations in various applied fields have created an ecologically valid ability to gain opportunities for creating higher skills standards and quasi-experienced sufficiency. By using computer-based simulations, we can vastly broaden the range of things students can learn by training without risks. These pedagogical tools replace traditional learning of every possible skill with learning by doing. When real-life situations are limited, simulations can effectively prepare students.

The capability of training surgeons within a virtual environment has advanced dramatically since it was first reported by Satava (1993). Virtual reality (VR) simulation in surgical training has become widely used and intensely investigated in an effort to develop safer, more efficient, and measurable training procedures. More powerful desktop computers have also propelled surgical virtual reality into mainstream training methods in surgical education on a widespread basis. Most of the current surgical VR systems aid students learn surgical skills by shaping behaviours required for performing clinical surgery. Consequently, recent simulator-based exercises complement medical training (Kneebone, 2003; Clark et al., 2005), allowing medical novices, residents, and experienced surgeons to develop and sharpen their skills within a contextual realistic, yet simulated, environment. Scerbo (2005) concluded that a surgical curriculum benefiting from the aid of virtual reality (VR) simulations will allow students to acquire and refine their skills without putting patients at risk, provide immediate performance feedback and objective measures of performance, allow students to encounter and interact with rare pathologies, and reduce the need for animal and human cadaver labs.

Few studies have examined the role of cognitive abilities and surgical performance and working memory has so far been neglected. This Licentiate thesis will contribute to the ongoing development of a better surgical VR simulation curriculum by exploring the role of some cognitive abilities, visual-spatial ability, and working memory (WM) in medical training in general and in the field of endoscopic simulation in particular.

BACKGROUND

Training research

There are several factors involved in evaluating training performance; events that occur before, during, and after training influences the total performance outcome for any training session (Figure 1). Salas and Cannon-Bowers (2001) note that these factors fall into three categories: what trainees bring to the training setting (individual characteristics); variables that engage the trainee to learn to participate in developmental activities (training motivation); and how the training can be prepared so as to maximize the learning experience (training induction and pre-training environment). Individual characteristics consist of three subcomponents: cognitive ability, self-efficacy, and goal orientation. In addition, the role of cognitive ability and job training is of special interest. Several studies have shown that ability influenced the attainment of job knowledge directly and that general cognitive ability influenced work samples through job knowledge (Ree et al., 1995; Colquitt et al., 2000). These and other findings indicate that those who have high cognitive ability (all other things being equal) will probably learn more and have a higher success rate in job training. Salas and Cannon-Bowers suggest that the research community should look more closely at the low-ability trainees and develop a training program that will optimize learning for them and promote the idea to examine in more depth concepts such as tacit knowledge and practical intelligence in relation to on-the-job learning. It is also pointed out that cognitive abilities are a good predictor for training performance (learning) but not necessarily job performance. Many jobs require skills such as psychomotor skills or motivation rather than cognitive ability for success. The nature of a job determines if cognitive ability will be a valid predictor of superior training transfer.

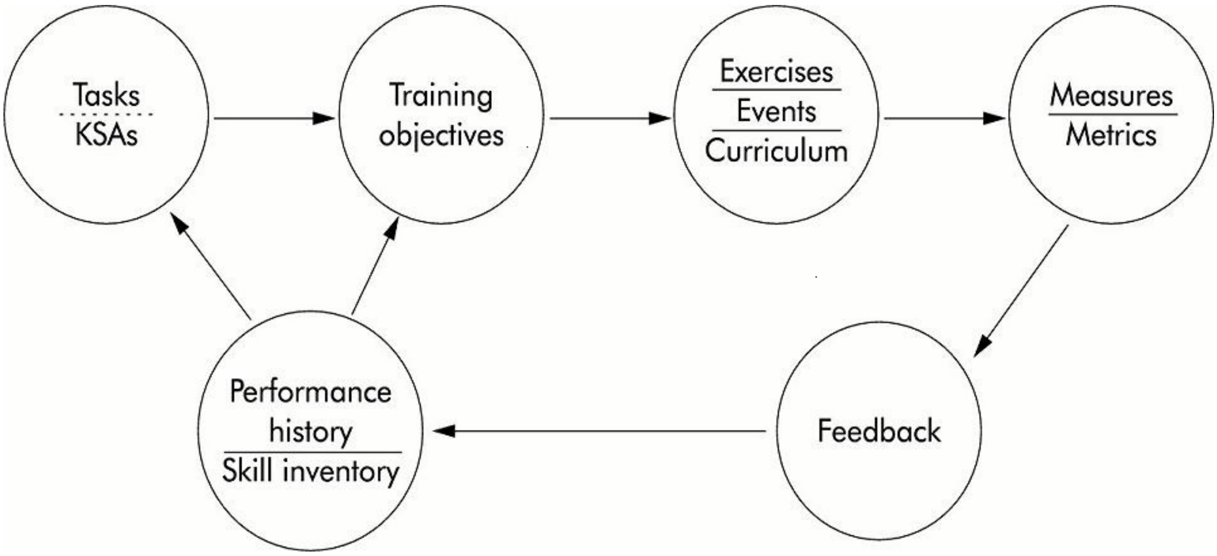


Figure 1. Components of scenario-based training (adapted from Cannon-Bowers et al., 1998).

The scenario-based training model was used in Study 1 & 2 of this thesis. The surgical residents were presented with the training objectives and exercises and simulated endoscopic tasks. They were also given feedback based on the measured performance scores by a senior surgical resident acting as an instructor. Therefore, the training sessions should reflect changes within the surgical residents' knowledge, skill, and attitude.

The simulations take part in a learning environment that requires clear instructional guidelines; there should be a series of links that create a learning environment (Figure 1). Simulations can benefit the medical community by training both individuals and teams to reduce human error and promote patient safety. Salas and Burke (2002) suggest several guidelines for developing simulation: simulations should be designed so that instructional features are embedded within the simulation; carefully crafted scenarios should contain opportunities for performance measurement and diagnostic feedback; the learning experience should be guided; and simulation fidelity should be matched to task requirements. Issenberg et al. (2005) reviewed and identified 10 features and used medical simulations as educational interventions. They identify several features that will lead to effective learning: feedback during learning experience, repetitive practice on the simulator, curriculum integration, increased difficulty of simulation as students progress, the use of complement multiple learning strategies, simulations that reflect clinical variation, learning should take place in a controlled environment, individualized learning opportunities, and clearly defined outcomes or benchmarks.

