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see me, touch me, heal me

Jan Maarten Luursema

see me touch me heal me

The Role of Visuo-Spatial Ability in Virtual Anatomical Learning and Endoscopic Simulator Training

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SEE ME, TOUCH ME, HEAL ME

The Role of Visuo-spatial Ability in
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Endoscopic Simulator Training

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SEE ME, TOUCH ME, HEAL ME

THE ROLE OF VISUO-SPATIAL ABILITY IN VIRTUAL ANATOMICAL LEARNING AND SURGICAL SIMULATOR TRAINING

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
prof. dr. H. Brinksma,
on account of the decision of the graduation committee,
to be publicly defended
on Friday June 4th, 2010 at 16:45

by

Jan-Maarten Luursema
born on November 18th, 1967
in Bennebroek, The Netherlands

Dit proefschrift is goedgekeurd door de promotor:
Prof. dr. ing. W. B. Verwey

Acknowledgements

No man is an island, but some would say every PhD student is. Logic now tells us that PhD students cannot be human.

So what are we? Are we mythical creatures such as encountered by Saint Brendan of legend? On their epic seafaring journey, Saint Brendan's shipmates board an island to celebrate Easter. When they start making a fire the next day, the island ripples and starts swimming away, revealing it to be the giant fish Jasconius. If we liken the fish Jasconius to the PhD student, one clear similarity stands out: both drift silently for years on end in a single spot, and where Jasconius grows a complete ecosystem on his back, the PhD student grows a thesis. When the PhD student finally swims away and dives to find new waters of yet uncharted data, he is like Jasconius who swims to new fishing grounds but drags a forest underwater; the thesis dives with the student, never to be seen again...

A more benevolent analogy would hold that the PhD student *is* human but *lives* on an island, cultivating a thesis in relative isolation. On this island we do entertain regular visitors, who share their knowledge and experience in growing fruitful papers and chapters.

I'd like to thank the following visitors to island C331 at the Cubicus building, University of Twente, for their contributions to the work presented in this thesis: My promotor Willem Verwey for his commitment to improving all aspects of my research and papers; Piet Kommers for his boldness in hiring me and his work on the TwoCents learning environment; my co-workers at the department of Cognitive Psychology and Ergonomics for their support and willingness to discuss a wide range of topics; my fellow PhD students and co-workers at the faculty of Behavioral Sciences for additional fun and inspiration. I also like to thank the DIME project partners for hosting and participating in many engaging meetings. Finally, many thanks and hugs for my friends and family for distracting me the good way!

Table of Contents

1. Introduction and Theory

1 General Introduction

Medical learning and training are fields in transition. Catalyst in this change is the introduction of digital technology, for example in the form of simulator technology in surgical training, and virtual learning environments in anatomical learning. The primary aim of this thesis is to help understand and optimize this new situation. More specifically, the mediating role of cognitive abilities such as visuo-spatial ability in this learning and training is investigated.

In professional fields where the costs of errors are very large, training is preferably done using some form of simulation technology. Surgical training can be considered prime amongst those fields: Already around 500 BC, a Hindu surgeon known as Sushruta advocated, amongst others, the use of watermelons for practicing incision, and the use of a ‘full-sized doll made of stuffed linen’ for practicing bandaging (Sushruta, 3rd century BC/1907; available at archive.org). Since the 1960s, the advent of computer-mediated simulation technology has given rise to a new generation of training opportunities; pioneered by the use of flight simulators in pilot training (Koonce et al., 1998). Perhaps surprisingly, the use of this technology in surgical training has been lagging behind somewhat: development of the first computerized surgical simulators starts only in the late 1980s (Satava, 2008). Partly this is caused by the human body being hard to simulate (compared to say, the controls of an airplane), and for another part this is caused by a lack of incentive to change a well-established surgical training curriculum (Dawson and Kaufman, 1998). This situation has changed, and simulator training has become an important part of the surgical curriculum (Satava, 2008).

Knowledge of human anatomy is essential for surgeons, or indeed anyone seeking to practice medicine. It is as central to medicine as the table of elements is to chemistry, or evolution is to biology. An understanding of physiology, pathology, and trauma is impossible without anatomical knowledge. Similarly, being skilled in the diverse technologies that have been developed to cure disease, disorder, or trauma (or to provide palliative care when a cure is not available) is unthinkable without knowledge of human anatomy. Similar to surgical training, anatomical learning too is changing, in that virtual learning environments offer a new approach to anatomical instruction (e.g., Brenton et al., 2007).

People are similar, yet different. This is reflected by two broad research areas within psychology: whereas experimental psychology traditionally has been interested in similarities between people, differential psychologists have focused on individual differences, such as differences in personality or cognitive abilities (Hegarty and Waller, 2005; Cronbach, 1957). Each area is associated with specific methodology; in experimental psychology often different conditions are compared for similar groups of people, whereas in differential psychology typically traits are correlated within groups of people.

Traditionally these approaches have been practiced separately rather than jointly. This is regrettable, since a combined approach would have many practical applications. An example would be designing medical training courses, where one not only would want to compare different designs for effectiveness, but also how such designs affect people of differing cognitive abilities. Individual differences in cognitive abilities are long known to be correlated with success in the workplace (Ghiselli, 1973), and, relevant to this thesis, performance in surgery is correlated with the cognitive ability of visuo-spatial ability (Anastakis et al., 2000).

To further explore the role of visuo-spatial ability in anatomical learning and surgical training, this ability was measured for all participants in the studies reported in this thesis. The first three experimental chapters compare different aspects of anatomical learning environments, taking into account the visuo-spatial ability factor of visualization. The last two experimental chapters investigate how success in surgical simulator training correlates with the major five individual factors that together form visuo-spatial ability.

2 Anatomical learning and surgical training

In this section a short history of anatomical learning and surgical training is provided, followed by a discussion of the benefits and drawbacks of the various learning- and training methods as they are currently utilized in those fields. This discussion raises a number of questions regarding the effectiveness of key features of anatomical learning methods, and identifies areas in which our knowledge of endoscopic simulator training can be improved.

2.1 Anatomical learning

Although the study of human anatomy has a long and international history, it is only in 16th century Italy that the human body starts to be studied in a systematic and critical manner, largely due to the efforts of the anatomist Vesalius (Cushing, 1962). In an academic culture that valued tradition over observation, lectures on human anatomy were based on the texts of the Roman physician Galen, accompanied by live prosection that was performed merely to illustrate the lecture. That these dissections invariably contradicted the lecture on key points did not change this curious situation, until Vesalius challenged this practice by performing his own dissections during his lectures (up to then the role of lecturer and prosector were separate), and by no longer tolerating the obvious flaws in the traditional texts. Vesalius was also amongst the first to realize the power of the new medium of print in distributing ideas, and had a comprehensive, illustrated account of his investigations printed, effectively creating the first science-based anatomical atlas. During the 17th century, the first wax models of human anatomy were created (Chen et al., 1999), to support the study of anatomy by providing a visual and spatial source of anatomical information both more accessible and less susceptible to putrefaction than actual dead bodies. The medical curriculum reform in the wake of the French revolution made it common practice for medical students to perform their own dissections (Weiner and Sauter, 2003); this came to be known as the Paris school, whose influence spread rapidly to other countries. By then, the essentially modern situation of anatomical learning through dissection, supported by anatomical atlases and 3D models was in place. This situation however is now changing.

Fuelled by then novel imaging techniques such as CT and MRI, in combination with the ubiquity of networked computers, the 1980s mark the first development of environments for virtual anatomical learning (Jastrow and Vollrath, 2003, and Brenton et al., 2007 provide overviews of the current situation). Many felt these environments provided a viable alternative to the burden of having to maintain expensive and laborious facilities for dissection. This opened a heated and ongoing debate on the role of dissection in medical curricula (Aziz et al., 2002). Table 1-1 lists the relative strengths and weaknesses of these educational tools, which is mostly informed by Aziz et al.'s discussion of the subject, but also builds on the author's personal experience as a student of anatomy at the department of Anatomy and Embryology, University of Maastricht. The features listed in this table will be discussed below in some detail.

Table 1-1 Strengths and Weaknesses of Current Educational Tools for Anatomical Learning

Features	**Atlases**	**Dissection**	**Manikins**	**Virtual learning Environments**
Anatomical Variability	+/-	+	-	+
Haptic Information	-	++	+	+/-
Structural Detail	+	++	+/-	+
Stereopsis	-	+	+	+
Dynamic Exploration	-	+	+	+
Practical Implementation	++	-	+	+

2.1.1 Anatomical variability

An appreciation of *anatomical variability*, the variation of all traits when assessed as part of a population (Aziz et al., 2002), is important for medical diagnostic and clinical practice. An oversimplified presentation of human anatomy can lead to misdiagnosis and even malpractice (Willan and Humperson, 1999). In atlases and virtual learning environments one can easily illustrate the main anatomical variants of a given structure; including their statistical distribution over a population (the series of Lanz und Wachsmuth anatomical atlases provide a great example). A wide range of variants can in principle be encountered during dissection, but only insofar they are present in the local dissection room, which may present an incomplete or biased sample. Manikins typically do not display anatomical variability.

2.1.2 Haptic information

People experience a wide range of characteristics through haptic mediation, such as weight, flexibility, structure, robustness, conduction of heat, size, and shape. Haptic experience during training is thought to transfer to such touch-based medical skills as palpation, percussion, and auscultation (Moore, 1998), and of course surgical skills. Dissection will give the best approximation (although the processes associated with death and preservation do change the haptic experience), followed by manikins, where actually size and shape are the only characteristics that preserve their correspondence with the characteristics of the structures they represent. The implementation of haptic information in virtual learning environments is currently very limited, and is mainly concerned with those aspects of haptic feedback that can be simulated through force feedback; i.e. resistance to exerted force, shape, size and flexibility (Liu et al., 2003; Misra et al., 2008). Tactile information, such as surface structure and conduction of heat is at the time of writing only available in highly experimental settings.

2.1.3 Structural detail

In contrast to dissection, *mediated* anatomical information sources (atlases, manikins, and virtual learning environments) filter out much of the richness of the original anatomy, presenting students a representation that merely retains the conceptual model of its makers. This can lead to a situation where students discover only what they are supposed to discover, preventing them to enrich their knowledge beyond the provided model. The training of medical skills is likely to be facilitated if at an earlier (anatomical learning) stage students have had the opportunity to test provided conceptual models against the reality of first hand dissection experience.

2.1.4 Stereopsis

Stereopsis refers to the visual experience of space derived from slightly different patterns of light (stemming from the same scene) being simultaneously received by either retina. This phenomenon was first reported by Wheatstone in 1838. Stereopsis is one of the most important visual depth cues in one's *personal space*, which is defined as 'the zone immediately surrounding the observer's head, generally within arm's reach and slightly beyond' (Cutting and Vishton, 1995). Stereopsis is a given in both dissection and manikins. It can be implemented in both anatomical atlases and virtual learning environments, usually necessitating the student to wear special headgear. Stereopsis for virtual anatomical learning as such has not been studied before (as far as we know), but in surgical simulator training some literature exists. These studies assessing the usefulness of computer implemented stereopsis (usually by means of shutter glasses) have been inconclusive as to the benefits of this feature to learning. Moreover, technical problems resulting in noticeable flicker in the stereoptic condition have likely confounded the results of such studies (e.g., Wentink et al., 2002). Other studies suffer from methodological problems, in that systems are compared that not only differ in their implementation of stereopsis, but also in image resolution, brightness, and other relevant variables (Huber et al., 2003 provide an overview of this older work). A recent study that was able to better control such variables, and also used fully matured technology, did show a benefit for the implementation of stereopsis for endoscopic simulator training (Byrn et al., 2007). More studies are needed to assess the role of stereopsis both in surgical simulator training and in other medical training fields, such as anatomical learning.

2.1.5 Dynamic exploration

Dynamic exploration refers to the possibility to directly manipulate the visual material under study, and thus to change one's viewpoint interactively with respect to this material. Tong, Marlin, and Frost (1995) had active participants explore a virtual environment on a stationary bike, while passive participants were shown recordings of the active participants' explorations. The active participants performed better in knowledge tests that assessed their topographical knowledge of the virtual environment. James et al. (2001) have shown this benefit for dynamic exploration to hold true even for abstract virtual objects in a desktop virtual environment. In their study trackball movement was coupled to visual rotation on-screen. Again, passive participants were shown recordings of the active participants' explorations. Active participants scored better on a subsequent recognition test. This shows that the benefits of dynamic exploration are not confined to *action space*, and extend to personal space. Action space refers to the space slightly beyond one's arms reach, to about 30 meters around a person (Cutting and Vishton, 1995). Thus, dynamic exploration is likely to be important in constructing a high-quality mental model of human anatomy. Dissection and manikins afford this, atlases do not, and virtual learning environments differ in this respect. In virtual learning environments, implementation issues cause a somewhat low fidelity for this feature compared to dissection or manikins.

2.1.6 Practical implementation

With respect to practical implementation, atlases are a clear winner. Anatomical atlases are relatively cheap, virtually without maintenance, and require the space of a book shelf. Dissection represents the opposite end of this spectrum: dissection facilities are expensive, spacious, and arduous to maintain. Manikins and virtual learning environments fall in between.

Summing up, traditional anatomical learning methods involve direct and mediated methods, each having their unique qualities. Direct methods (i.e., dissection) offer haptic information, 3D visual information, and dynamic exploration, while mediated methods (i.e. anatomical atlases and manikins), provide conceptual knowledge, and convenience of use. For the development of detailed anatomical knowledge, a combination of methods would likely reap the greatest learning benefits. Virtual learning environments offer the option to implement two features traditionally associated with dissection and not with mediated medical learning, namely stereopsis and dynamic exploration, though implementation issues remain. Stereopsis and dynamic exploration are thought to be functionally coupled for goal-directed motor behavior in personal space (Bradshaw et al., 2004), which is corroborated by recent research in endoscopic skills training (Byrn et al., 2007). The importance of the combination of these factors in visuo-spatial *learning* (as contrasted to skills training) is less clear. The first three experimental chapters report a series of experiments designed to learn more about the effectiveness of stereopsis and dynamic exploration in virtual anatomical learning environments.

2.2 Surgical training

Surgical training as it is currently practiced was first established by the American surgeon William Halsted in the late nineteenth century. Dissatisfied with the essentially self-taught way in which surgeons practiced their trade, and inspired by a stay in Germany (where scientific training was par for the course for junior surgeons) he introduced basic laboratory training in clinical practice, and formalized the master-apprenticeship approach to surgical training (Halsted, 1904). In Halsted's approach, junior surgeons are supervised on a one-on-one basis in the operating room, and over time are allowed to perform increasingly more of a specific surgical procedure (the 'see one, do one, teach one' method). Whereas European curricula with their lengthy university training and uncertain academic career prospects made such a career less attractive, Halsted's approach provided trainees with direct career opportunities (Osborne, 2007), which greatly influenced medical culture.

One advantage of this approach to surgical training is that a close working relationship between master and apprentice is established, and close attention can be paid to the strengths and weaknesses of any specific apprentice. Also, surgical technique has to be made explicit under such an approach, making technique subject to discussion, improvement, and standardization. Drawbacks of such a close working relationship can include inadequate training due to incompatible personalities, apprentices practicing on actual patients, and a training outcome that is limited by the level of expertise that one specific master surgeon has acquired.