Simulation research

Simulation has been defined as the technique of imitating the behaviour of some situation or process–economic, military, mechanical and so on–by means of a suitably analogous situation or apparatus, especially for the purpose of study or personnel training. The military has been a long time user of simulation: chess probably represents one of the earliest attempts at war gaming and the 18^{th} century Kriegspeil represented a development with more face validity, which led to modern, complex, and computerized warfare simulation. The aviation industry has developed high-fidelity flight simulation and has led to improving the non-technical skills of teams through crew management programmes. Similarly, the space programme has made extensive use of simulation for training and testing. The nuclear power industry, aware of incidents such as Three Mile Island and Chernobyl, is another business with a major commitment to simulation. What these groups have in common is that training or systems testing in the real world would be too costly or too dangerous to undertake. Therefore, it is not surprising that the medical profession should take steps to adopt the principles of high-reliability organisational systems (Bradley, 2006). The historical pioneer of minimally invasive surgery is considered to be Philipp Bozzini; in 1804 he developed the first Lichtleiter (light conductor). The light conductor redirected light from internal cavities to the observer's eyes through illumination. The main impetus for the development of endoscopy at the end of the nineteenth century came from inspection of the rectum, bladder, and larynx. In 1910, Hans Christian Jacobaeus from Stockholm carried out the first known laparoscopy and thoracoscopy and in 1913 he burnt away adhesions under thoracoscopic vision. By 1983, Kurt Semm, a gynaecologist from Kiel, performed the first laparoscopic appendectomy. With the introduction of the computerized video camera in the late 1980s, laparoscopic cholecystectomy had become a standard surgical routine procedure. The introduction of the modern laparoscopy is considered one of greatest success stories in the history of surgery; it accelerated the development of surgical endoscopy and marked the end of the era of traditional open surgery (Litynski, 1999).

In clinical simulation, models have long been used to help students learn about anatomical structures. The modern era of medical simulation has its origins in the second half of the 20^{th} century. Three distinct movements have been identified that helped its development. The first major step was taken by Åsmund Laerdal, a Norwegian publisher and toy manufacturer, who developed the Resusci-Anne, a low-cost and effective training device that revolutionized resuscitation training. The second movement began with the introduction of Sim One, a manikin developed by Abrahamson and Denson in the 1960s that addressed human reproduction. The third major movement was the medical education reforms that are still ongoing today. These reforms have been driven by the obvious need for medical students to prepare for the working life after undergraduate education. The recognition of information overload within the curriculum at the expense of clinical and communicative skills has resulted in the widespread increase of programmes in clinical skills learning and the development of clinical skills education facilities to support that learning. The need for continuing medical training and revalidation has also been part of this process. This has led to a rise in the use of simulator methodologies in both undergraduate and postgraduate education and increasing attention is being paid to high-fidelity simulation and educational curricula for providing safe experiences (Bradley, 2006). The simulation technology provides yet another alternative for assessing surgical technical skills; earlier skills were obtained by watching live operations and training on human cadavers, animal models, and box trainers. The high-fidelity (high-end) VR simulations used today have haptic feedback and anatomical graphics. Furthermore, they are highly realistic in a comparison with a real operating room (OR) situation.

Endoscopy (looking inside) is a minimally invasive medical technique used to evaluate organs by inserting a small tube into the body, often through a natural body opening. The procedure enables a doctor to see lesions and other surface conditions through the scope. The instrument may have a rigid or flexible tube, containing one or more optical fibre systems. In addition to providing an image, the instrument can be used for biopsies and retrieval of foreign objects. Endoscopic procedures are relatively painless, although the patients are sedated for most procedures; they are safe with an estimated 5% complication rate (Masci et al., 2001). Endoscopic training is an effective tool for acquiring surgical skills and a compliment to standard medical training. Recently conducted studies have shown that both shorter training periods, 1 day, (Maiss et al., 2005) and longer courses, 2 years, (Clark et al., 2005) using endoscopic simulator training lead to improvements in objective performance. In a review of the literature, Issenberg et al. (2005) identified the most effective learning in high fidelity, visual- and motion systems, and medical simulations. They found that learning was most successful when feedback, repetitive practice, and curriculum integration were provided. Additional training for medical students secures patient safety and can reduce per-hour reimbursements at teaching institutions (McCashland et al., 2000). There is a wealth of information pertaining to the existence of medical errors as a very serious problem. However, when it comes to identifying the major causes of medical error, it was a matter of piecing information together from numerous sources. The human cost of medical errors is high. Based on the findings of one major study by the Institute of Medicine in 2000, medical errors kill some 44,000 people in U.S. hospitals each year; the real number could be much higher, as high as 98,000. Even using the lower estimate, more people die from medical mistakes each year than from highway accidents, breast cancer, or AIDS. Moreover, while errors may be more easily detected in hospitals, they afflict every health care setting: day-surgery and outpatient clinics, retail pharmacies, nursing homes, as well as home care. Deaths from medication errors that take place both in and out of hospitals–more than 7,000 annually–exceed workplace injuries.

All kinds of surgery involve a wide range of technical, clinical, and communicative skills. These complex tasks entail a rigorous demand on any surgeon's multi-task capacity, since a mental slip can result in fatal errors. It is estimated that 50% of all medical errors that lead to permanent disability and death are the result of cognitive failures such as judgment errors (Gawande et al., 2003). Several studies quantify human performance during simulation training. We use training evaluation strategies described by Satava (1993) and Gallagher et al. (2003) from clinical, medical, and psychology literature. Using these strategies, we assessed the effectiveness of simulator training on the performance of residents. We examined the medical students' level of visual-spatial ability, working memory (WM), and important background variables, such as level of concentration and mental strain, and performance variables during simulator sessions. Basic cognitive variables have been identified as critical indices of effectiveness in training intervention. Because most surgery requires multiplex tasks and requirements that go beyond just one or two particular skills, broad measurements of several skills is needed (Baldwin et al., 1999; Malik et al., 2003). So far, little systematic attention has been paid to the cognitive processes involved in surgical proficiency, which also seems to be less understood by surgeons (Hall et al., 2003; Gallagher et al., 2005). Research in the fields of cognitive psychology and neurosciences has indicated that WM is a limited capacity system that temporarily stores and processes information. WM has been called a "mental workspace", and its capacity is considered a measure of information processing capacity that underlies generic cognitive skills and individual differences (Baddeley, 2002; Miyake, 2001; Cabeza & Nyberg, 2003).

Visual-spatial ability

Carpenter and Just (1986) define visual-spatial ability as the capacity to generate a mental representation of a two- or three-dimensional structure and then assessing its properties or performing a transformation of the representation. There have been numerous attempts to group and arrange the different visual-spatial abilities into categories. Cornoldi and Vecci (2003) identified some fundamental visual-spatial abilities: Visual Organization (e.g., Street Completion Test, Embedded Figures Test); the ability to organize incomplete or fragmented patterns–Planned Visual Scanning (e.g., Elithorn's Perceptual Maze); the ability to scan a visual configuration rapidly and efficiently to reach a particular goal–Spatial Orientation (e.g., Judgment of Line Orientation); the ability to perceive an recall a particular spatial orientation or be able to orient oneself generally in space–Visual Reconstructive Ability (e.g., Koh's Blocks, Bender Gestalt Test); the ability to reconstruct a pattern on the basis of a given model–Imagery Generation Ability (e.g., VVIQ); the ability to generate vivid visual spatial mental images quickly–Imagery Manipulation Ability (e.g., Mental Rotation Test, Spatial Subtest of DAT); the ability to manipulate a visual spatial mental image in order to transform or evaluate it–Spatial Sequential Short-Term Memory (e.g., Corsi test, Tomal Subtests); the ability to remember a sequence of different locations–Visual Spatial Simultaneous Short-Term Memory (e.g., Visual Pattern test); the ability to remember different locations presented simultaneously–Visual Memory (e.g., Contribution of memory in the Complex Figure test); the ability to remember visual information–Long-Term Spatial Memory (e.g., Spatial Labyrinth); the ability to maintain spatial information over long periods of time. The different tasks can be classified as passive or active tasks. Visual memory tasks are considered passive tasks and tasks involving imagery manipulation or integration are considered active.