Another drawback of the master-apprentice approach that recently has come to weigh more heavily on the surgical curriculum is the demands it makes on the master surgeon's time. In Europe the 80-hour working week has been laid to rest, both for masters and apprentices; whereas surgical technique is becoming increasingly more complex and diversified, and consequently more time consuming to master (Dawson and Kaufman, 1998; Wallack, 2001). A prime example of this is the rise of laparoscopic surgery. In laparoscopic surgery, surgical instruments and movable optics are introduced into the patient's body through tiny holes in their body wall. This is beneficial for the patient (smaller scars, faster return to normal daily activity), but more difficult for the surgeon, for a number of reasons (discussed by Berguer, 1999): 1. Fulcrum effect. A movement with the instrument handle to the right will cause the actual instrument tip inside the patient to move to the left. 2. Visual feedback through a monitor causes binocular depth cues such as stereopsis to be lost. 3. Visual monitor feedback is not co-located with the surgeon's actual working area. 4. The camera angle will mostly not be aligned with the surgeon's line of sight. 5. The camera angle will be changing over the course of a surgical procedure. 6. Tactile feedback is reduced compared to open surgical procedures.

For endoscopic surgery, alternatives to surgical master-apprentice training include simulation approaches such as dissection room training, vivisection, box-trainer approaches, and virtual reality training (or VR-training for short). Advantages and disadvantages of these alternatives will be discussed in the next couple of paragraphs.

2.2.1 Dissection room

Dissection room training for surgeons has the great benefit of training on actual human bodies, which are the best models available for living bodies in terms of fidelity (Blaschko et al., 2007). Also, because the outcome of a procedure is less critical, supervision doesn't have to be as intensive as it needs to be in an operating room. Disadvantages are the lack of bodily function (e.g. bleeding, breathing), the changed tissue structure (Parker, 2002), the bias in age group (mostly elderly bodies, Parker, 2002), and of course dissection facilities are expensive and arduous to maintain.

2.2.2 Vivisection

Vivisection (invasive training on live animals, in surgery usually pigs or rats) provides another alternative to master apprentice training. An important advantage of vivisection is the presence of bodily function, in bodies that are sufficiently similar to human bodies to make meaningful practice possible (Villegas et al., 2003). Here too, supervision can be less intensive compared to the operating room. Drawbacks include cost, the possibility of overtraining on non-human bodies (leading to inappropriate, hard to correct surgical habits), and ethical concerns (Villegas et al., 2003; Balcombe, 2004).

2.2.3 Box trainers

Box-trainers simulate endoscopic surgery by allowing real instruments to be introduced in a box that contains further training material. A video system similar to the ones used in actual laparoscopic surgery provides the trainee with visual feedback. Box trainers require much less maintenance and special facilities than vivisection or human dissection facilities. Disadvantages include the lower degree of fidelity (Aggarwal et al., 2004), and the lack of anatomical variation.

2.2.4 Virtual reality trainers

Most available medical VR-trainers have been developed to simulate endoscopic surgery. The simulation of *haptic feedback* (force feedback and tactile feedback transmitted through the sense of touch) is difficult to implement in such trainers. In contrast to open surgery, the importance of haptic feedback is much reduced during endoscopic surgery, making this type of surgery relatively easy to simulate in VR-trainers. These trainers require little maintenance, and can display a broad range of anatomical variability. Another important advantage is the possibility to take exact measurements of a surgical trainee's performance, allowing objective assessment of a trainee's progress (Kneebone, 2003; Feldman et al., 2004).

In order to use VR-trainers for actual surgical training, questions need to be answered as to the usefulness of such training tools. Two types of study are most commonly performed to examine construct validity for surgical VR-trainers; these are transfer studies, and studies in which validity is established by using a VR-trainer to distinguish between people of differing surgical experience. Transfer studies assess the benefits of simulation training to learning the intended skill. This is usually done by comparing performance on the intended skill by two groups of participants, of which only one engaged in simulator training. Sometimes another, already validated, type of simulation will be used as a proxy for the intended skill (e.g. transfer from a VR-trainer to an animal model will be assessed, animal models presenting a well established model for actual surgery). In the second type of study, better performance of the more experienced group on the simulator is interpreted as an indication of construct validity.

Most of such work is done in two areas of endoscopic surgery; namely *flexible endoscopy* and *laparoscopic surgery*. In flexible endoscopy techniques (such as colonoscopy or gastroscopy), a flexible scope containing both a camera and surgical manipulation tools is introduced into the patient's body through a natural orifice. In laparoscopic surgery a camera and surgical instruments are introduced into the patient's body through separate, tiny incisions in the abdominal wall after which the abdominal cavity is inflated to create space for surgical manipulation.

In general, construct validity for VR-trainers is well-established in most areas of endoscopic surgery. Gerson and Van Dam's 2004 paper reviews the use of (mostly) VR-trainers in flexible endoscopy and concludes that whereas the tested simulators differentiate between experts and novices, transfer studies have not yet shown a clear benefit for endoscopic training (Gerson and Van Dam, 2004). Inadequate sample size, insufficient training time on the simulator, and/ or lack of appropriate clinical difficulty in the simulations are indicated by them as possible culprits for this lack of benefits. As far as we know, only two transfer studies in this area have been executed since Gerson and Van Dam's review, however both of them find significant transfer to the operating room after VR colonoscopy training (Park et al., 2005; Ahlberg et al., 2005).

In a meta-analysis, Leanne Sutherland and her colleagues (Sutherland et al., 2006) review 30 studies that compare different laparoscopic training approaches, focusing on the value of box-trainers and VR-trainers for such training. Despite low sample sizes, methodological issues (such as short training duration and non-blinded performance assessment), and a lack of studies directly comparing box-trainers and VR-trainers with vivisection or cadaver training, they find VR-training to be better than no training, and on par with other training approaches, showing the validity of VR-training for laparoscopic surgery. More recent studies confirm the benefits of VR-training in the development of laparoscopic skill (Ahlberg et al., 2007; Munz et al., 2007).

As noted, a problem with these transfer studies is that the simulator training phases often are very short due to practical constraints (limited availability of medical personnel for participation in such studies). To optimize transfer, more information needs to become available on the development of surgical skill over time. Long term training studies are needed that will allow us to distil learning curves of various simulator performance measures, as well as fine-grained cognitive task-analyses that will help bridge the gap between a traditional qualitative framework for assessing surgical performance and the various quantitative measures that are available in surgical VR-trainers. Another little explored factor in the development of surgical skill is that training strategy likely changes over time, possibly involving a changing involvement of cognitive abilities in different training stages. The role of cognitive abilities in (the development of) laparoscopic skill will be discussed next.

3 Relevant cognitive abilities

People are similar, but not identical. Where most of Psychology is interested in the similarities between people, research into cognitive abilities has been driven by an interest in individual differences (Cronbach, 1957). Factor-analytic research has enabled researchers to differentiate between several cognitive abilities (see Figure 1-1), and to arrange those in a three-tiered, hierarchical model of general to specific cognitive abilities (Carroll, 1993).

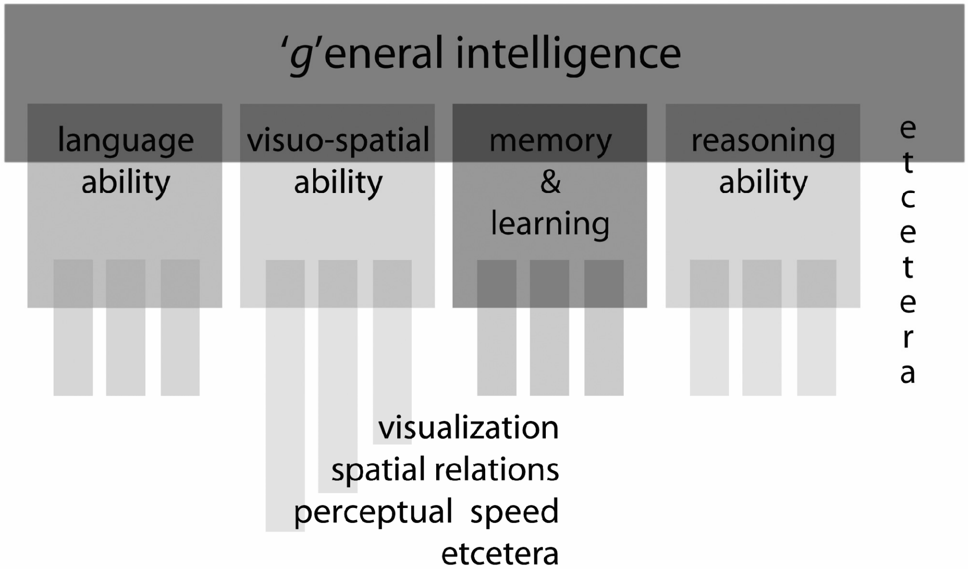


Figure 1-1 Carroll's Model of Cognitive Abilities

The top tier is represented by a single factor, g, or general intelligence, which is defined as the shared factor loadings of a number of second tier factors such as verbal intelligence, numerical ability, visuo-spatial ability, and memory. These second tier factors in turn are themselves each composed of a number of third tier factors, e.g. visuo-spatial ability consists of the shared factor loadings of the factors visualization, spatial relations, perceptual speed, flexibility of closure, and speed of closure (Carroll, 1993). Third tier factors are the ones that are actually measured by standard paper-and-pencil tests of intelligence, after which the higher level factors are derived from the resultant data.

A better understanding of the role cognitive abilities play in anatomy learning and in the development of surgical skills is likely to inform system design in this area, for instance in designing adaptive interfaces that take into account both cognitive skill level and training phase of a particular student. Theories of skill acquisition (Anderson, 1982; Fitts, 1964), posit increasing automation of skills over time, from an initial phase that involves extensive cognitive control, through a phase where skill-related actions are collated in chunks to the final phase where the learned skills are fully automatic. Based on these theories and a cognitive ability model that is very similar to Carroll's model discussed above (the Radex model of Marshalek and colleagues, 1983), Ackerman (1987a, 1992) developed and verified a model for predicting individual differences in complex skill acquisition in which ability determinants indicate the acquisition phase a specific skill is in. In this model general cognitive abilities (defined as a composite measure of reasoning ability, spatial ability, perceptual speed, and psychomotor ability) correlate with initial phase learning; the visuo-spatial ability factor Perceptual speed with middle phase learning (chunking); and psychomotor abilities with late phase learning (automation). Ackerman makes a caveat stating that unpredictable aspects of a complex skill will not (and should not) automate over time, and will therefore show a continuing correlation with general cognitive ability. We will return to this in our section on the involvement of cognitive abilities in the development of surgical skills. A general cognitive ability that has been shown to be important in anatomical learning (Rochford, 1985; Guillot et al., 2007; Garg et al. 2001) and in surgical skill acquisition (Anastakis, 2000) is visuo-spatial ability.

Visuo-spatial ability refers to the human cognitive ability to form, retrieve, and manipulate mental models of a visual and spatial nature (Lohman, 1979a). Carroll (1993) distinguishes five main factors that together form visuo-spatial ability. These are: *Visualization*, the ability to manipulate complex mental representations of a visuo-spatial nature. Most research takes visualization as a proxy for visuo-spatial ability; *Spatial relations*, the ability to quickly manipulate simple mental representations of a visuo-spatial nature; *Speed of closure*, the ability to match incomplete stimuli to memory representations of the corresponding complete stimuli; *Flexibility of closure*, the ability to identify given patterns in a cluttered visual environment; *Perceptual speed*, the ability to quickly identify a given shape from a number of alternatives.

Visual working memory, the ability to correctly identify visual stimuli presented earlier from a mix of those earlier stimuli and novel ones, is discussed by Carroll in his chapter on memory rather than visual perception (Carroll, 1993). This is somewhat arbitrary since, as Carroll notes, tests for visual working memory tend to have a high loading on the second-tier factor of visuo-spatial ability too. Visual working memory is therefore included in the current discussion.

3.1 Visuo-spatial ability in virtual anatomy learning

Somewhat surprisingly, not much work can be found exploring the impact of visuo-spatial ability on anatomy learning, virtual or otherwise. Most papers in virtual anatomy learning detail the design and implementation of specific virtual anatomy learning environments (e.g. Heng et al., 2006). For traditional anatomy learning, Rochford (1985) found a significant positive correlation between spatial learning disabilities and underachievement in an anatomy course for second-year medical students at Cape Town University. Similarly, Guillotet al. (2007) found visuo-spatial ability to be a predictor of performance on an anatomical test. In a series of experiments specifically designed to assess the value of computer models in learning anatomy, Amit Garg and colleagues (Garg et al., 1999, 2001, 2002) compare dynamic exploration and the number of presented differently oriented views of a virtual anatomical model of the carpal bones of the hand (key views versus multiple views). Although their results as to the compared conditions are inconclusive, they do find visuo-spatial ability to be the main predictor of performance on an anatomical learning test. Another series of learning studies (by Keehner and Khooshabeh, 2002) investigated the role of dynamic exploration and visuo-spatial ability in a task that required participants to draw cross-sections of a studied virtual anatomy-like structure. They found that participants of low visuo-spatial ability benefited more from dynamic exploration than participants of high visuo-spatial ability did, after the low visuo-spatial participants had been cued to manipulate the virtual structure more actively during the experiment. Again, visuo-spatial ability was found to predict task performance. Visuo-spatial ability strongly predicts anatomical learning, but more work is needed on the interactions of visuo-spatial ability with features such as dynamic exploration (and stereopsis, see section 2.1).

3.2 Visuo-spatial ability in surgical training

Three sources of individual differences have caught the attention of researchers interested in the relation between such differences and surgical performance; they are manual dexterity, personality, and visuo-spatial ability. Research in manual dexterity has so far not led to any evidence of involvement of this factor in surgical performance (Hamstra and Dubrowski, 2005; Bann and Darzi, 2005). Personality factors such as extroversion and conscientiousness have been shown to correlate with being a surgeon (McGreevy and Wiebe, 2002), yet it is unclear how this should inform surgical training, or practice. Visuo-spatial ability has been successfully linked to a variety of surgical and other medical skills (Hegarty et al., 2007, provide a useful overview). In research investigating the relation between visuo-spatial ability and surgical training however, usually only tests for the third-tier factor of visualization are used, scores of which are then taken as a proxy for visuo-spatial ability. Below, an introduction is provided to visuo-spatial ability in light of surgical training, organized along the five third-tier factors that together form visuo-spatial ability, and visual working memory.

The visuo-spatial ability factor of visualization correlates with time on task on a number of endoscopic surgery tasks (Keehner et al., 2006; Risucci et al., 2001; Risucci et al., 2000), with surgical quality as measured by rating scales (Keehner et al., 2004; Schueneman et al., 1984; Wanzel et al., 2002; Wanzel et al., 2003), and with endoscopic quality as measured by simulator training outcomes (Eyal and Tendick, 2001; Hedman et al., 2006). Additionally, Risucci (2002) found that surgeons score higher on visualization tests than a comparable normative sample from the general population.

Ritter et al. (2006) found a correlation between spatial relations and both duration of training and number of trials on a flexible endoscope simulator task. Westman et al. (2006), Haluck et al. (2002), and Eyal and Tendick (2001) all find a significant correlation between quality in a number of surgical simulator training tasks and spatial relations.

Both Wanzel et al. (2002; 2003) and Risucci et al. (2001; 2000; 2002) used speed of closure tests in their research. Only in Risucci's 2001 study a low, but significant correlation between speed of closure and speed on several simulator dexterity drills is found. This factor seems to contribute little to surgical skill.

Steele, Walder, and Herbert (1992), and Gibbons, Baker, and Skinner (1986) found a significant correlation between fluency of closure and quality as measured by rating scales. Schueneman (1984) uses fluency of closure tests as well, but finds no significant correlations. The contribution of fluency of closure to surgical skill is not clear.

Perceptual speed has not been included in surgical training studies yet, as far as we know, whereas given the time critical nature of surgery, perceptual speed would appear to be an important cognitive ability for the surgical practitioner.

Wanzel et al. (2002), and Haluck et al. (2002) use a visual working memory test in their research. Haluck et al. found a significant correlation with a quality measure in an Endotower simulation task. Wanzel et al. found no such correlation. Not much is known yet as to the contribution of visual working memory to surgical learning and surgical skills.
In conclusion, there is good evidence for a contribution of visualization and spatial relations to surgical training, and some evidence against a contribution of speed of closure to such training. Fluency of closure, perceptual speed, and visual working memory remain little researched in this context.

One important way in which test items for visuo-spatial ability factors differ is the place on a complexity-speed continuum of these items (Vandenberg and Kuse, 1978; Hegarty and Waller, 2005). Visualization is measured by test items of high complexity, and often mental rotation is involved. In spatial relations test, mental rotation is usually involved as well, but test items are easier, typically involving only 2D rotation. Perceptual speed tests represent the other end of the spectrum, offering a large number of test items that are easy to solve. The other two visuo-spatial factors (speed of closure and fluency of closure) stand somewhat apart from the three factors above, because pattern recognition is involved instead of the mental manipulations required for solving visualization or spatial relations items. Being able to pinpoint what exactly in visuo-spatial ability is responsible for its positive correlation with endoscopic performance will lead to more specific theories of skill development, which can in turn inform the design of both curricula and learning environments.

In order to develop such theories, more needs to be known about endoscopic skill and its development, and this is becoming possible because of the advent of endoscopic simulators. Not only can performance now be quantified for different variables such as time, manual dexterity and damage, also learning curves can be established for such performance variables which makes it possible to assess the role of cognitive abilities in different training stages. A first study investigating endoscopic learning curves, reasoning ability and the visuo-spatial ability factor of visualization was performed in 2006 by Madeleine Keehner and colleagues (Keehner et al., 2006). Building on Ackerman's theory of changing ability determinants during skill acquisition (Ackerman, 1987; 1992), Keehner and her colleagues investigated the contributions of visualization and reasoning ability to learning a spatial skill using an angled laparoscope in a virtual reality training environment (Keehner et al., 2006). Confirming Ackerman's hypothesized impact of general intelligence (*g*) on early learning, reasoning ability (thought to load heavily on *g*, see for instance Engle et al., 1999) only correlated with skill (measured by time on task) over the first couple of sessions. Visualization remained important over all twelve training sessions. The authors explain this by assuming that content specific elements of the task under study necessitate an ongoing involvement of visualization.

Concluding, visuo-spatial ability is involved in virtual anatomical learning, several aspects of surgical simulator training, and a start has been made to investigate the contribution of visuo-spatial ability to endoscopic skill development (Keehner et al, 2006). However, more specific accounts of endoscopic skill development and its relation to visuo-spatial ability are needed to inform learning environment design, to help optimize transfer, and to be able to predict an individual's endoscopic skill level over time. In chapters 5 and 6 two such studies are reported.

4 Overview of the empirical chapters

The study presented in chapter two examined whether a combination of dynamic exploration and stereopsis improves virtual anatomical learning, and whether participants of low visuo-spatial ability benefit differently from these features than participants of high visuo-spatial ability. Participants inexperienced with human anatomy learned about the human abdominal parts in a study phase that involved either both stereopsis and interactivity, or neither of these. Learning was assessed with an identification test and with a localization test. Visuo-spatial ability predicted high learning outcome. Participants in the stereopsis-dynamic exploration condition performed better than participants in the alternative condition. Participants of low visuo-spatial ability benefitted more from the stereopsis-dynamic exploration condition, causing them to perform on par with their high visuo-spatial peers.

In chapter three a study is reported that aimed at finding out whether stereopsis caused the beneficial effect of the combined stereopsis/ dynamic exploration condition of the study reported in chapter two. In a similar paradigm, two learning conditions were compared by assessing anatomical knowledge of the human abdomen in two post-tests. One condition implemented stereopsis, the other did not. Visuo-spatial ability predicted high test scores, and a benefit from computer-implemented stereopsis for one of the post-tests was found. No interaction effects for visuo-spatial ability and condition were found.

Chapter four reports the third experiment in this series, aimed at finding the contribution of dynamic exploration to virtual anatomical learning. Participants were tested in pairs matched for visuo-spatial ability. During the study phase, one individual of the pair actively manipulated a on-screen 3D reconstruction of the human abdomen; the other individual passively, and simultaneously, watched the interactions of the first individual on a separate screen. Learning was again assessed by two tests. Dynamic exploration provided a small but significant benefit to anatomical learning.

In chapter five a study is reported in which a group of medical trainees engaged in two colonoscopy simulator training tasks, for a total of four sessions. Participants were tested for four visuo-spatial factors. Time on task was used as colonoscopy simulator performance measure. Participants improved during the course, and the visuo-spatial factor of visualization (complex test items) predicted learning. Additionally, visualization correlated with learning *rate*.

Chapter six describes a long-term training study during which a medical student group participated in a two month laparoscopic training course, engaging in a total of eight simulator training sessions. All participants were tested for four visuo-spatial ability factors and two memory factors. Three simulator performance measures were derived; namely time on task, motion efficiency, and damage. Learning was established for all performance variables. A separate look was taken into the first three sessions (early learning) and the last three sessions (late learning). Significant improvement was found for all early learning performance variables, but only for the time on task late learning performance variable.

Of the visuo-spatial factors, visualization and perceptual speed predicted early learning motion efficiency. The memory factor memory span predicted both early learning motion efficiency and early learning damage.

The concluding chapter seven discusses and synthesizes the results of the empirical chapters.

2. Optimizing Conditions for Computer-assisted Anatomical Learning

Abstract
An experiment evaluated the impact of two typical features of virtual learning environments on anatomical learning for users of differing visuo-spatial ability. The two features studied are computer-implemented *stereopsis* (the spatial information that is based on differences in visual patterns projected in both eyes) and *interactivity* (the possibility to actively and continuously change one's view of computer-mediated objects). Participants of differing visuo-spatial ability learned about human abdominal organs via anatomical 3-dimensional reconstructions using either a stereoptic study phase (involving stereopsis and interactivity) or using a biocular study phase that involved neither stereopsis nor interactivity. Subsequent tests assessed the acquired knowledge in tasks involving (a) identification of anatomical structures in anatomical 2-dimensional cross-sections (i.e. typical Computed Tomography pictures) in an *identification task*, and (b) localization of these cross-sections in a frontal view of the anatomy in a *localization task*. The results show that the stereoptic group performed significantly better on both tasks and that participants of low visuo-spatial ability benefited more from the stereoptic study phase than those of high visuo-spatial ability.

Adapted from: Luursema, J. M., Verwey, W. B., Kommers, P. A. M., Geelkerken, R. H., & Vos, H. J. (2006). Optimizing conditions for computer-assisted anatomical learning. *Interacting with Computers, 18*, 1123-1138.

1 Introduction

1.1 Anatomical learning

A recurring theme in medical practice is the necessity to form a visuo-spatial mental representation of a patient's anatomy based on 2-dimensional images. During diagnosis, practitioners review patient-specific cross sections made by non-invasive imaging technologies (See Figure 2-1), endoscopic surgeons get 2-dimensional video feedback on their actions (often presenting a viewing angle that is not aligned with the surgeon's view), and medical students learn anatomy by studying illustrated texts. *Visuo-spatial ability*, the capacity to construct and manipulate mental, visuo-spatial representations of objects and environments, allows people to transform 2-dimensional (2D) images to visuo-spatial mental representations and to mentally rotate these representations (Gordon, 1986; Kozhevnikov and Hegarty, 2001). This capacity is therefore likely to play an important part in being a successful medical practitioner. This is supported by several studies that found visuo-spatial ability to be highly correlated with success as an endoscopic surgeon (e.g. Risucci, 2002; Wanzel et al., 2002). Rochford (1985) found a correlation between spatial learning disabilities and underachievement in an anatomy course for second-year medical students at Cape Town University. Additional support comes from Schueneman et al. (1984), who found that visuo-spatial ability is one of three factors in standard aptitude tests that predict success as a surgeon (the other two being visuo-motor skills and sensitivity to stress).

Two phases that bear upon the use of mental representations can be distinguished: an acquisition phase and a manipulation phase. The acquisition phase refers to the construction of a visuo-spatial mental representation, e.g. during anatomical learning or medical diagnosis, the manipulation phase refers to the mental manipulation of these representations, e.g. during pre-surgical planning

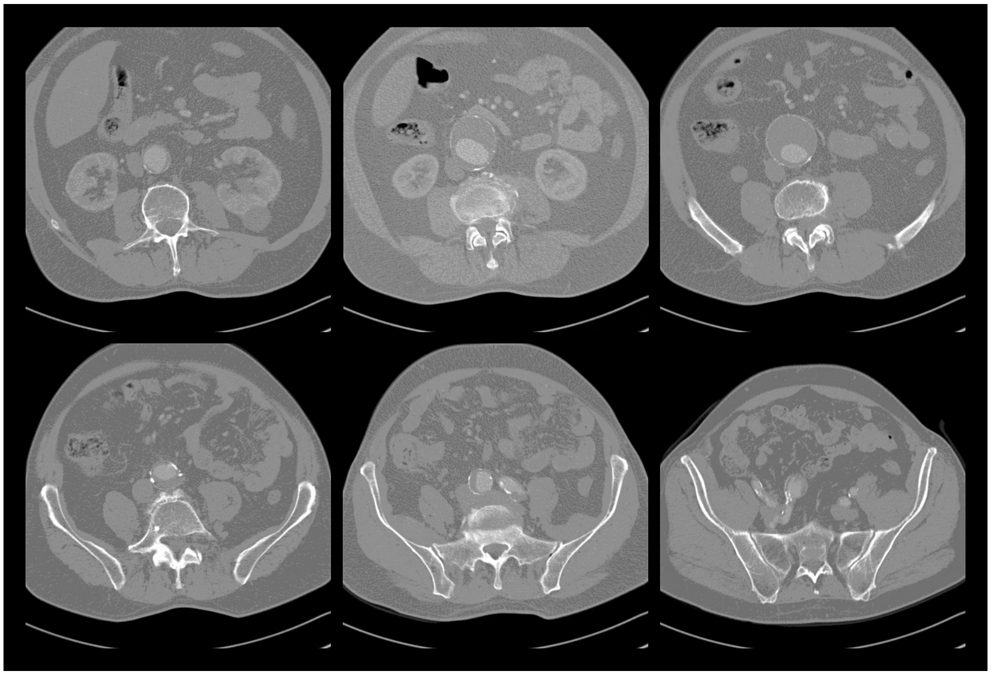


Figure 2-1 Examples of anatomical cross-sections derived from CT-imaging of the lower abdominal region.

or during endoscopic surgery. Having acquired a visuo-spatial mental representation (from this point called a 'mental representation') is evidently a prerequisite to mentally manipulate such a representation. This distinction between acquiring a mental representation and manipulating a mental representation leads to a number of questions: What is the role of visuo-spatial ability in each of these phases? Do medical practitioners of low visuo-spatial ability perform worse because of a deficiency in their mental representations or because of an inability to manipulate these representations? Is there a way to optimally help learners acquire mental representations? Several practices in anatomical learning can be distinguished.

Traditionally, anatomical learning takes place in the dissection room, with the help of anatomical manikins or self study with anatomical atlases. Each of these methods has its drawbacks: A dissection room is expensive and arduous to maintain, both manikins and dissection rooms are not readily available, anatomical variety in manikins is limited, anatomical atlases are limited to 2-dimensional representations and offer neither interactivity nor feedback. These limitations can be largely overcome by the relatively recent alternative found in virtual learning environments (e.g. see Jastrow and Vollrath, 2003, who give an overview of anatomically oriented virtual learning environments based on the visible human project). Basic questions with respect to the transfer of skills and/or knowledge acquired in a virtual learning environment however are largely unanswered (Stanney, 2002; Verwey et al., 2005), and one wonders to what extent these systems can be made more efficient by adjusting them to the learning styles and capacities of the trainees. Especially relevant to the capacity of visuo-spatial ability is the implementation of stereopsis and interactivity.

1.2 Stereopsis and interactivity

People have various mechanisms that contribute to the depth perception of the world around them. One mechanism, the disparity of visual information entering the left and right eye, is especially important for objects within an arm's reach (Cutting and Vishton, 1995). This mechanism is known as s*tereopsis*. When direct visual feedback from a 3-dimensional object or environment is received through mediation by a standard computer screen (or other 2-dimensional visual feedback device) people are said to receive *biocular* visual feedback, meaning that both eyes are exposed to the same image. There is substantial evidence that stereoptic feedback benefits the execution of endoscopic tasks (Wanzel et al., 2002; Falk et al., 2001; Ijsselstein et al., 2001). Whether stereoptic feedback benefits the acquisition of anatomical knowledge in the context of virtual learning environments is as yet uncertain. The resolution of this question has implications for the way anatomical information is best presented in learning situations. Several technologies exist that allow the experience of stereopsis, such as head-mounted displays that uses different display channels for each eye, or displays coupled to shutter-glasses that make odd and even numbered images reach the left and right eye separately. The higher costs associated with the implementation and maintenance of such systems will have to be balanced against their usefulness.

A second way to improve the acquisition of anatomical knowledge is allowing people to explore the presented anatomy by giving them the possibility to change the perspective shown. Such systems can be considered systems with high *interactivity*. In contrast, systems with one or just a few alternative perspectives are systems with low interactivity. A recent study by James et al. (2002) suggests that interactivity helps people to develop visuo-spatial mental representations. In their study, interactivity consisted of the possibility to freely rotate computer-mediated, non-stereoptic 3D objects. Each participant explored some objects actively and other objects passively. Each participant in the passive condition watched the recorded explorations of an active participant. Later all participants made same/different judgments on a series of 2D views of these objects from various perspectives. James et al. found that participants from the active condition recognized objects faster. So, it seems that both stereopsis and interactivity support people in creating visuo-spatial mental representations of objects in the real world. This may well benefit students' learning of human anatomy too, especially those of low visuo-spatial ability.

The present study examined whether stereopsis and interactivity contribute to the development of flexible visuo-spatial mental representations of human abdominal anatomy, and whether this might help overcome the disadvantage low visuo-spatial individuals have in developing such representations. To that end, the following experiment was performed. First, participants' visuo-spatial ability was determined by a mental rotation test, the outcome of which was used to form matched pairs over two learning conditions. The *stereoptic group* studied human abdominal anatomy in a condition involving stereopsis and extensive interactivity. The *biocular group* studied the same anatomy in a condition with biocular information presentation and with limited interactivity. Subsequently, knowledge of the abdominal anatomy was tested by two tasks that are assumed to require mental manipulation of 3D representations. The *identification task* required participants from both groups to identify anatomical structures in 2D cross-sections (typical Computed Tomography, or CT, pictures) they had not seen before. The *localization task* required them to indicate the level in a front side view of the human abdomen, from which a presented cross section was taken. We expected that the stereoptic group would outperform the biocular group, and that this difference would be larger for participants of low visuo-spatial ability than for participants of high visuo-spatial ability.

2 Method

2.1 Participants

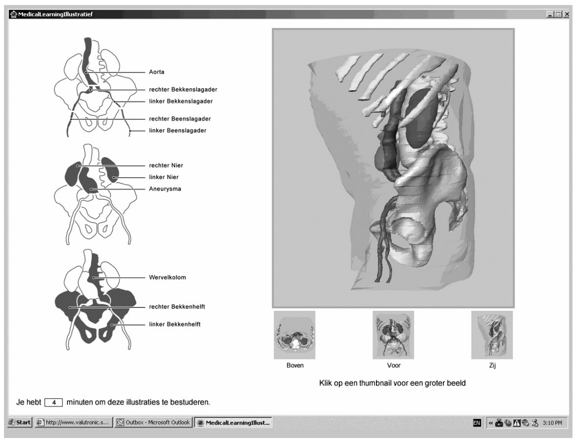
Participants were Dutch university students and employees from the faculty of Behavioral Sciences. All had limited knowledge of human abdominal anatomy. Participants were between 18 and 50 years of age. A total of 36 participants took part (21 women and 15 men). All reported normal or corrected to normal vision. The participants were selected from a pool of 73 potential participants on the basis of pretest-results (see below).