Not many studies have thoroughly investigated the relationship between visual-spatial ability and working memory. According to Miyake et al. (2001), there are special relations between WM and psychometric spatial abilities when investigating individual differences. Based on Carroll's (1993) classification, there are three major spatial ability factors (spatial visualization, spatial relation, and perceptual speed). The goal was to find similarities and differences for these three factors from the perspective of a multi-component view of WM capacity. The three factors examined all involve the visual-spatial component of WM; these factors differ in terms of the demand on the executive functions. A major finding was that these three factors differ in a standardized path coefficients analysis associated with the Executive Functioning variable, with the executive involvement being the highest for the Spatial Visualization factor (r=.91), followed by the Spatial Relation factor (r=.83), and the lowest for the Perceptual Speed factor (r=.43). This finding is interesting since spatial ability tests are considered a good measure for *g* or general fluid intelligence (Lohman, 2000).

Working memory

Psychological theories of human memory have a long history of postulating different subdivisions of functions and/or stores, dating back (at least) to William James (1890) distinction between short-term (active) memory and long-term (passive) memory. Several classification schemes have been detailed in the literature (Tulving, 1972; Squire, 1992; Schacter & Tulving, 1994) and the criteria by which parsing of memory should be determined and characterized have been the subject of intense debate and longstanding controversy (Parkin, 1999).

A theoretical model that has endured the grinding of intense scientific scrutiny for more than three decades is the classical WM model proposed by Baddeleyand Hitch (1974). The original model posits a tripartite component system that constitutes two separate short-term memory buffers dedicated to the temporary retention of verbal and visuo-spatial information, respectively, both of which are governed by a supervisory attentional control mechanism referred to as the central executive (Baddeley & Hitch, 1974; Baddeley, 1986). It has been suggested (Baddeley, 1998) that there is an asymmetry between the two subsidiary slave systems, the phonological domain and the visuo-spatial domain, and that the visuo-spatial domain requires a stronger cognitive workload on the central executive due to the lack of a common rehearsal mechanism when it comes to short-term maintenance of information. A fourth component to this WM theory was later added called the episodic buffer, a limited capacity store that binds information to form integrated episodes. The phonological loop, or the articulatory loop, can be articulated into two subcomponents; *the inner ear,* or the phonological store, which is a storage subcomponent that maintains the information in a phonological format for a few seconds, and *the inner voice*, or the articulatory store, which recodes nonauditory information in an articulatory format and repeats the information on a loop in order to prevent it from decay. There are four main findings that provide evidence for the use of the phonological loop during short-term memory tasks (Baddeley et al., 1975; Larsen et al., 2000): 1) The phonological similarity effect, recall of phonologically similar words, has a disruptive effect on memory compared to words that are phonologically dissimilar; 2) The unattended speech effect, memory loss caused by presenting spoken material that the subject is explicitly invited to disregard; 3) The word-length effect, recall of a series of short words easier than a series of long words; 4) The articulation suppression effect, memory for verbal material is impaired when people are asked to name something irrelevant aloud during the presentation of words, letters, or digits to be remembered. The visuo-spatial sketchpad stores and manipulates visual and spatial information in the temporary storage. Although the concept of WM has largely developed in agreement with empirical evidence regarding verbal processes, recently the number of studies investigating visual-spatial processes has increased greatly. Additional information about Baddeley's visuo-spatial sketchpad has been used to further investigate the overall functioning of WM. Logie (1995) believes the sketchpad has two components, the visual cache and the inner scribe. This subsystem has been called the visual-spatial working memory (VSWM), characterized by the capacity to maintain visual-spatial information in a temporary memory system and process it regardless of the stimuli source, whether perception (not only visual but also haptic or auditory) or long-term systems (Cornoldi & Vecci, 2003). Thus visual and spatial components can be distinguished within VSWM and the visual component works much like phonological-articulatory loop system. Studies have shown support for the VSWM and the dissociation into its subcomponents. The visual cache passively stores information about visual form and colour and the inner scribe actively takes care of the spatial and movement information through rehearsal in the visual cache and transfers information to the central executive. A Quinn and McConnell study (1996) suggests that participants that learn lists of words in two different ways and/or being presented with visual or spatial tasks either mainly use visual processing, depending on the visual cache, or uses spatial processing or using both visual and spatial processing for their memory performance. Brain imaging data suggests that the two subcomponents of the visuo-spatial sketchpad are located in different brain regions (e.g., Smith and Jonides, 1997). The central executive is responsible for controlling transmission between the two slave systems and other parts of the cognitive system. Baddeley (1996) identifies three major functions of the central executive:

switching of retrieval plans, timesharing in dual-task studies, and selective attention to certain stimuli while ignoring others. Damage to the frontal lobes of the cortex can cause impairments to the central executive, possibly causing dysexecutive syndrome, the inability to learn new types of tasks in new situations. The episodic buffer is a temporary storage system that holds and integrates information from the phonological loop, the visuo-spatial sketchpad, long-term memory, and is controlled by the central executive, which leads to a complex structure, an episode (Baddeley, 2000).

A matter of considerable debate and disagreement among contemporary models of working memory concerns the cognitive and neural architecture of working memory regarding the nature of the 'stores' or representational basis that entail temporary retention of information within working memory and the relationships between working memory and long-term memory in general. One perspective conjectures that internal on-line maintenance of information that has been removed from our sensorial apparatus is achieved by the persistent activation of a subset of long-term memory representations stored in the posterior cortices (Crowder, 1993). According to this theoretical conception of working memory, the same brain systems are responsible for the mechanisms underlying perception, memory storage, and selective activation of representations of long-term memory within working memory (Engle et al., 1999). Proponents of the competing account holds that temporary retention of representations is accomplished via transfer of to-be-retained information into either of two material-specific buffers for its short-term storage, both of which constitute parts of a distinct working memory system assumed to be separate from the long-term memory systems (Baddeley, 1986, Shallice, 1988). Both sides claim to have strong support from empirical data (see above section on theoretical models of the relationship between working memory and episodic memory). Ruchkin et al. (2003) note that this is an empirical issue rather than a theoretical issue that requires more sophisticated neuroscientific examination. Given that the general notion of WM is the mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition (Miyake & Shah, 1999), it should not come as a surprise that this concept has been frequently used in cognitive psychology to describe everyday mental challenges such as reading, planning, reasoning, and comprehending complex situations in the external world (Cowan, 2001).