2.2 Procedure

Before the actual experiment, the 73 participants took part in two pretests, a stereoscopic vision test to ascertain that they could see stereoptically, and a test for visuo-spatial ability. The first test involved the TNO-test for stereoscopic vision which requires participants to distinguish figures from a background in random-dot figures within one minute (Okuda and Wanters, 1977). On the basis of this test result, four subjects were excluded from further participation. The remaining 69 participants were tested for visuo-spatial ability using Vandenberg and Kruse's mental rotation test (Vandenberg and Kuse, 1978; Peters et al., 1995). Starting from the low end of the resulting scale, 18 participants (16 females and 2 males) were matched in pairs over two groups. One member of each matched pair was randomly assigned to the biocular group; the other to the stereoptic group. The same procedure was followed starting from the high end of the scale resulting from the pretest (5 females and 13 males). Participants who scored in the mean region of the pretests' scale were excluded from the experiment. After a study phase that differed for the two groups, performance was measured in an identification task and a localization task. Apart from the study phase, the experiment was identical for all participants. The study phase and both tests were administered to each participant individually in a specially prepared cubicle in the presence of a researcher. The cubicle contained the hardware and software necessary for the experiment and was shut of from possible disturbances during the experiment. All explanations were provided on screen, subjects were only verbally prompted to use the possibility of interactive rotation or clickable thumbnails (during one of either study phases) if they didn't start using this possibility on their own accord. After the experiment, participants were asked to describe their problem solving strategies for each task.

2.3 Study phase

A short example of the study phase, identification task and localization task were presented to participants at the beginning of the experiment. They were told to use the study phase to prepare for these two tasks (see Figure 2-2). Both study phases contained labelled reference figures for the eleven anatomical parts of the abdomen relevant to the tasks.



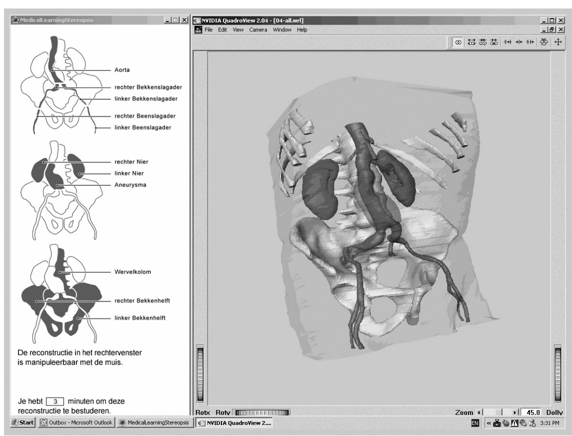


Figure 2-2 The biocular (top) and stereoptic study phases of the experiment. The biocular study phase allowed participants to alternate between three, two-dimensional screenshots of the anatomical objects by clicking one of the three thumbnails below the image. The stereoptic study phase provided stereopsis and interactivity involving free, mouse-controlled rotation of the anatomical objects.

In the study phase, the *biocular group* (9 women and 9 men) explored 2D stills of this abdominal anatomy. They had limited interactivity in that they could change between just three views (frontal, side and top). The *stereoptic group* (12 women and 6 men) explored computerized 3D-reconstructions of the same abdominal anatomy in a condition that provided stereopsis and extended interactivity. In contrast to the biocular participants, stereoptic participants wore shutter-glasses to perceive depth (stereopsis). Extended interactivity involved the possibility to rotate the virtual 3D anatomy in any direction using the mouse. All participants were given four minutes to learn the form and location of these eleven anatomical parts of the abdomen, during which time they were free to manipulate the provided representation.

2.4 Identification task

The identification task (see upper frame of Figure 2-3) consisted of four familiarization trials and twenty test trials. Participants were told to start a trial by pushing the ‘5’ button on the numeric keypad at the right side of the keyboard. This action made an anatomical CT cross-section with a highlighted anatomical structure appear, as well as a list with names of the eleven anatomical structures. With the release of the ‘5’ button the picture of the cross-section disappeared. The anatomical cross-sections used for this task were the same ones that had been used to construct the various visual materials used during the study phase. Participants were instructed to release the ‘5’ button only when they had identified the highlighted structure, and then to mouse-click the corresponding name in the list at their own pace. Reaction times were defined as the time the ‘5’ button was pressed during each trial. If after 10 seconds the ‘5’ button had not been released, the picture with the cross-section disappeared anyway. Errors were defined as clicking an incorrect name or no name at all.

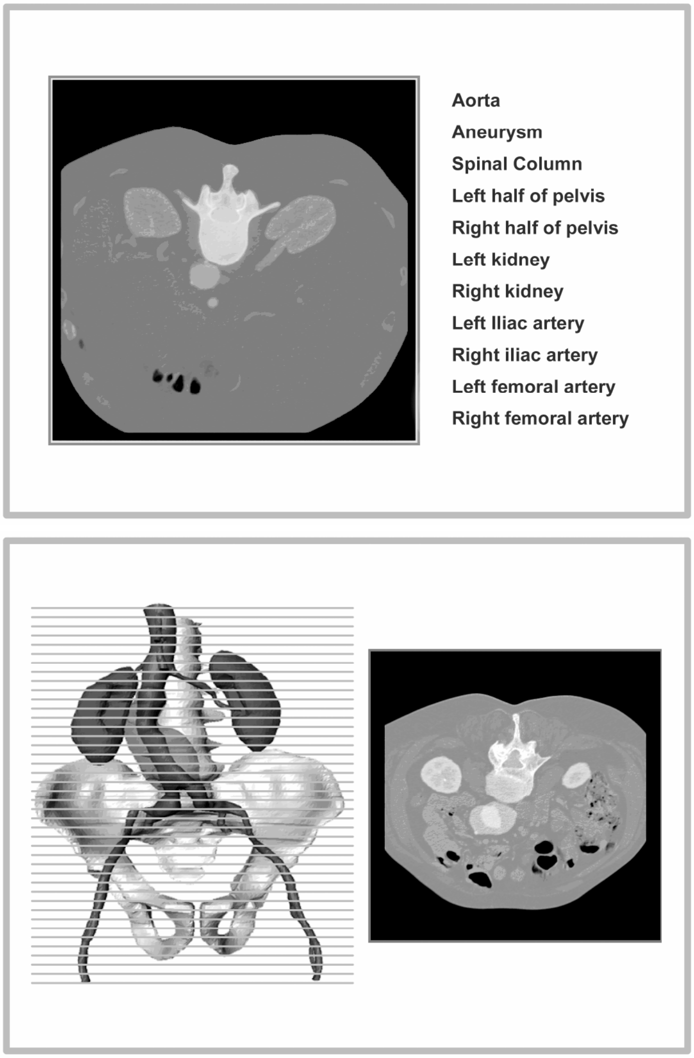


Figure 2-3 Screenshots of an item of each of the two tasks. On top, the identification task with the eleven possible names of the highlighted structure, at the bottom the localization task that involved selecting the level in the left image from which the right image was taken.

After each trial error feedback was given. When a participant verbally indicated they released the '5' key accidentally, or that they wished to change their answer, the trial was excluded from further analysis. No shutter-glasses were worn during this task.

2.5 Localization task

The localization task consisted of three familiarization trials and eighteen test trials. Participants were asked to indicate on a frontal-view screenshot of the studied anatomy, the correct horizontal level of a CT-based anatomical cross-section (lower frame of Figure 2-3). Again, the cross-sections were taken from the same scans that had been used to develop the material for the study phase of the experiment. In each trial a different cross-section was shown. The order in which the cross-sections appeared was randomized for each participant. Participants were instructed to start a trial by pushing the ‘5’ button on the numeric keypad to make a cross-section appear. With the release of the ‘5’ button the picture of the cross-section disappeared. They were further instructed to release the ‘5’ button as soon as they had identified the level from which this cross-section was taken, and then to click at their own pace the corresponding line out of a series of lines overlaying the frontal-view screenshot. If after 15 seconds the ‘5’ button was not released, the cross-section disappeared and an error was scored. Reaction time was defined as the time the ‘5’ button was held during each trial. A correct answer was defined as clicking the line corresponding exactly with the cross-section, or the line directly above or below it. After each trial error feedback was given. When, as in the identification task, a participant verbally indicated they released the ‘5’ key accidentally, or wished to correct the given answer, this trial was excluded from further analysis. This task did not involve the use of shutter-glasses either.

2.6 Apparatus

In the stereoptic condition, stereopsis was implemented by a setup including Stereographics’s CrystalEyes CE-3 active shutter-glasses, an E-2 emitter and StereoEnabler, a Pentium 4 computer running Windows XP, a 19” CRT-monitor (Ilyama Vision Master Pro 454) and a PNY-Quadro 4 580XGL videocard. This setup allowed for a monitor refresh rate of 140 Hz, and thus for an effective refresh rate of 70 Hz with left and right alternating shutter-glasses. This enabled participants in both conditions to study the anatomical objects without a noticeable flicker. The 3D anatomical objects were constructed on the basis of CT-data from a patient suffering from an abdominal aortic aneurysm. The Surfdriver software package was used to trace the relevant anatomy in every slice, after which Surfdriver automatically generated 3D DXF-models. These models were post-processed in 3D Max and Cosmoworlds, after which the resulting VRML models were ready for use in the stereoptic study phase. In this study phase, they could be explored by means of the Nvidia QuadroView 2.04 application. The images used in the biocular study phase were derived from these models by means of screenshots and further processing in Adobe Photoshop. Adobe's Authorware software was used to create the software part of this experiment, including study phases, experimental tasks, and logfiles for each participant necessary for data-analysis.

2.7 Software used in this experiment

In this experiment, we sought to optimize conditions for the visuo-spatial component of anatomical learning. This was reflected in the software built for this experiment: we ignored the integration with other than anatomical knowledge domains (e.g. physiology, pathology) necessary for real-world medical learning software. Also, in order to be able to test a sufficient number of participants, we created a simple anatomical model that would not be particularly useful for medical students, but that was sufficiently challenging for students of behavioral sciences. Consequently, there are no plans to further develop this software for other than experimental purposes.

3 Results

For the localization task, one of the matched participant pairs was removed from the analyses because one of the two had not understood the task correctly. For the identification task all pairs were kept. Pretest score correlations between matched pairs were high, $r(16) = .975$, $p < .001$. For each participant, three correct-answer proportion scores were calculated by dividing the total number of good answers for each test by the total number of test items for each test, the three tests being the pretest, the identification task and the localization task. Descriptive statistics for the identification task and the localization task are shown in Figure 2-4.

Across biocular participants, there was a positive correlation between the correct-answer proportion scores of the pretest (assessing visuo-spatial ability) and each experimental task: identification task: $r(16) = .48$, $p < .05$, localization task: $r(15) = .72$, $p < .001$. This confirms that performance in the experimental tasks increased with visuo-spatial ability for the biocular group. In contrast, across stereoptic participants these correlations did not reach significance, identification task: $r(16) = .014$, $p > .95$, localization task: $r(15) = .41$, $p > .1$.

These data show that visuo-spatial ability increased learning in the biocular group but not significantly in the stereoptic group.

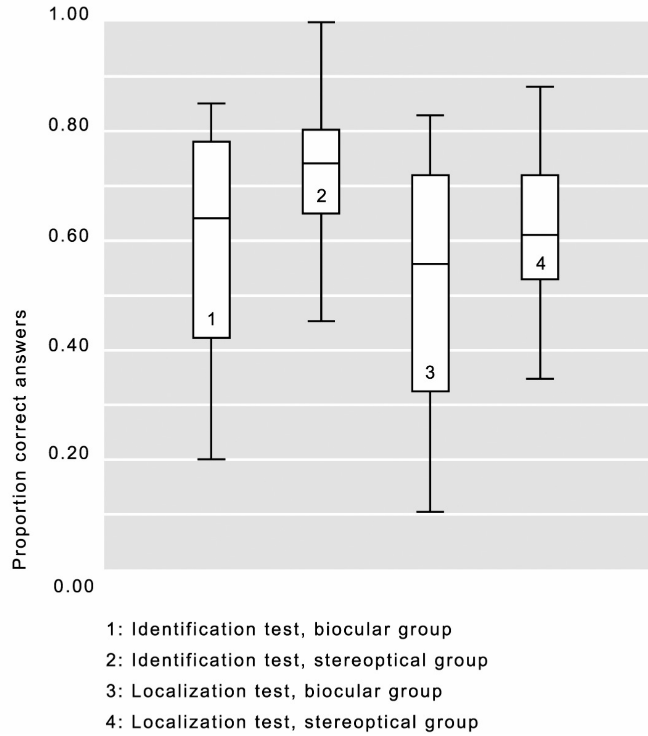


Figure 2-4 Median, interquartile range and extreme values of correct answers per group and task

Two multiple linear regression analyses were used to further evaluate the data, separately for each experimental task. Independent variables were pretest correct-answer proportion scores, experimental treatment (biocular versus stereoptical, rendered as a dichotomous variable of zero or one), and an interaction variable (pretest correct-answer proportion scores x experimental treatment). In the first analysis, the dependent variable consisted of the correct-answer proportion scores on the identification task, in the second analysis the dependent variable consisted of the correct-answer proportion scores on the localization task.

3.1 Results for the identification task

The *F* statistic $F(3,32)$ was 4.59, $p < .01$, demonstrating that together the independent variables accounted for most of the observed variance in this task. Effect for experimental treatment (single-tailed) was $t(32) = 2.8$, $p < .005$, confirming that the stereoptic group as a whole outperformed the biocular group. Effect for interaction (single-tailed) was $t(32) = 1.75$, $p < .05$ (Figure 2-5, next page), which shows that participants of low visuo-spatial ability (as measured by the mental rotation pretest) benefited significantly more from the stereoptic study-phase than participants of high visuo-spatial ability (top panel of Figure 2-5, next page).

3.2 Results for the localization task

The *F* statistic $F(3,30)$ was 8.08, $p < .001$, showing that together the independent variables accounted for most of the observed variance in the localization task as well. Effect for experimental treatment (single-tailed) was $t(30) = 2.59$, $p < .01$, demonstrating superior performance for the stereoptic group on this task. Effect for interaction (single-tailed) was $t(30) = 2.08$, $p < .03$, again showing that participants of low visuo-spatial ability (as measured by the mental rotation pretest) benefited significantly more from the stereoptic study-phase than participants of high visuo-spatial ability did (bottom panel of Figure 2-5).

A large effect size (magnitude of treatment effect) was found on the identification task, Cohen's $d = .87$, whereas effect size on the localization task was moderate, Cohen's $d = .44$.

No significant correlations were found between reaction time and correct-answer proportions, ruling out a speed-accuracy trade-off. Finally, the experimental tasks were subjected to a reliability analysis. The identification task (20 multiple choice items, eleven choices per item) was reliable at a Cronbach's α of .75. The localization task (20 multiple choice items, 14 choices per item) was reliable at a Cronbach's α of .80. This indicates that the items in each task were of similar difficulty and measured the same construct.