An important feature within the WM model pertains to the inherent capacity-limitation with regard to the amount of information that can be maintained or held "online" (and/or undergo context-appropriate processing) at any given time. Miller (1956), who suggested that working memory has a limited storage capacity, argued for a capacity limit of around 7 (+/– 2) items. This limitation has since been questioned, and current suggestions only credit the capacity with the ability to store four items (Cowan, 2001) or even a single unit (Olsson & Poom, 2005). Another important distinction in information processing and memory system is between declarative and content knowledge and procedural and processing knowledge tasks. Declarative knowledge is factual knowledge about the meaning or perceptual characteristics of things, spanning from simple daily events to highly organized conceptual knowledge of some subject matter. Anderson (1993) distinguishes between two types of declarative knowledge representations: a meaning-based memory code (abstract propositions) and a variety of perception-based codes (images, etc.). Procedural knowledge is described as knowledge of how to do something, from how to peel a potato to fly an aeroplane, to transforming and rehearsing information in working memory for creating new methods of problem solving and for enable monitoring of how these new methods are being implemented. There are sufficient neuroanatomic findings that support the idea of these two memory systems and that they differ in their operating characteristics and in the nature of representation they use (Cohen & Eisenbaum, 1993).

Visual-spatial ability and working memory in surgery

Macmillan and Cuschieri (1999) identified aspects of operative performance that did not improve with practice, indicating that some innate abilities ultimately could predict the level of operative skill. Some individuals might not possess capacities favouring acquisition and execution of image guided surgical skills. A major task for a better understanding the role of spatial abilities for surgical performance should be to explain the following: (i.) the systematic individual difference variance that is uniquely spatial and (ii.) the much larger portion of the variation of such tasks that is shared with general abilities. Although several studies using correlation analyses consistently and successfully have shown that psychomotor and perceptual ability predicts minimal access surgical performance (e.g., Gallagher et al., 1998; Rosser et al., 1998), there is a controversy in the literature regarding the–role of innate abilities or aptitudes of surgical applicants for anticipating future surgical proficiency. For example, a few studies have yielded potentially useful results in finding correlations between visual-spatial ability, defined as the capacity to generate surgical performance in novices (e.g., Risucci et al., 2001; Ström et al., 2003), while others have not (Sidhu et al., 2004). Wantzel et al. (2003) remarked that early contradictory findings may have been due to methodological differences in assessing surgical performance objectively, differences in understanding the role of visual-spatial ability as surgical experience increases from initial to late phases of training, as well as differences in view on the question if different levels of visual-spatial ability might be required for different surgical tasks. For example, it is commonly accepted in the field of visual neuroscience that the processing of visual information occurs in a number of stages, from simple edge and surface encoding to more complex whole-object processing (Mountcastle, 1998). According to the literature, the role for WM on performance in simulator training has only recently been analyzed (Hedman et al., in press), indicating that working memory may be a significant component to surgical endoscopic performance.

Simulators and performance variables

The Procedicus KSA is a PC-based virtual reality system for laparoscopic simulation with anatomic graphics and haptic (force) feedback (Figure 2). The screen was 17 inches with a resolution of 2560 × 1024. The participants were standing on the left side of an imagined patient. The specific bimanual eye–hand coordination IN task is to navigate with the optic device (30° angle) held in the left hand and the probe held in the right hand and to find and probe 10 spheres randomly interspaced throughout a virtual upper abdomen. One sphere has to be found and touched with the tip of the probe. As a consequence it disappears and another sphere has to be found. The simulator measures performance and provides the results at the end of each test. If an organ is touched, a haptic feedback is sensed. The measured variables of performance are time, movement economy, collisions with the optic device and the probe, and total score. The variable time in the KSA simulator is calculated as the time passed from the end of the calibration of the instruments until the last target is hit. The movement economy variable is calculated as the optimal path length divided by the actual path length. The optimal path length is the sum of the straight-line distances between the randomly interspaced targets. Collisions with the instruments are calculated as the sum of all shaft and tip collisions. The total score is composed of the collisions with the instruments together with movement economy.

Figure 2. Instrument Navigation in the Procedicus KSA (Mentice AB, Gothenburg, Sweden).

The Procedicus MIST is a PC-based VR system for objective ambidextrous psychomotor surgical training and assessment has no anatomical graphics and no haptic feedback (Figure 3). It has been validated extensively for the training and assessment of basic laparoscopic skills (Taffinder et al., 1998; Gallagher et al., 2001). It has tasks of progressive and graded complexity for teaching different basic skills. The participants trained on all six tasks (core skills one) during the one-hour session. All tasks begin with bilateral movements in order to touch a virtual sphere with the tips of the virtual instruments. In the first task, the participants are required to grasp a virtual sphere and place it in the centre of a virtual wire frame. In task two, the virtual sphere is grasped and then transferred between the instruments and finally placed inside the wire frame. In the third task, the segments of a virtual cylinder are grasped alternatively. In task four, the participants are required to grasp a virtual sphere, touch it with the tip of the other instrument that is then withdrawn and reinserted and once again touches the sphere now inside a wire frame. In the fifth task, once the virtual sphere has been grasped, three small cubes appear on the surface of the sphere. The cubes appear one at a time at 90º angles. They are virtually diathermied away using an L-hook (precisely positioned on the cube) and a foot pedal. Task six combines the actions of the fourth and fifth tasks and its scores were used for correlation analyses.

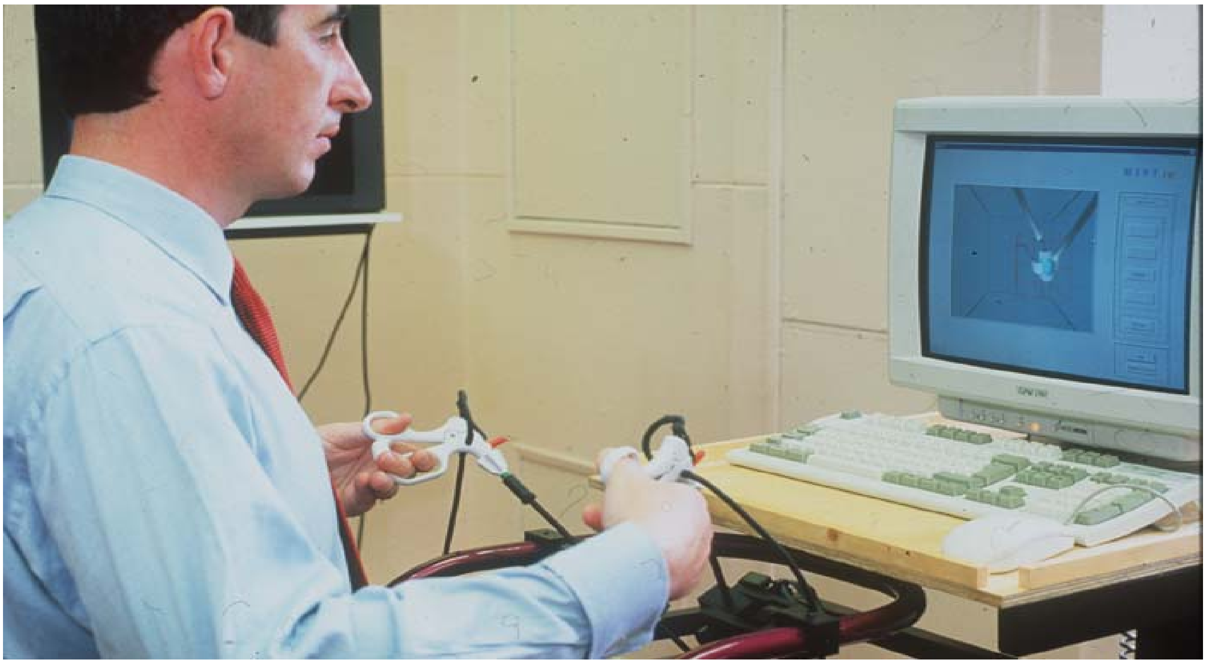


Figure 3. Manipulate and Diathermy in the Procedicus MIST (Mentice AB, Gothenburg, Sweden).

The GI Mentor II is a computerized interactive training simulator for gastrointestinal endoscopy. It consists of a specially designed mannequin that switches between upper and lower gastrointestinal positions and contains a realistic endoscope and provides tactile sensations while simultaneously receiving visual feedback from a monitor. The students were asked to perform one gastroscopy (case 1 module 1) in the GI-Mentor II, Simbionix, USA, Cleveland, OH (Figure 4). The case was chosen because it represents a technically moderately challenging training task for gastroscopy. All students received the following instructions on how to perform the gastroscopy:

1. Go down to the second duodenum as quickly as you can with the instrument.
2. On your way up, inspect as much of the mucosa as you can.
3. Perform retroversion of the instrument in the stomach and inspect the cardia from below.
4. After inspection of the cardia, straighten out the instrument and inspect parts of the mucosa not yet inspected.
5. After withdrawing the instrument from the esophagus, deflate the stomach.

When the simulated gastroscopy task was finished, the following metrics were presented for each of the participants:

1. Time to second duodenum in seconds.
2. Total endoscopy time in seconds.
3. Percent of time spent with clear view, i.e., the time in which no obstacle covered the camera of the scope (such as blood and other residues).
4. Percent of the gastric mucosal surface examined.
5. Efficiency of screening. This parameter is a “score”, written as a percentage value, to assess how much of the mucosal surface the trainee has inspected in relation to the total time it took him to finish the procedure.

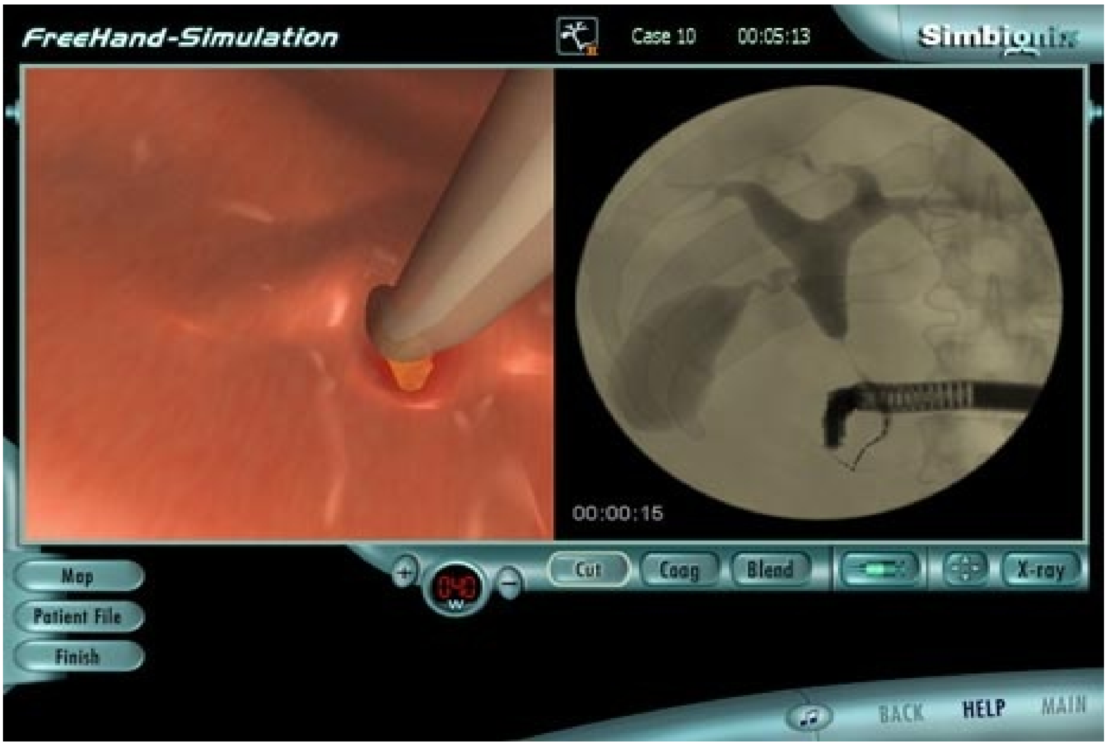


Figure 4. GI Mentor II, Gastroendoscopy Simulator (Mentice AB, Gothenburg, Sweden).

OBJECTIVES

The aim of the studies reported in this thesis is to provide initial outlines of the cognitive abilities that may underlie endoscopic simulator performance. We have addressed how high-level visual-spatial ability of surgical novices is related to performance of two simulator tasks with and without anatomical graphics and haptic feedback, tasks that differ in visual-spatial complexity. Moreover, we have investigated if visual and verbal working WM are related to the outcome of task performance scores in simulated laparoscopic cholecystectomy and gastroscopy training. To complement a growing line of research in minimally access surgery, at the Centre for Advanced Medical Simulation, Huddinge University Hospital and Karolinska Institutet we are trying to address the role of cognitive abilities (Figure 5).