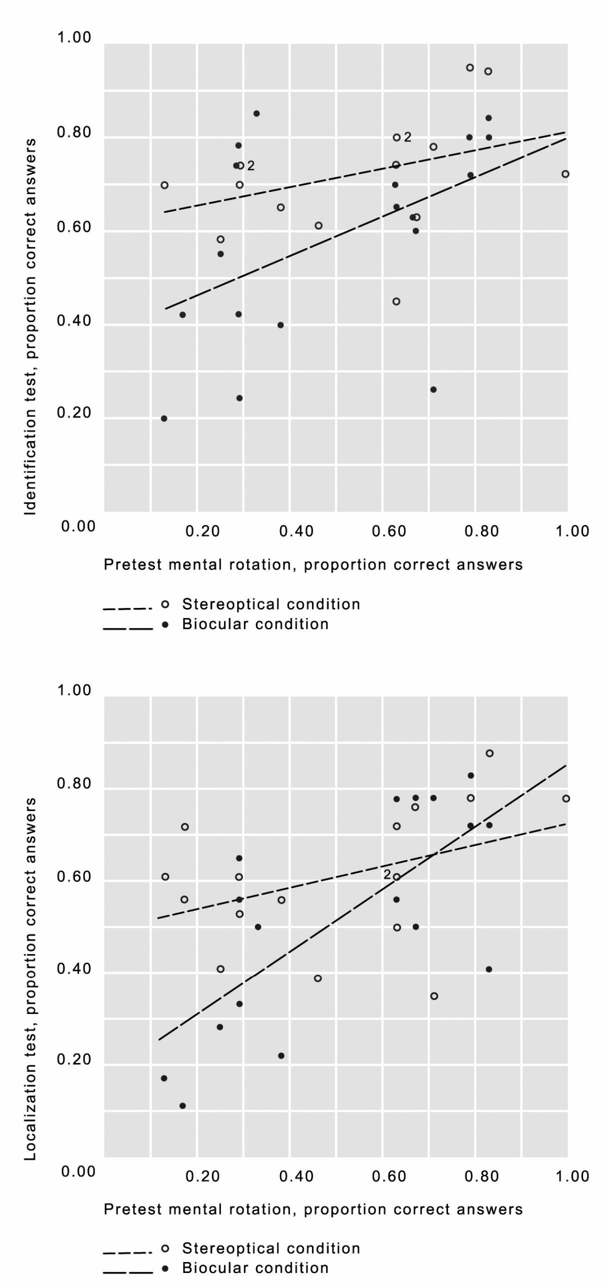


Figure 2-5 Regression lines for the biocular and stereoptic groups depicting the relationship between the results of the pretest and the results of the identification task (top panel) and the localization task (bottom panel).

4 Discussion

4.1 Discussion of the results

The present study tested whether (a) interactivity (implemented as mouse-controlled object rotation) and stereopsis (depth perception enabled by the use of shutter-glasses) improves anatomical learning, and (b) whether participants of low visuo-spatial ability benefit more from these features than participants of high visuo-spatial ability. Towards that end, participants inexperienced with human anatomy learned about the human abdominal parts in a study phase that involved either both stereopsis and interactivity (i.e. the stereoptic group), or neither of these (i.e. the biocular group). Learning was assessed in an identification task and in a localization task.

Performance was better in the stereoptic group than in the biocular group for both tasks, suggesting better anatomical learning for the stereoptic group. The data also confirmed our expectation that participants of low visuo-spatial ability benefit more from the combination of stereopsis and interactivity in the stereoptic study condition than participants of high visuo-spatial ability. This is an important finding as it suggests that, given the proper learning conditions, low visuo-spatial ability is less of a problem for developing visuo-spatial representations of anatomy and, perhaps even, for becoming a skilled endoscopist/ laparoscopist. This suggests that subjects of low visuo-spatial ability have difficulty constructing visuo-spatial representations, but are quite able to mentally manipulate these representations once formed. The finding that a combination of 3D reconstructions and interactivity benefits learning, and benefits learning especially for subjects of low visuo-spatial ability contradicts earlier findings by Garg et al, who report no benefits for either 3D reconstructions, or interactivity. This will be explored further in the following paragraphs.

Garg et al. (1999, 2001, and 2002) reported a series of experiments that investigated the usefulness in anatomical learning of computer mediated anatomical 3D reconstructions, and active control of these reconstructions. In the first of these studies they used an anatomical learning task that compared a multiple view condition (anatomy rotating 15 degrees every twenty seconds) with a key view condition (front view and back view exchanged every twenty seconds). After this study phase, an anatomical knowledge test assessed the participants' learning. They found that learners of low visuo-spatial ability performed worse on the anatomical knowledge test following the multiple view condition, compared to the key view condition. However, in a second experiment, where learners were allowed active control of the rotation, they found a significant benefit for the multiple view condition for all learners. In a third experiment they compared a learner-controlled multiple view condition with a learner-controlled condition that only allowed a front and a back view with a 'wiggle' of ten percent around either view. This effectively cancelled out the benefits of the multiple view condition, which Garg and his colleagues took to support the view that visuo-spatial memory basically uses key-views that are then transformed to match a novel view. One is then tempted to conclude that neither 3D anatomical models nor interactivity seem to benefit anatomical learning beyond traditional anatomical atlases.

To explain the contradicting outcomes of Garg et al's experiments and the experiment reported here four points come to mind. Firstly, the most important visuo spatial depth cue for near (<2m) objects is stereopsis (Cutting and Vishton, 1995), which was not implemented in Garg et al.'s studies. The lack of stereopsis could add extra difficulty for participants of low visuo spatial ability to build a mental model from the material presented. Secondly, the conditions in Garg et al's experiments didn't allow for a continuous visual transformation between views, possibly adding further difficulty to forming an appropriate mental model. Thirdly, their very observation that introducing a ‘wiggle’ (a ten percent rotation around the y-axis on both sides of the key-view) apparently adds structural 3D information to the key-view based mental model lends support to the alternative hypothesis that spatial mental models contain structural 3D information. Lastly, the material Garg et al. used in their studies (carpal bones of the hand) contains very little relevant 3D information as it consists essentially of two rows of four bones in a flat plane.

Further experiments should assess the relative importance of stereopsis and interactivity in the development of visuo-spatial mental representations, and why these features contribute to learning. Perhaps, interactivity increases attention to the material studied (e.g., because questions can be explored and answered immediately). The possible benefits of stereopsis are more difficult to explain, given the amount of alternative (monocular) depth cues available in the study phase material. If stereopsis turns out to be a critical factor in learning, this would lend support to the hypothesis that mental representations can include structural 3-

dimensional information, a notion that is debated in the literature (Christou and Bülthoff, 2000; Tarr and Bülthoff, 1998). Basically, two views are held: One view holds that mental representations are essentially flat 'key-views' that are somehow mentally transformed to match a novel view of the same object, the other view holds that mental representations can include spatial information. These two views of visuo spatial mental models that are debated in the literature are not necessarily mutually exclusive however (Tarr and Bülthoff, 1998). Two ideas come to mind that could reconcile these models. One is that the qualities of the mental model formed depend on the nature of the input (Jolicoeur and Milliken, 1989. Kourtzi et al., 2003). In the present context this would mean that multiple views stimulate a key view based mental model, and stereoptical 3D models stimulate a structural 3D mental model. A second idea is that the qualities of the mental model depend on the use a participant expects to make of these models: A recognition task would stimulate key view mental models, a mental rotation task or perceptual motor task would stimulate a structural 3D mental model. In short, goal orientation could be an important variable in constructing (or constricting) mental models.

The observation that visuo-spatial ability allows participants to correlate anatomical cross-sections that are new to them with the anatomical 3D reconstructions that were studied supports the view that mental representations can include spatial information. Another area for future research would be to assess the effect of these higher quality mental representations on surgical performance, especially in the fields of endoscopic and laparoscopic surgery. In conclusion, virtual learning environments hold great promise as an alternative to traditional anatomical learning, and a combination of stereopsis and interactivity makes an important contribution to their effectiveness.

4.2 Observations made during the experiment

Additional qualitative data were gathered by means of a one-question interview at the end of each experimental session. When asked about their problem solving strategies, participants usually reported one or more of the following:

- In the identification task, participants had to realize that in the cross sections shown, the one highlighted member of a pair of bilaterally symmetrical organs had to be reversed in its left-right orientation for the correct answer. After an initial mental rotation strategy, most participants switched to a rule-based strategy (left on screen is right for the anatomical part and vice-versa).

- In the localization task, the cross-section view was compared with the frontal anatomical view in several passes, first comparing the anatomical parts presented in the anatomical view with those in the cross-section view, then, after identification of identical organs, comparing details of shape of those organs between the two views, until a decision was made. This suggests that other strategies than strictly visuo-spatial ones might play a role in performance on this task.

- In the localization task, some participants projected the cross-section view in their own body, and compared that mental model with the anatomical view (to identify the correct height). If this is a common strategy, results from similar experiments might differ over different knowledge domains.

3. The Role of Stereopsis in Virtual Anatomical Learning

Abstract

The use of virtual learning environments in the medical field is on the rise. An earlier experiment (Luursema et al. 2006, chapter 2 of this thesis) found that a combination of computer-implemented *stereopsis* (visual depth through seeing with both eyes) and *dynamic exploration* (being able to continuously change one's viewpoint with respect to the objects studied in real-time) is beneficial to anatomical learning, especially for subjects of low *visuo-spatial ability* (the ability to form, retrieve and manipulate mental representations of a visuo-spatial nature). The present experiment investigated the contribution of computer-implemented stereopsis alone to anatomical learning. Two groups with a similar distribution of visuo-spatial ability were formed; one group studied a 3D computer model of the human abdominal anatomy in a stereoptic condition, the other group studied the same anatomy in a *biocular* condition (both eyes exposed to the same image). Although visuo-spatial ability was the most important variable predicting anatomical learning, computer implemented stereopsis provided a significant benefit for one of the post-tasks assessing this learning.

Adapted from: Luursema, J. M., Verwey, W. B., Kommers, P. A. M., & Annema, J. H. (2008). The role of stereopsis in virtual anatomical learning. *Interacting with Computers, 20*(4-5), 455-460.

1 Introduction

1.1 Background

The use of Virtual Learning Environments (VLEs) in the medical curriculum is on the rise. Over the last decade, many dedicated medical VLEs have been developed. High end, stand-alone examples include laparoscopic simulators (e.g., Immersion's LapSim, or the Xitact series) and electronically enhanced manikins (e.g. Laerdal's product series). E-learning examples include electronic patient simulations (see Le Beux and Fieschi, 2007 for a recent survey) and anatomical learning environments (Jastrow and Vollrath, 2003 give an overview of such learning environments based on *the visible human project*, a high profile project that included the creation of computerized 3D models of human anatomy based on anatomical cross sections). Acquiring accurate mental representations of human anatomy is a sine-qua-non for the medical practitioner, the human body being the frame of reference for all other medical knowledge and skills. In earlier research, we reported on the beneficial effects of a combination of computer-implemented stereopsis and dynamic exploration on virtual anatomical learning, especially for participants of low visuo-spatial ability (Luursema et al. 2006, chapter 2 of this thesis). The experiment reported here continues this line of research by taking a closer look at the effects of computer-implemented stereopsis on anatomical learning, without dynamic exploration.

1.2 Media for anatomical learning

Traditionally, human anatomy is taught by means of dissection, complemented by anatomical atlases and manikins. Three self-evident features of dissection will be made explicit here, as they bear on the discussion of anatomical VLEs below. A first important feature of dissection is the availability of *haptic information*: Even though a living body provides a very different haptic experience compared to a dead body that has been chemically treated to prevent decay, haptic cues still provide relevant information as to qualities such as weight, flexibility, surface structure, size, and shape. Since the technical implementation of haptic feedback in other media, including VLEs, is still far from satisfactory, haptic information can be considered a unique and irreplaceable feature of dissection.

Secondly, a number of visual depth cues that are available in dissection usually lack in other media. Prime amongst those is s*tereopsis* which is the visual sense of depth that is based on differences in patterns of light projected on both retinas. Stereopsis is one of the most important visual depth cues in one's *personal space*, which can be defined as "the zone immediately surrounding the observer's head, generally within arm's reach and slightly beyond" (Cutting and Vishton, 1995). The perception of stereoptic depth is available in dissection, as well as in studying manikins.

The third feature of dissection is *dynamic exploration* (the possibility to actively and continuously change one's view towards objects of study). This is a given in dissection and manikins, and can be implemented in VLEs too.

In contrast to these advantages of dissection, anatomical atlases and VLEs provide the possibility to contextualize the presented anatomy within a medical knowledge frame. In this sense, both anatomical atlases and VLEs make a great companion to dissection, helping students to create a mental representation of the studied anatomy where topological knowledge of this anatomy is integrated with medical concepts not provided by dissection.

Another advantage of anatomical atlases, manikins and VLEs over dissection is the convenience of use of the former: A dissection room is arduous and expensive to maintain, and not as flexible in its deployment as atlases, manikins, and VLEs are. Obviously, it is necessary to indicate that, in contrast to dissection, *mediated* anatomical learning (e.g., through atlases, manikins, VLEs) filters out much of the richness of the original anatomy, presenting students a representation that merely retains the conceptual model of its makers instead. This can lead to a situation where students discover only what they are supposed to discover, preventing them to enrich their knowledge beyond the provided model. The training of medical skills is likely to be facilitated if in an earlier (anatomical learning) stage students had the opportunity to test provided conceptual models against the reality of first hand dissection experience. Additionally, keenness to incidental anatomical exceptions and the uniqueness of patients' morphologies as provided by dissection is likely to be crucial to medical competence.

Summing up, traditional anatomical learning methods involved direct and mediated methods, each having their unique qualities. Direct methods (i.e., dissection) offer haptic information, 3D visual information, and dynamic exploration, while mediated methods (i.e. anatomical atlases and manikins), provide conceptual knowledge, and convenience of use. For the development of detailed anatomical knowledge, these methods should be seen as supplementary rather than supernumerary. Nowadays, VLEs offer the possibility to implement two features traditionally associated with dissection and not with mediated medical learning, namely stereopsis and dynamic exploration. However, little is currently known as to the effectiveness of these two features for anatomical learning.

1.3 Human factors

Stereopsis is one of the most important visual depth cues in personal space, especially for prehension (Servos et al., 1992; Bradshaw et al., 2004). One could say that stereopsis and prehension are functionally coupled with respect to goal-directed motor behavior in personal space (dynamic exploration being the goal-directed motor behavior under study here). Endoscopic surgery, where practitioners generally get visual feedback on their actions by means of a two-dimensional video display, has over the years provided an important applied field to test the ecological validity of this coupling.

Initially, inconclusive results were reported, mostly due to technical limitations; e.g. a combination of shutter glasses and a relatively low monitor refresh rate will lead to noticeable flicker (as in Wentink et al. 2002), which is very likely to influence test results. Other studies implemented stereoptic feedback and biocular feedback on different systems, without controlling for image resolution and other relevant system differences. The reader is referred to Huberet al. (2003) for a more detailed discussion of this older work. A recent, better controlled study has confirmed the expected superiority of endoscopic performance under three-dimensional (stereoptic) imaging, compared to two-dimensional (biocular) imaging (Byrn et al., 2007).

In contrast, we do not know whether the coupling of stereopsis and dynamic exploration contributes also to visuo-spatial learning (of which anatomical learning is but one example). However, Luursema et al. (2006, chapter 2 of this thesis) recently showed that a virtual anatomical study phase that combines stereopsis and dynamic exploration, led to better learning than a study phase that involved only exploration of standard anatomical views (top, side, and front). Whether this can be ascribed to stereopsis, dynamic exploration, or its combination is as yet unclear.