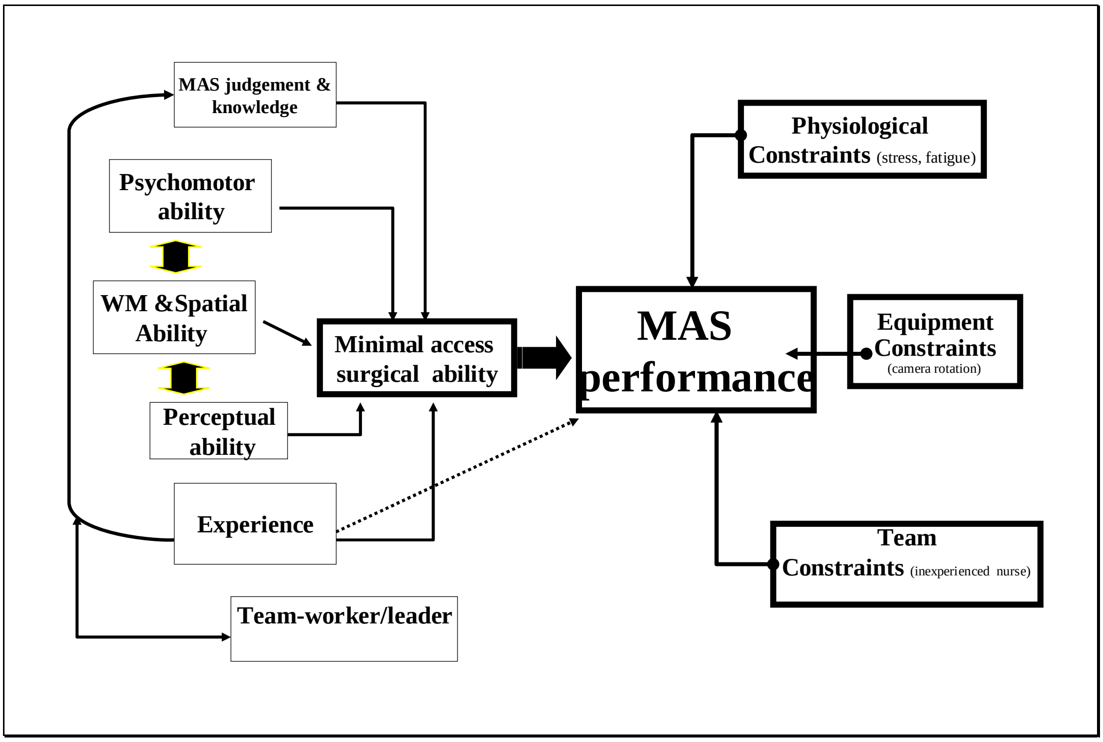


Figure 5. Minimally Access Surgical Performance model (modified from A.G. Gallagher, Seminar Nov. 2003).

Figure 5 summarizes the ongoing research objectives in the field of simulated minimally invasive surgery (MAS) and all of the different influences that can be encountered during a simulator performance session. The complexity of the model itself, with different constraints, abilities, and knowledge, suggest that testing of human working memory functions is also needed. Taken into account all the possible influential internal and external factors, the cognitive load should be considered significant. As a complement to the ongoing investigation of prior knowledge, experience, effects of team workers, measures of perceptual abilities, and visual-spatial abilities, measures of the working memory concept will benefit the understanding of the MAS ability concept. Baddeley's multicomponent model of working memory has research acceptance and it fits well into the role of investigating the underlying cognitive mechanisms that are involved in surgical performance. Since the simulated MAS performance scores will contain fewer constraints (no team constraints), the actual real world cognitive load should be considered higher. This means that any significant findings between MAS performance scores and working memory abilities in our study should have an even greater support in real life operation situations.

EMPIRICAL STUDIES

Study 1

This study addresses how high-level visual-spatial ability of surgical novices is related to performance of two simulator tasks with Key Surgical Activities (KSA) and without Minimally Invasive Surgical Training (MIST) anatomic graphics and haptic feedback, tasks that have different levels of visual-spatial complexity. We examined whether Wanzel et al. (2002) findings of a correlation between high-level visual-spatial ability for novices and surgical proficiency and stronger correlations for more complex spatial tasks are also applicable to image-guided surgical simulator training. The main hypothesis was that surgical novices' high-level visual-spatial ability scores (confounded or not confounded with general cognitive ability) are positively and significantly related to Instrument Navigation task performance scores in the Procedicus KSA. We did not expect any significant correlations between high-level visual-spatial ability scores and performance scores in another ambidextrous but less complex visual-spatial surgical training task (Manipulate and Diathermy) in the Procedicus MIST. Wanzel et al. addressed some of these limitations and showed that junior surgical residents with high visual-spatial scores assessed by the Mental Rotation test, MRT (Peters et al., 2000), performed better in completing and learning a visual-spatial complex surgical Z-plasty (a technique used for scar revision and camouflage) procedure on a pig.

Fifty-four medical students in surgery participated in the study (27 women, mean age 24.8 years, and 27 men, mean age 25.7 years). Tests for assessing visual-spatial ability confounded with general ability were the revised Vanderberg and Kuse (Peters et al., 2000) mental rotation tests MRT-A and MRT-C. We differentiated between high-level visual-spatial ability confounded as well as not confounded by general cognitive processes by using the BasIQ test. This psychometric test Mårdberg et al. (2000) assesses the systematic individual difference variance that is uniquely visual-spatial, which is unrelated to general cognitive ability or the g-factor. It uses nested factor analysis and modelling techniques to generate a measure of g as well as unconfounded (unique) measures of visual-spatial and verbal and numerical ability (Gustafsson, 1998). After each completed simulator session, the medical students were asked to complete a Flow experience test and the Borg test. The Flow experience questionnaire (14 items on a Likert-type scale) asked about the subject's experienced enjoyment, concentration, control, exploratory use, and challenge in the task (Ghani & Deshpande, 1994). The subject's perception of mental strain–how strenuous the exercise in the simulator-task felt–was assessed by the Borg category-ratio 10 scale (CR-10). We used two ambidextrous surgical training tasks differing in visual-spatial complexity: Instrument Navigation (IN) in the Procedicus KSA (Mentice AB, Gothenburg, Sweden) and Manipulate and Diathermy (MD) in the Procedicus MIST (Mentice AB, Gothenburg, Sweden).

Results

There was a difference between visual-spatial ability and general cognitive ability for both tasks; total scores in KSA correlated with spatial ability but not with general cognitive ability, and total scores in MIST correlated with cognitive ability but not with visual-spatial ability (Table 1).

Table 1.

*Descriptives and Pearson's r correlations for psychometric test scores and performance scores in Instrument Navigation (IN) and Manipulate and Diathermy (MD). **Correlation significant at the 0.01 level. * Correlation significant at the 0.05 level.*

Descriptives &	Psychometric Test Scores			
Performance scores	MRT-A	MRT-C	BASIQ-G	BASIQ-Spat
n	54	54	25	25
M	13.35	8.68	11.00	-0.60
S.D	0.74	0.65	0.43	1.34
IN Total score, first trial	-0.21	0.097	0.041	0.443*
IN Total score, last trial	0.250	0.278*	0.257	0.489*
IN Time, last trial	-0.325*	0.372**	-0.402*	-0.432*
IN Movement economy, last trial	-0.291*	-0.345*	-0.168	-0.289
MD Total score, last trial	0.000	-0.239	-0.405*	-0.234

Pearson's *r* correlations were obtained between total score from the last trial in IN for the KSA task, and visual-spatial scores correlated with general cognitive ability (the g factor). There was a significant improvement after one hour of training in the Procedicus MIST regarding total score (Paired t-test, $p<0.001$) and in the Procedicus KSA regarding time, movement economy, collisions with the probe, and total score (Wilcoxon Signed Rank Sum Test, $p<0.001$). There were no significant Pearson's *r* correlations between the simulator performance-, MRT-, BasIQ scores and the scores in the Flow- and Borg scale.