Successful learning depends on the formation of mental representations of the information to be learned. For anatomical learning, where the information to be learned is visual and spatial in nature, *visuo-spatial ability* is a cognitive ability that needs to be taken into account. Visuo-spatial ability refers to the ability to form, retrieve and manipulate visuo-spatial mental representations (Carroll, 1993; Hegarty and Waller, 2005). The relevance of visuo-spatial ability for medical practitioners was demonstrated in several studies that found visuo-spatial ability to correlate highly with success as an endoscopic surgeon (e.g. Risucci, 2002; Wanzel et al., 2002). Additionally, Rochford (1985) found a significant positive correlation between spatial learning disabilities and underachievement in an anatomy course for second-year medical students at Cape Town University. A comprehensive review of the important role of spatial cognition in medicine, with special attention to its practical implications, can be found in Hegarty et al. (2007). Luursema et al. (2006, chapter 2 of this thesis) found that participants of low visuo-spatial ability benefited more from the condition that included both stereopsis and dynamic exploration than participants of high visuo-spatial ability. This finding could potentially impact anatomical instruction by suggesting a way to support students of low visuo-spatial ability.

To assess the contribution of stereopsis to the benefit of combined stereopsis and dynamic exploration for anatomical learning, we compared two groups of participants, which were subjected to different anatomical study phases after which they were tested for their amount of anatomical learning. For both groups, the study phase showed an auto rotating 3D model of human abdominal anatomy. Participants in the stereoptic study phase wore shutter glasses by means of which they experienced the presented models stereoptically. Participants in the biocular study phase didn't wear any specific headgear, and consequently experienced the model *biocularly* (both eyes were exposed to identical images). Anatomical learning was assessed by two tests, an identification task and a localization task. Visuo-spatial ability was measured by the Vandenberg and Kuse mental rotation test (Vandenberg and Kuse, 1978; Peters et al., 1995).

Having established a learning benefit for the combination of stereopsis and dynamic exploration, we were interested to assess the learning benefit of stereopsis alone. Similar to our earlier study, we expected participants of low visuo-spatial ability to benefit more from computer-implemented stereopsis than participants of high visuo-spatial ability because they are probably less able to construct a 3D mental representation from a biocular presentation.

Also, although stereopsis can be easily implemented across the whole range of virtual learning environments, its potential for learning has been largely unexplored. If computer-implemented stereopsis proves to be beneficial to visuo-spatial learning, this would be of consequence to the implementation of educational practices in virtual environments where this type of learning is critical.

2 Method

2.1 Participants

Participants were university students and employees from the faculty of Behavioral Sciences, University of Twente. All participants were native Dutch speakers. All reported limited knowledge of human abdominal anatomy (not exceeding high school biology level). Participants were between 19 and 34 years of age. A total of 46 participants took part (30 women and 16 men). All reported normal or corrected to normal vision. All participants were naïve to the tasks they were to perform in this experiment.

2.2 Procedure

Before the actual experiment, 91 potential participants were tested for the ability to see stereoptically, and for visuo-spatial ability. Stereopsis was tested with the TNO-test for stereoscopic vision. It demands participants to distinguish figures from a background in random dot figures within thirty seconds (Okuda and Wanters, 1977). Six participants of insufficient stereoptic ability were excluded from further participation. The remaining 85 participants were tested for visuo-spatial ability using Vandenberg and Kuse's mental rotation test (Vandenberg and Kuse, 1978; Peters et al., 1995). From this group, 46 subjects were randomly selected for participating in the study reported here. The selected participants were ranked according to visuo-spatial ability, and alternately matched in pairs over the two conditions of the experiment. This provided an equal distribution of visuo-spatial ability over both conditions.

The selected participants then learned about human anatomy in a study phase that differed for the two groups. Afterwards their knowledge was assessed with an identification task and a localization task. The order of these two tasks was counterbalanced across the participants in each group. The study phase and both tasks were carried out on an individual basis in a specially prepared experimental room. It contained the hardware and software necessary for the experiment and was shut off from possible disturbances during the experiment. All task-instruction and error feedback was provided on screen in Dutch.

2.2.1 Study phase

At the beginning of the experiment, example items of the two tasks (described in the next two sections) were presented to participants. They were informed to use the study phase to prepare for these two tasks. The study phases of each group contained labelled reference figures for the eleven anatomical parts of the abdomen relevant to the tasks. Figure 3-1, next page, shows a screenshot of the study phase). During this study phase, the *biocular group* watched a 3D model of the referenced abdominal anatomy, which rotated around its vertical axis. Participants could not interfere with, or influence, this animation. The *stereoptic group* explored the same auto-rotating 3D-reconstructions of the abdominal anatomy, but here stereopsis was implemented by means of shutter glasses.

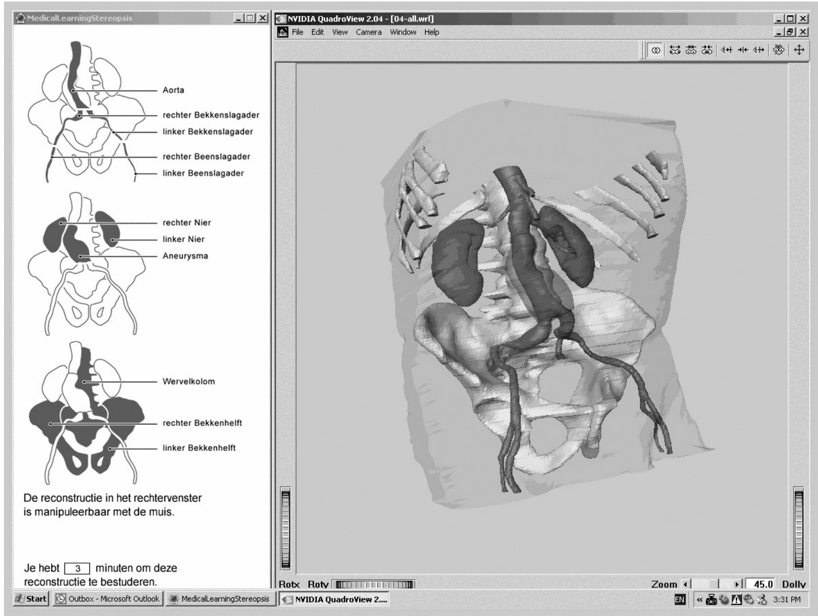


Figure 3-1 Screenshot of the study phase. Participants studied either the autorotating 3D anatomy stereoptically (with shutter glasses) or biocularly (without shutter glasses).

All participants were given three minutes to study the shape and mutual relations of these eleven anatomical parts of the abdomen. Only participants in the stereoptic group wore shutter-glasses, reasoning that asking participants in the biocular group to wear special headgear that turns out to be non-functional would distract them, and thus bias test results.

2.2.2 Identification task

One test used to assess anatomical knowledge was the identification task (see top frame of Figure 3-2). It consisted of four familiarization trials and twenty test trials. Participants were instructed to start a trial by pushing the ‘5’ button on the numeric keypad at the right side of the keyboard. This action made an anatomical CT cross-section appear with one highlighted anatomical structure, joined by a list with eleven names of anatomical structures. With the release of the button the picture of the cross-section disappeared. The anatomical cross-sections used for this task were the ones that had also been used for constructing the 3D visual materials of the study phase.

Participants were instructed to release the button only when they had identified the highlighted structure by selecting one of the given anatomical names. They then mouse-clicked the corresponding name in the list at their own pace. Reaction times were defined as the time the button was held down during each trial. If after 10 s the button had not been released, the picture with the cross-section disappeared anyway. Errors were defined as clicking an incorrect name or no name at all. After each trial error feedback was given. No shutter-glasses were worn during this task.

2.2.3 Localization task

The other test of anatomical knowledge was the localization task which consisted of three familiarization trials and twenty test trials. Participants were instructed to indicate on a frontal-view screenshot of the studied anatomy (see bottom frame of Figure 3-2), the correct horizontal level of a CT-based anatomical cross-section (lower right frame of these cross-sections were taken also from the scans used to develop the material for the study phase. Each trial involved presentation of another cross-section. The order in which the cross-sections appeared was randomized across participants.

Participants were instructed to start a trial by pushing the ‘5’ button on the numeric keypad to make a cross-section appear. With the release of the button the cross-section disappeared. They were further instructed to release the button as soon as they had identified the level from which this cross-section was taken, and then to click at their own pace with the mouse the corresponding line out of a series of lines overlaying the frontal-view screenshot.

If after 15 s the button had not been released, the cross-section disappeared and an error was scored. Reaction time was defined as the time the button was held during each trial. A correct answer was defined as clicking the line corresponding exactly with the cross-section, or the line directly above or below it. After each trial error feedback was given. This task did not involve the use of shutter-glasses either.

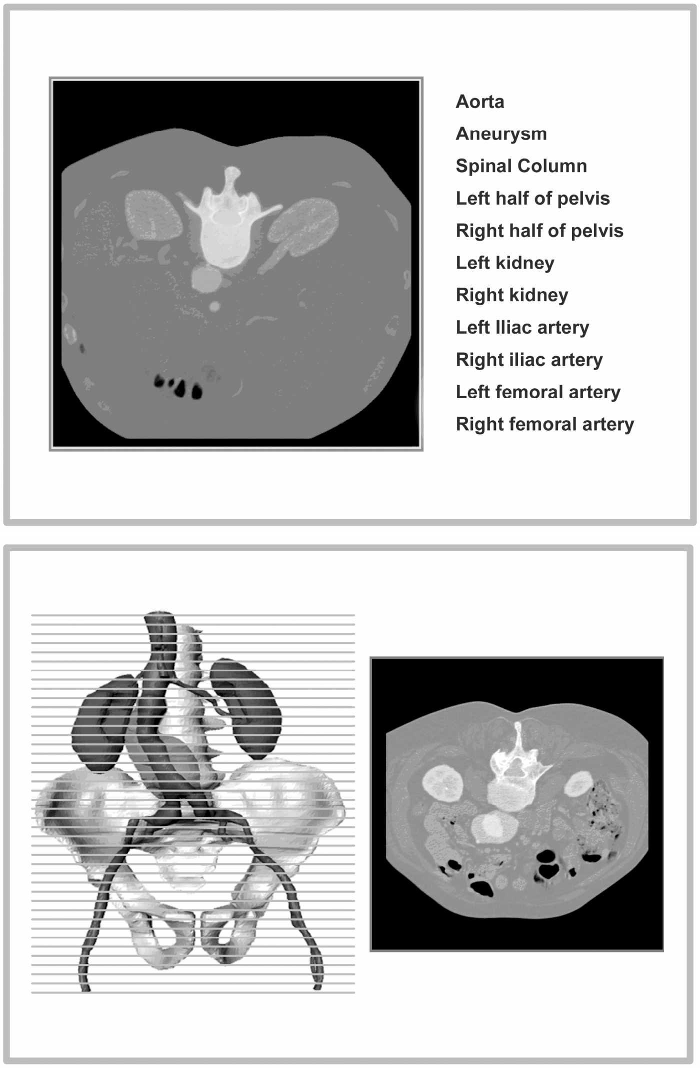


Figure 3-2 Screenshots of an item of each of the two tasks. On top the identification task with the eleven possible names of the highlighted structure, at the bottom the localization task that involved selecting the level in the left image from which the right image was taken. Names were in Dutch, but are given in English here for purposes of illustration.

2.3 Apparatus

In the stereoptic condition, stereopsis was implemented by a setup including Stereographics's CrystalEyes CE-3 active shutter-glasses, an E-2 emitter and Stereo Enabler, a Pentium 4 computer running Windows XP, a 1900 CRT-monitor (Ilyama Vision Master Pro 454) and a PNY-Quadro 4 580XGL videocard. This set-up allowed for a monitor refresh rate of 140 Hz, and thus for an effective refresh rate of 70 Hz for each eye, which is sufficient to prevent flicker.

The 3D anatomical objects were constructed on the basis of CT-data from a patient suffering from an abdominal aortic aneurysm. The Surfdriver software package was used to trace the relevant anatomy in every slice, after which Surfdriver automatically generated 3D DXF-models. These models were post-processed in 3D Max and Cosmoworlds, after which the resulting VRML models were ready for use in both conditions of the study phase. During the study phase, these models could be explored by means of the Nvidia QuadroView 2.04 application. Adobe's Authorware software was used to create the software part of this experiment, including study phases, experimental tasks, and logfiles for each participant necessary for data-analysis.

3 Results

Scores for the mental rotation test and accuracy scores for the identification- and localization tasks were transformed to proportions correct for easier reading. Descriptive statistics for the accuracy scores on the identification- and localization tasks are shown in Figure 3-3. For these knowledge tasks, latency was recorded as well, which was used to rule out an accuracy/ latency trade-off (r = -.58 and r = -.24 for the identification- and localization task, respectively). Three participants verbally indicated not to have comprehended the localization task, which was corroborated by their task scores (zero); their results were coded as missing data in the subsequent analyses. Trials clocked under .5 seconds were defined as missing values, and were left out in the analysis of the logfiles.

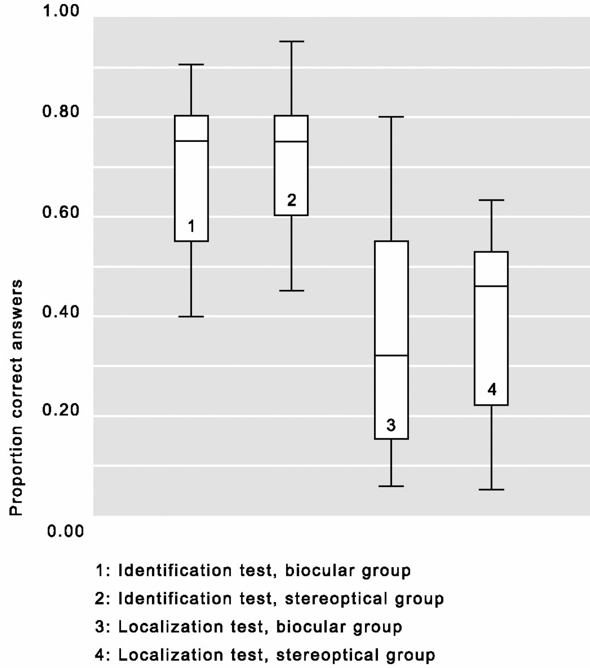


Figure 3-3 Median, interquartile range and extreme values of the accuracy scores for each group and task.

To assess differences in performance on the identification- and localization task as a function of visuo-spatial ability, experimental condition, and the interaction of these last two variables, two ANCOVAs were performed. One ANCOVA had identification task accuracy as its dependent variable, the other had localization task accuracy as its dependent variable. Both ANCOVAs had stereopsis (biocular versus stereoptic) as independent variable, visuo-spatial ability (as measured by the pretest) as a co-variable, and ‘stereopsis' x ‘visuo-spatial ability' as an interaction variable. This interaction variable was included both based on earlier similar research (Luursema et al. 2006, chapter 2 of this thesis), where this interaction proved significant, and on scatterplots that suggested such an effect for the current data Figures 3-4 and 3-5). Table 3-1 gives an overview of the results for these ANCOVAs (single tailed). Visuo-spatial ability proved to be significant for both post-task results, stereopsis only for the localization task. The ‘visuo-spatial ability’ x ‘stereopsis’ interaction was not significant for either post-task.

Table 3-1 Analysis of Variance for both Dependent Variables (single-tailed)

Source	*df*	*F*	*p*
	Accuracy on the identification task ($n = 43$)		
Visuo-spatial ability (VSA)	1	15.4	.00
Stereopsis (ST)	1	1.9	.09
VSA x ST	1	1.9	.09
	Accuracy on the localization task ($n = 43$)		
Visuo-spatial ability (VSA)	1	5.7	.01
Stereopsis (ST)	1	2.8	.05
VSA x ST	1	1.8	.09

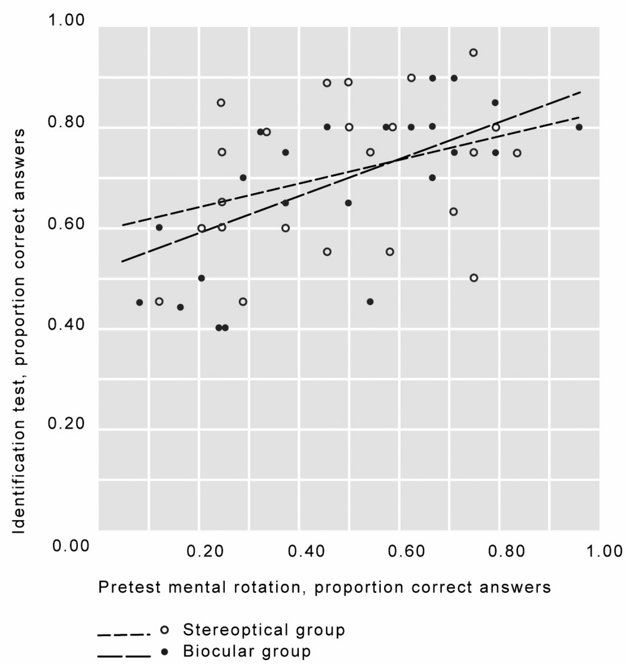


Figure 3-4 Scatterplot for the biocular and stereoptic groups depicting the relationship between the results of the visuo-spatial ability test and the results of the identification task.

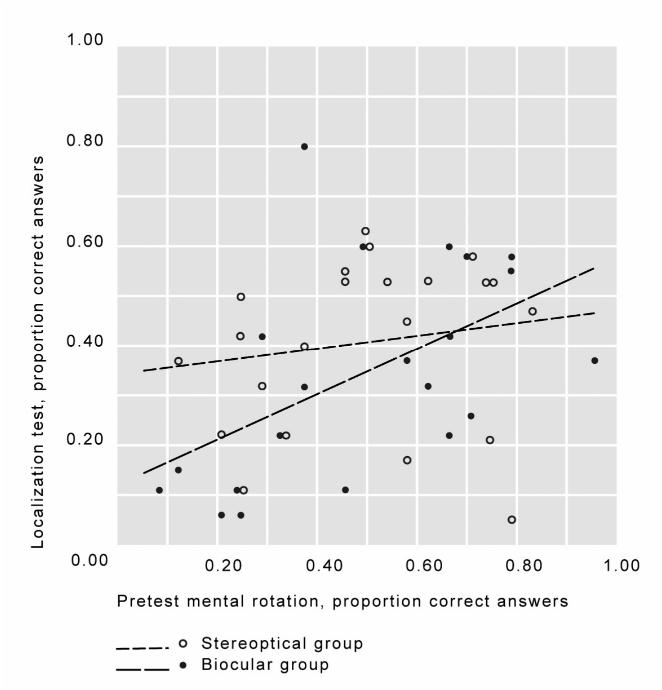


Figure 3-5 Scatterplot for the biocular and stereoptic groups depicting the relationship between the results of the visuo-spatial ability test and the results of the localization task.

4 Discussion

In the Introduction, we argued that the use of Virtual Learning Environments (VLEs) in the medical curriculum makes it possible to implement both stereopsis and dynamic exploration, two features traditionally available only in dissection and anatomical manikins. Additionally, in VLEs conceptual knowledge can be provided, traditionally associated with anatomical atlases and medical textbooks. An earlier study (Luursema et al. 2006, chapter 2 of this thesis) showed that the combination of dynamic exploration and stereoptic presentation yielded better anatomical learning (especially for participants of low visuo-spatial ability). We now report an experiment that investigated the contribution of computer-implemented stereopsis on anatomical learning for participants of differing visuo-spatial ability.

The results confirm earlier research that shows higher visuo-spatial ability significantly indicates better anatomical learning (Garg et al., 1999, 2001, 2002; Rochford, 1985). Additionally, having been exposed to a study phase with computer-implemented stereopsis implied significantly higher accuracy on an anatomical localization task. This confirms our hypothesis that computer-implemented stereopsis is partly responsible for the learning effect found from a combination of computer-implemented stereopsis and dynamic exploration on anatomical learning (Luursema et al. 2006, chapter 2 of this thesis).

An effect found in the latter study was that participants of low visuo-spatial ability benefited more from a combination of stereopsis and dynamic exploration than participants of high visuo-spatial ability, who did not benefit significantly from this combination. This interaction effect was not found for visuo-spatial ability and stereopsis (without dynamic exploration) in the current study. As can be gleaned from figure 4 and table 3-1, there is a tendency towards such an interaction, but this failed to reach significance ($p = .09$). The difference in magnitude of experimental effect between the two studies cannot yet be wholly attributed to dynamic exploration; in contrast to the experiment reported here, our previous study featured a control condition with static stimuli, causing the visual depth cue of motion parallax to be absent. This also reduced the total number of anatomical views the participants were exposed to.

Given the small effect size of stereopsis alone on anatomical learning, and the low ecological validity of the experiment reported here (simplified anatomical learning task, no participants of a medical background), judgment has to be postponed on the advisability of implementing stereopsis enabling hardware in medical study settings. A study geared towards medical professionals, with more realistic learning tasks, would be a necessary step before any solid recommendations can be made with respect to the practical implementation of this technology. Studies similar to the one reported here, but additionally manipulating task difficulty would be very useful too.

An important topic for future research also would be investigating the social aspects of VLE use, i.e. to what extent does having to wear special headgear interfere with normal communication between users. Case studies reported by Montgomery et al. (2005) suggest that being able to make eye contact is essential in social situations (such as preoperative planning, or surgical practice), restricting the use of specialized headgear to specific, single-user scenarios. At the moment of writing, autostereoptic monitors are becoming available, but do not yet offer the specifications necessary for serious use in a professional setting.

The role of dynamic exploration alone in virtual anatomical learning warrants further exploration too. A new study is in progress to investigate the importance of dynamic exploration for virtual anatomical learning.
Concluding, the implementation of stereopsis in VLEs is not just beneficial for movement execution in endoscopic surgery (and by implication for the training of surgical skills), but also impacts the construction of visuo-spatial mental representations, a cognitive skill that forms the backbone of anatomical learning. The slight, but positive, contribution of stereopsis to aspects of visuo-spatial learning is a novel find, and potentially of great practical value, if corroborated and mapped out by future studies.

4. The Contribution of Dynamic Exploration to Virtual Anatomical Learning

Abstract

Virtual Learning Environments are increasingly becoming part of the medical curriculum. An earlier experiment (Luursema et al., 2006, chapter 2 of this thesis) found that a combination of computer-implemented *stereopsis* (visual depth through seeing with both eyes) and *dynamic exploration* (being able to continuously change one's viewpoint relative to the studied objects in real-time) is beneficial to anatomical learning, especially for subjects of low *visuo-spatial ability* (the ability to form, retrieve and manipulate mental representations of a visuo-spatial nature). A second experiment (Luursema et al., 2008, chapter 3 of this thesis) found the contribution of just computer-implemented stereopsis to this effect to be small but significant. The present experiment investigated the contribution of dynamic exploration to anatomical learning by means of a virtual learning environment. Seventy participants were tested for visuo-spatial ability and were grouped in pairs matched for this ability. One individual of the pair actively manipulated a 3D reconstruction of the human abdomen; the other individual passively watched the interactions of the first individual on a separate screen. Learning was assessed by two anatomical learning tests. Dynamic exploration provided a small but significant benefit to anatomical learning.

1 Introduction

1.1 Background

Increasingly, Virtual Learning Environments (VLEs) are becoming a staple of the medical curriculum. Surgical simulators help young surgeons train laparoscopic skills (e.g., Seymour et al., 2002), and electronically enhanced manikins add physiological parameters to procedures traditionally trained on non-augmented manikins (e.g., Laerdal's product series). In anatomical learning too, VLEs are increasingly used to complement traditional media such as anatomical atlases, anatomical manikins, and dissection (Jastrow and Vollrath, 2003). Acquiring a mental model of human anatomy, including its visuo-spatial aspects, provides the medical student with an essential framework for any further study in the medical field. In searching to optimize the effectiveness of VLEs for anatomical learning, earlier research assessed the effect of a combination of computer implemented stereopsis and dynamic exploration, and the effectiveness of computer-implemented stereopsis alone on this learning (Luursema et al., 2006, chapter 2 of this thesis; Luursema et al., 2008, chapter 3 of this thesis). The research reported here continues this series by investigating the contribution of computer implemented dynamic exploration to anatomical learning.

1.2 Functional coupling of dynamic exploration and stereopsis

Anatomical learning is largely learning of a visuo-spatial nature. Two factors present in anatomical learning by dissection are stereopsis and dynamic exploration, both of which are lost in anatomical atlases. *Stereopsis* is the visual sense of depth that is based on differences in patterns of light projected on both retinas. Stereopsis is one of the most important visual depth cues in one's *personal space*, which can be defined as "the zone immediately surrounding the observer's head, generally within arm's reach and slightly beyond" (Cutting and Vishton, 1995). *Dynamic exploration* refers to the possibility to actively and continuously change one's view towards objects under study. Stereopsis and dynamic exploration are thought to be functionally coupled for goal-directed motor behavior in personal space (Bradshaw et al., 2004), which is corroborated by recent research in endoscopic skills training (Byrn et al., 2007).

The importance of the combination of these factors in visuo-spatial *learning* (as contrasted to training) is less clear. Although Luursema et al. (2006) recently showed that a combination of VLE implemented stereopsis and dynamic exploration during an anatomical study phase led to better results on subsequent anatomical tests, stereopsis alone only had a slight positive impact on anatomical learning in a similar experiment (Luursema et al.2008, chapter 3 of this thesis). It is not clear whether a large effect for dynamic exploration, or the effect of the functional coupling of stereopsis and dynamic exploration are responsible for the effect found in the former experiment.

1.3 Visuo-spatial ability

Another factor influencing anatomical learning is *visuo-spatial ability*, which refers to the ability to form, retrieve, and manipulate visuo-spatial mental representations (Carroll, 1993). The relevance of visuo-spatial ability for medical practitioners was demonstrated in several studies that found visuo-spatial ability to correlate highly with success as an endoscopic surgeon (e.g., Risucci, 2002; Wanzel et al., 2002). Additionally, Rochford (1985) found a significant positive correlation between spatial learning disabilities and underachievement in an anatomy course for second-year medical students at Cape Town University. A comprehensive review of the important role of spatial cognition in medicine, with special attention to its practical implications, can be found in Hegarty et al. (2007). In addition, Luursema et al. (2006, chapter 2 of this thesis) found that participants of low visuo-spatial ability benefited more from the condition that included both stereopsis and dynamic exploration than participants of high visuo-spatial ability.

Having established a learning benefit for the combination of stereopsis and dynamic exploration, and having found a small benefit for stereopsis alone, we were interested to assess the learning benefit of dynamic exploration. Similar to our earlier study, we expected participants of low visuo-spatial ability to benefit more from dynamic exploration than participants of high visuo-spatial ability because they are probably less able to construct a 3D mental representation through passive viewing alone.

Dynamic exploration' as an experimental condition was implemented by coupling participants of similar visuo-spatial ability, allowing one participant to actively manipulate the stimulus material, and making the other participant passively watch the explorations of the first participant.

2 Method

2.1 Participants

Participants were university students from the University of Twente. All participants were naïve to the used experimental setup. They received either course credit or six Euros for their participation. All participants were native Dutch speakers. All had limited knowledge of human abdominal anatomy (not exceeding high school level, this was verbally indicated by the participants in response to a question to that effect by the experimenter). Participants were between 18 and 53 years of age. A total of 70 participants took part (20 women and 50 men). All reported normal or corrected to normal vision.

2.2 Procedure

Before the actual experiment, all participants were tested for visuo-spatial ability, using the Vandenberg and Kuse mental rotation test (Vandenberg and Kuse, 1978; Peters et al., 1995). Based on the outcome of this test, participants were ranked according to visuo-spatial ability, and pairs were formed by alternately assigning participants to either the active or the passive condition of the experiment. A yoked design (James et al., 2001) was used for the study phase of the experiment. This means that the two participants of each pair were simultaneously tested, with one participant actively manipulating the 3D reconstructions of the human abdominal anatomy that were displayed (active condition). The other participant passively watched the explorations of the active participant on a separate screen (passive condition). Participants were kept unaware of this design during the experiment. A screen divided the experiment space, making it impossible for the participants to see each other's actions. During the study phase participants were asked to wear headphones that exposed them to white noise, to cancel out the sound of mouse clicks that might otherwise have cued the participants to the experimental design.

After the study phase, learning was measured with an identification test and a localization test. Test order was randomized over the pairs, but the tests themselves were identical for all participants. The study phase was administered from a computer that allowed for stereoptic vision being implemented by shutter glasses.

Two monitors were attached to this computer. The introduction to the study phase, as well as the tests following the study phase, were administered from a separate computer setup, allowing both participants of each pair to work individually in those phases of the experiment. A researcher always was present during the experiment. The room was equipped with all the hardware and software necessary, and was shut off from possible disturbances during the experiment. All explanations were provided on screen, in Dutch.

2.2.1 Study phase

Example items of the identification test and localization test were presented to participants prior to the experiment. They were told to use the study phase to prepare for these two tests (Fig. 4.1 shows a screenshot of the study phase). During the study phase, labelled reference figures for the eleven anatomical parts of the abdomen relevant to the tests were visible (top of Figure 4-2). The active participant of a pair manipulated a 3D model of the referenced abdominal anatomy, by using the mouse to change the viewpoint towards the 3D model. Viewpoint manipulation was restricted to rotation over any of the reconstruction's Cartesian axes. Passive participants could not interfere with- or influence this reconstruction, and witnessed the active participant's explorations.

Stereopsis was implemented for all participants by shutter glasses. All participants were given three minutes to learn the shape, name, and spatial relations of these eleven anatomical parts of the abdomen.

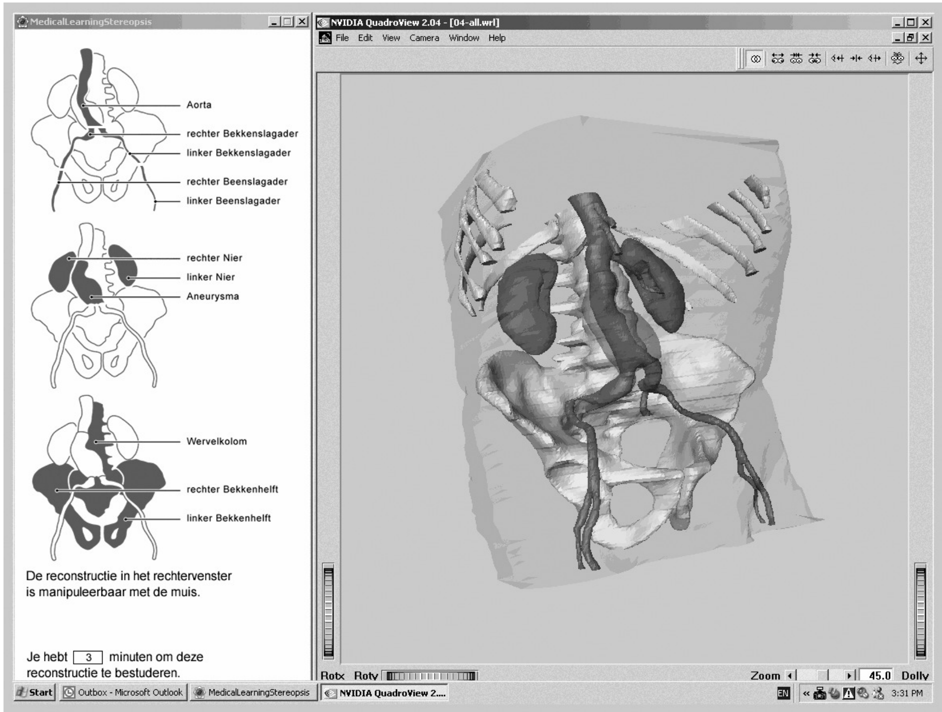


Figure 4-1. Screenshot of the study phase. Participants either actively manipulated the 3D anatomy on the right, or passively watched the manipulations of the active participant.