Discussion

We were able to demonstrate a relationship between several visual-spatial test scores and performance scores for subjects with no prior experience with the present surgical simulator training procedures. Surgical novices' high level visual-spatial ability scores were positively and significantly related to IN performance scores in the Procedicus KSA (confounded as well as not confounded with general cognitive ability). The correlations were even higher for visual-spatial ability not confounded with general cognitive ability. As expected, we did not find any significant correlations between visual-spatial ability and the less complex visual-spatial surgical training task (MD) in the Procedicus MIST. This task involves more verbal instructions than the KSA task and is structured in a logically similar way as the subtests of BasIQ. These task characteristics could explain why we found a significant correlation between general cognitive ability (as measured by BasIQ) and total performance scores in the MIST task. Our findings, which are similar to the recent findings by Wanzel et al., show that visual-spatial ability among novices is associated with skilled performance on a spatially complex surgical procedure.

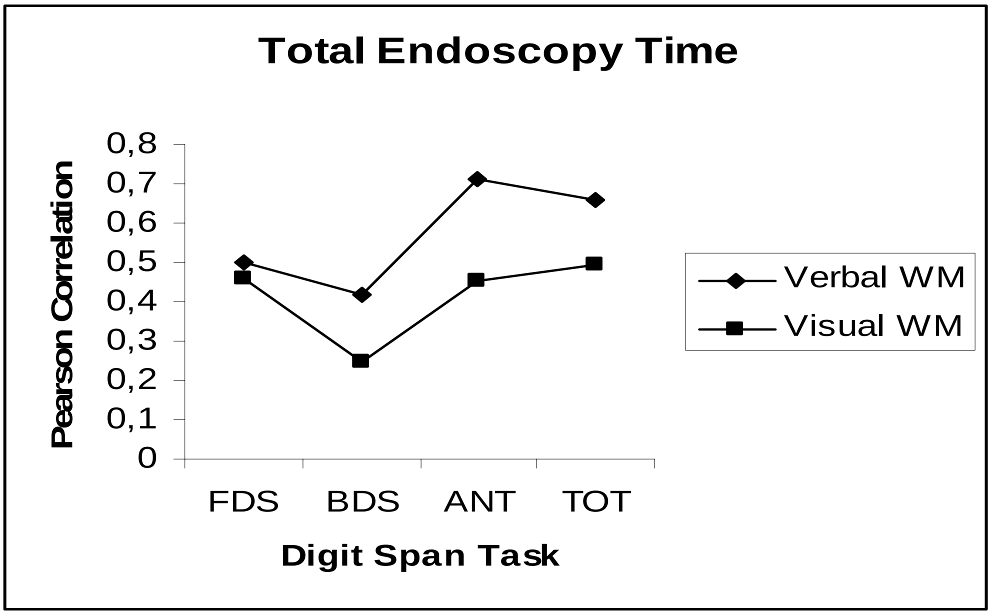
Study 2

In study 2, we investigated the relationship between visual WM and verbal WM and a performance measure in endoscopic instrument navigation in MIST and GI Mentor II (a simulator for gastroendoscopy). Thirty-two medical students (novices, 16 women and 16 men ranging between 22 and 40 years) at the Karolinska Institutet, Karolinska University Hospital in Sweden participated in the study. Performance data (Gastroscopy case 1 module 1) from the GI Mentor II and MIST (MD level easy) were compared with WM data from the WAIS test battery.

WM can be viewed as a four-component entity (Baddeley, 1998) that contains a central executive, which coordinates attention activities and governs responses, an episodic buffer, which integrates information from various parts of the WM and two subsidiary slave systems – the phonological loop and the visual-spatial sketchpad. In this study, we focus on the phonological loop. The visual- and the verbal WM falls primarily within the phonological loop category when using digit- and alphabetical span tasks. The WM tests were taken from the WAIS III test battery (Wechsler, 2003). It is an individually administered battery of learning, memory, and WM measures in both the verbal and visual domains. We computed three scores of particular interest in this study: scores for forward digit span task (FDS) – recall of digits in the order they were presented; backward digit span task (BDS) – recall of the digits starting from the last presented item; and an alphanumerical task (ANT) in which the participants were asked to memorize a series of letters and digits and arranging them in alphabetical order and numerical order with the forward digit span being the least demanding on the central executive function and with the alphanumerical task being the most demanding. A fourth test of visual WM, the Rey Complex Figure Test and Recognition Trial (RCFT), was administered. It was included in our WM test battery since it is more associated with visuo-spatial abilities than the span tasks that are orientated around phonological abilities (Meyers & Meyers, 1995). After each completed session in the MIST and GI Mentor II tasks, all participants answered two additional psychometric tests to control for possible differences in flow experiences (Csikszentmihalyi & Rathunde, 1992) and mental effort (Borg, 1998) between training tasks.

Results

There were significant Pearson's r correlations found between the visual WM test scores and the GI Mentor II simulator performance scores (Figures 6 & 7).



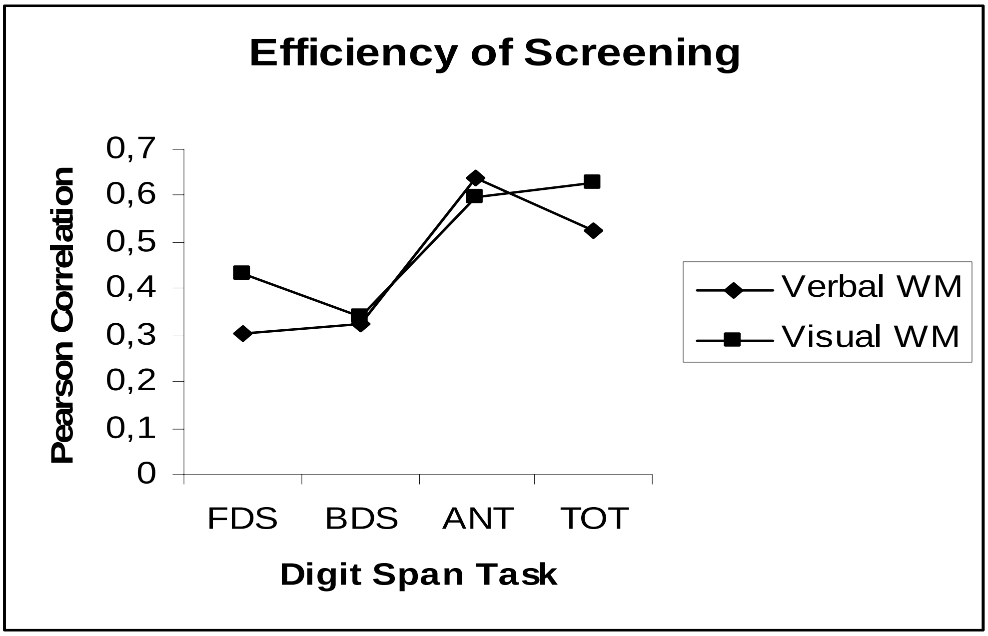


Figure 6 and 7. Correlation between WM tasks and total endoscopy time and correlations between WM tasks and efficiency of screening. Forward digit span task (FDS), backward digit span task (BDS), alphanumerical task (ANT), total WM score (TOT).

Efficiency of screening correlated significance with the Alphanumerical task (r=.598, p=.005) and the Total digit span score (r=.630, p=.003). The Total endoscopy time correlated significantly with the Forward digit span task (r=-.457, p=.043), Alphanumerical task (r=-.454, p=.044), and the Total digit span score (r=-.496, p=.026). The verbal working memory showed significance in the GI Mentor II; Total endoscopy time correlated significantly with the Alphanumerical task (r=-.709, p=.010) and the Total digit span score (r=-.668, p=.018) and Efficiency of screening correlated significantly with the Alphanumerical task (r=.639, p=.025). There were no significant correlations between the GI Mentor II performance scores and the RCFT-, Flow-, and Borg scores. There were no significant correlations between the Procedicus MIST performance scores and the visual WM tests or the RCFT test, and there were no significant correlations the Procedicus MIST performance scores and the Flow- and Borg scores.

Discussion

Our findings suggest that both visual- and verbal WM significantly correlate with the total endoscopy time and efficiency of screening, for the GI Mentor II task. The results for both the visual- and the verbal WM presentation show the same tendencies in general, which indicates that they may be equally good predictors for this simulator training performance. Furthermore, the results indicate that the WM capacity is related to performance speed and efficiency of the medical students. Students with a superior WM capacity are faster at adapting to the simulated situation and are more efficient in their screenings. The absence of correlations for the simulator performance measures and the Flow- and Borg scales presumably indicate that the surgical performance was unaffected by differences in flow and mental strain. The RCFT test, which is a visual-spatial oriented WM test, did not correlate with any simulator performance measure. Both the MIST task and the GI Mentor task do not offer any greater visual-spatial challenges, a result that possibly explains the lack of any significant correlations.

GENERAL DISCUSSION AND CONCLUSIONS

The general aim of this thesis was to initially investigate the role of two cognitive abilities, visual-spatial ability and working memory in endoscopic simulator performance. In Study 1, we found a pure spatial ability measure sorted from the intelligence g-score and background variables (flow and Borg measures) for the IN performance scores in the Procedicus KSA and not so for the less spatially complex MD score in the Procedicus MIST. The results also indicate that an increased visual-spatial cognitive workload increases the discrimination power for the simulator performance scores. We validated the open surgery studies by Wantzel et al. (2002) and Wantzel et al. (2003) and their findings of spatial abilities as a significant contributor to surgical performance. In our study, we found that this relationship also was true for simulated endoscopy. Our findings suggest that scores of visual-spatial ability of students at early phases of skill acquisition (Ackerman, 1988) seem to depend on the content and structure of the training task.

It should be noted that our study was conducted with a simulator and it is important to consider that our surgical performance scores derived from precise computer calculations compared to the inter-rater reliability measured by Wantzel et al. (2002), which could always be prone to bias and human cognitive shortcomings.

The findings in Study 1 demonstrate that individual differences in visual-spatial abilities significantly contributed to the surgical performance and since differences in spatial visualization are regarded as differences in WM resources of spatial information (Carpenter & Just, 1986), we wanted to explore the underlying structures of storage and processing in working memory connected to simulated endoscopic surgery. In Study 2, the goal was to predict simulator performance scores from WM tasks in complex procedures for two simulators (GI Mentor II & Procedicus MIST). We found that that both visual- and verbal WM tests are in general equally good predictors of simulator performance. The higher level of stress, or demand on the executive function in the WM tasks, the stronger is the correlation with the simulator performance scores. The Procedicus MIST task offers more psychomotor challenges than the GI Mentor II and seems to be less demanding on the WM.

This research should be expanded to the use more demanding spatial abilities and working memory tests using more processing demands on the executive function. For both Studies 1 and 2, the time factor was an influential indicator of the influence of our cognitive abilities on endoscopic simulation. The MRT-tests used in Study 1 is classified as belonging to the Spatial Relations (also called Speeded Rotation) category within spatial tests. It emphasizes speed and represents the ability to solve simple rotation problems quickly (Lohman, 1988). In addition, the more demanding MRT-C showed better discrimination power than the less demanding MRT-A. The alphanumerical WM task (ANT) in Study 2 had better discrimination power than the less demanding forward digit span WM task (FDS) regarding time consumption. The results in both studies also indicate that measures for both visual-spatial ability and WM with a high cognitive workload sharpen the discrimination of the endoscopic simulator error measures. Although these initial studies have investigated the relationships of visual-spatial ability and WM with simulated endoscopic surgery performance, the combined role of these cognitive abilities has not yet been tested. Therefore, it would be illuminating to use a more complex WM measure using continuous operation span tasks that involve a greater demand on the executive functions (Barrouliet et al., 2004), and introduce the three-factor classification used by Miyake et al. (2001) for the spatial ability measurement. This approach would give a deeper understanding of the internal structure of WM and visual-spatial ability and how they relate to each other in the context of surgical simulation and training. Tests with added cognitive workload along with prolonged training sessions may also better explain the nature of cognitive abilities in virtual endoscopy. Furthermore, our testing has been based on scenario-based training that should incorporate the major steps of simulated real life learning. From an ecological validity point of view, there are some limitations regarding the constraints during our testing. The team constraints and the physiological constraints, such as stress and the fact that a slip of the wrist can have disastrous consequences, are not present during our training sessions, stresses that should be considered in a comparison with a real life operation situation. The idea is that a real life operation situation requires a cognitive load on the individual surgeon higher than our training sessions can provide. We believe our results with respect to training should be even more significant in real life situations.

Due to practical factors at the Karolinska Institutet, we could not use a control group in our experiments. Our participants were medical students and attending surgical semester. They were not randomly sampled. Due to financial reasons and lack of testing time, we could not conduct in one single study an experiment that would have covered the surgical residents' visual-spatial abilities, working memory abilities, perceptual abilities, psychomotor abilities, and other important variables. Using regression analysis, such a study would have elucidated the minimally access surgical performance concept and answered to which extent each of these abilities contribute to the overall surgical experience.

Many kinds of visual-spatial training and everyday activities seem to benefit the performance of virtual endoscopy (Enochsson et al., 2004) and the same relation seems to be the case with WM training (Westerberg et al., 2004). The possibilities to train these abilities along with our initial results, indicating that these abilities can predict the outcome of endoscopic simulator performance, should be considered when planning a surgical resident curriculum. It is also important to take into consideration a simulation training curriculum for experienced and aging surgeons since studies have shown that age differences in working memory may be mediated by age-related reductions in the speed of executive elementary operations (Salthouse & Babcock, 1992). The performance at an endocscopic simulator and at a real life surgical operation is extremely hard to totally define since it is multifactorial. In addition to a wide individual difference in cognitive traits, there are ever changing situational factors that would include every single present state of mind or physical determinant for each of the participants including everything from daily fresh relational issues and recent nutritional intakes. Therefore, we can not recommend our current psychometric tests as selection criteria for a career in surgery. However, these tests can be applied to identify novice trainees who might benefit from supplementary instruction, training, and support in specific surgical tasks.

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