2.2.2 Identification test

One test to assess anatomical knowledge was the identification test (see upper frame of Figure 4-2). This test consisted of four familiarization trials and twenty test trials. Participants were told to start a trial by pushing the ‘5’ key on the numeric keypad at the right side of the keyboard. As a result of this action, an anatomical CT cross-section with one highlighted anatomical structure appeared, joined by a list with names of the eleven anatomical structures. At the release of this key the picture of the cross-section disappeared. The anatomical cross-sections used for this test were the same ones that had been used to construct the various visual materials used during the study phase.

Participants were instructed to release the key only when they had identified the highlighted structure as one of the listed anatomical structures, and then to mouse-click the corresponding name in the list at their own pace. Reaction times were defined as the time the key was pressed during each trial. If after 10 seconds the button had not been released, the picture with the cross-section disappeared anyway. Errors were defined as clicking an incorrect name or no name at all. After each trial error feedback was given. No shutter-glasses were worn during this test.

2.2.3 Localization test

The other anatomical knowledge test was the localization test, consisting of three familiarization trials and twenty test trials. Participants were asked to indicate on a frontal-view screenshot of the studied anatomy, the correct horizontal level of a CT-based anatomical cross-section (lower frame of Figure 4-2). Again, the cross-sections were taken from the same scans that had been used to develop the material for the study phase of the experiment. In each trial a different cross-section was shown. The order in which the cross-sections appeared was randomized between participants.

Participants were instructed to start a trial by pushing the ‘5’ key on the numeric keypad to make a cross-section appear. At the release of this key the picture of the cross-section disappeared. They were further instructed to release the key as soon as they had identified the level from which this cross-section was taken, and then to click at their own pace the corresponding line out of a series of lines overlaying the frontal-view screenshot. If after 15 s the key was not released, the cross-section disappeared and an error was scored. Reaction time was defined as the time the key was held during each trial. A correct answer was defined as clicking the line corresponding exactly with the cross-section, or the line directly above or below it. After each trial error feedback was given. As in the identification test, this test did not involve the use of shutter-glasses.

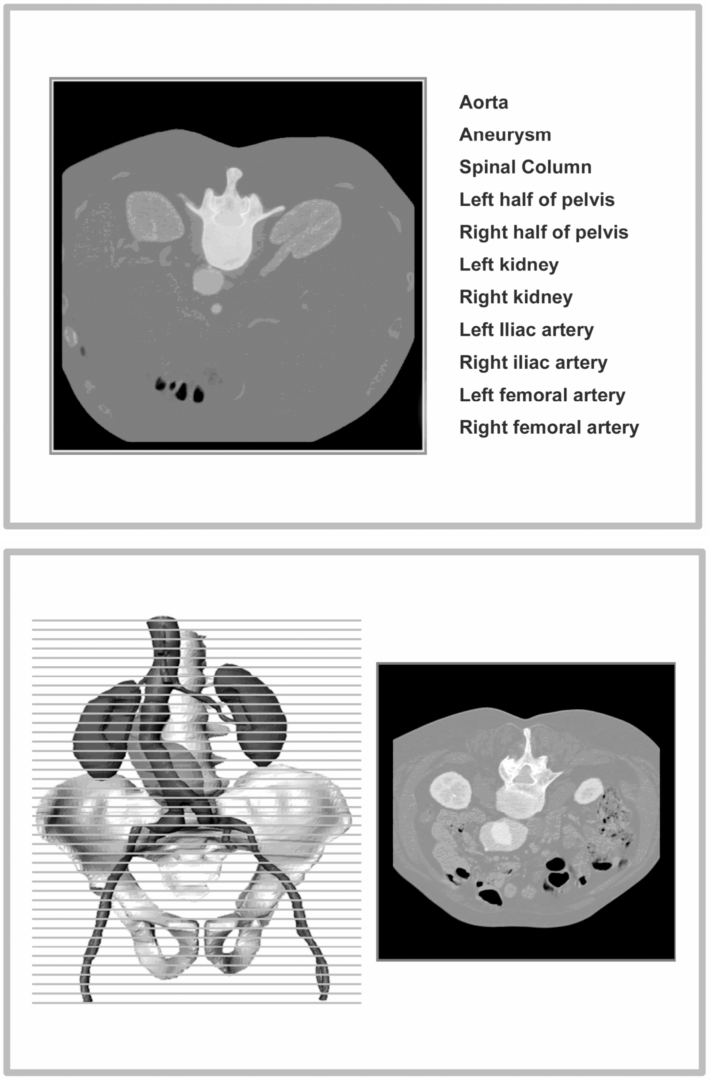


Figure 4-2. Screenshots of an item of each of the two tests. On top the identification test with the eleven possible names of the highlighted structure, at the bottom the localization test that involved selecting the level in the left image from which the right image was taken. Names were in Dutch, but are given in English here for purposes of illustration.

2.3 Apparatus

Stereopsis was implemented by a setup including two pairs of Stereographics's CrystalEyes CE-3 active shutter-glasses, an E-2 emitter and Stereo Enabler, a Pentium 4 computer running Windows XP, two 1900 CRT-monitors (Ilyama Vision Master Pro 454) and a PNY-Quadro 4 580XGL videocard. This set-up allowed for a monitor refresh rate of 140 Hz, and thus for an effective refresh rate of 70 Hz for each eye, preventing noticeable flicker.

The 3D anatomical objects were constructed on the basis of CT-data from a patient suffering from an abdominal aortic aneurysm. The Surfdriver software package was used to trace the relevant anatomy in every slice, after which Surfdriver automatically generated 3D DXF-models. These models were post-processed in 3D Max and Cosmoworlds, resulting in VRML models ready for use in both conditions of the study phase. During the study phase, these models could be

explored by means of the Nvidia QuadroView 2.04 application. The introduction to the study phase, as well as the tests following the study phase, were run from two Pentium 4 computers with 17" monitors. Adobe's Authorware software was used to create the software part of this experiment, including study phases, experimental tests, and logfiles for each participant necessary for data-analysis.

3 Results

Accuracy for the mental rotation test (used as a proxy for visuo-spatial ability) and accuracy for both anatomical learning tests were transformed to proportions correct for easier interpretation. Boxplots for accuracy and latency on both anatomical learning tests, an identification test and a localization test, are given in Figure 4-3. To rule out a latency/ accuracy trade-off, correlations were calculated between latency and accuracy for both tests. A latency/ accuracy trade-off could not be ruled out for the localization test ($r = .41$, $p < .001$), consequently latency was taken on board as a covariate in the ANCOVA bearing on that test.

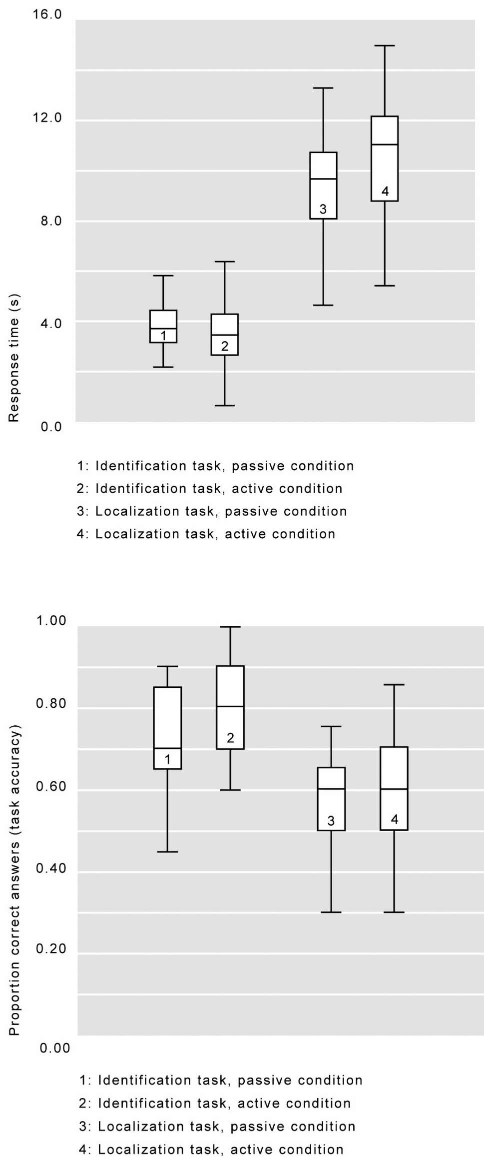


Figure 4-3. Boxplots show median, interquartile range and extreme values of both the accuracy- (bottom) and latency (top) scores, for each group and test.

All dependent variables were subjected to a Kolmogorov-Smirnov 1 test, no significant deviations from the normal distribution were found. Consequently, parametric tests were used for the statistical analysis. Two ANCOVAs were done with respectively identification test accuracy and localization test accuracy as dependent variables. For the identification test ANCOVA, between subjects factor was dynamic exploration (i.e., passive or active). Visuo-spatial ability (as measured by pretest accuracy) was used as a covariate. Visuo-spatial ability x dynamic exploration was calculated as well. For the localization test ANCOVA, dynamic exploration was again used as a between subjects factor. Latency and visuo-spatial ability were used as covariates. Visuo-spatial ability x dynamic exploration was used as an interaction variable. Results for these analyses are given in Table 4-1

Table 4-1 Analysis of Covariance results for post test accuracy (single tailed)

Source	*df*	*F*	*p*
Accuracy on the identification test (n = 70)			
Visuo-spatial ability (VSA)	1	4.81	.02
Dynamic exploration (DE)	1	3.01	.04
VSA x DE	1	1.05	.16
Accuracy on the localization test (n = 70)			
Visuo-spatial ability (VSA)	1	5.74	.01
Dynamic exploration (DE)	1	.04	.42
VSA x DE	1	.00	.47
Localization test latency	1	15.85	.00

4 Discussion

An experiment was reported that investigated the contribution of dynamic exploration during a study phase to anatomical learning, as measured by two anatomical tests. It was hypothesized that dynamic exploration would be beneficial to anatomical learning, especially for participants of low visuo-spatial ability. Dynamic exploration only affected the identification test, active participants performed significantly better on this test than passive participants. Localization test latency significantly affected localization test accuracy, which may have masked positive effects for dynamic exploration on this test. In earlier variations of this experiment, no such effect for latency was found. In future experiments latency will need to be controlled more strictly. The positive contribution of dynamic exploration to visuo-spatial learning represents an extension of earlier findings of James et al. (2001), who found a benefit for dynamic exploration to virtual learning on a recognition task, in a similar experimental paradigm.

Visuo-spatial ability significantly affected anatomical learning for all participants, on both post tests. No interaction effects were found for dynamic exploration and visuo-spatial ability, suggesting that the added value of dynamic exploration is similar for both people of high- and low visuo-spatial ability. This finding is in contrast with our earlier finding that a combination of stereopsis and dynamic exploration is more beneficial to learners of low visuo-spatial ability than to learners of high visuo-spatial ability (Luursema et al.2006, chapter 2 of this thesis). Effect magnitude of experimental treatment was largest for the combined stereopsis/ dynamic exploration study, mainly due to benefits of this combination for participants of low visuo-spatial ability. Apparently, learners of low visuo-spatial ability benefit most from an implementation of virtual anatomical learning that approaches natural exploratory behavior, extending the known benefits of combined stereopsis and dynamic exploration for task execution (Bradshaw et al., 2004) to visuo-spatial learning.

To bridge the gap between this ‘proof-of-principle’ study and the medical learning field, additional studies will have to be conducted with anatomical learning material more suitable to medical practice, and medical students or medical professionals as participants. We have however no reason to believe that basic learning mechanisms are different for medical professionals and our current participants.

In conclusion, dynamic exploration positively affects anatomical learning. Educational designers are well-advised to implement dynamic exploration in virtual learning environments that are meant to teach material of a complex visuo-spatial nature.

5. Visuo-spatial Ability in Colonoscopy Simulator Training

Abstract

Visuo-spatial ability is associated with a variety of surgical and medical skills. However, visuo-spatial ability is typically assessed using Visualization tests only, which led to an incomplete understanding of the involvement of visuo-spatial ability in these skills. To remedy this situation, the current study investigated the role of a broad range of visuo-spatial factors in colonoscopy simulator training. To this end, fifteen medical trainees (without clinical experience in colonoscopy) participated in two psycho-metric test sessions to assess four visuo-spatial ability factors. Next, participants trained flexible endoscope manipulation, and navigation to the cecum on the GI Mentor II simulator, for four sessions within one week. The 'Time on task' simulator performance measure was used for subsequent analysis. Visualization was the only visuo-spatial ability factor to correlate with 'Time on task' for both colonoscopy simulator training tasks, and additionally correlated with learning rate. High Visualization ability correlated with faster exercise completion.

Visualization is characterized by the ability to mentally manipulate complex visuo-spatial stimuli. The complexity of the visuo-spatial mental transformations required to successfully perform colonoscopy is likely responsible for the challenging nature of this technique, and should inform training- and assessment design.

Adapted from: Luursema, J. M., Buzink, S. M., Verwey, W. B., & Jakimowicz, J. J. (Accepted). Visuo-spatial Ability in Colonoscopy Simulator Training. *Advances in Health Sciences Education.*

1 Introduction

1.1 General introduction

Visuo-spatial ability is associated with a variety of surgical and medical skills (Hegarty et al., 2007). However, visuo-spatial ability is typically assessed using Visualization tests only. Since Visualization is but one of a number of factors that together make up visuo-spatial ability, more comprehensive studies are needed to assess the role of other aspects of visuo-spatial ability in medical skills. The study presented here is the first to investigate how a broad set of four critical visuo-spatial ability factors correspond to achievement in colonoscopy simulator training. This can inform both simulator software design and the design of tests specifically aimed at predicting an individual's success in acquiring skill in endoscopic surgery.

1.2 Visuo-spatial ability in surgery

A leading model of human cognitive abilities is John B. Carroll's Three Stratum Theory (Carroll, 1993). This three-tiered model, based on a re-analysis of over 400 datasets, holds that there is a first-tier general intelligence factor (*g*) that is defined as the shared factor loadings of second-tier factors such as verbal intelligence, analytical intelligence, and visuo-spatial ability. Each of these second-tier factors in turn is defined as the shared factor loadings of a number of third-tier factors. Third-tier factors are the ones that are measured by specific tests, e.g. Visualization (nested within the second-tier factor of visuo-spatial ability) is commonly measured with Vandenberg and Kuse's well-known Mental Rotation Test (Vandenberg and Kuse, 1978).

Visuo-spatial ability refers to the human cognitive ability to form, retrieve, and manipulate mental models of a visual and spatial nature (Lohman, 1979a). Carroll identifies five main third-tier factors nested within visuo-spatial ability, namely Visualization, Spatial relations, Speed of closure, Flexibility of closure, and Perceptual speed.

1. Visualization is the ability to manipulate complex mental representations of a visuo-spatial nature. Most research uses Visualization as a proxy for visuo-spatial ability. The relation between Visualization and surgical proficiency is consequently relatively well charted. Visualization correlates with Time on task for a number of laparoscopic tasks (Keehner et al., 2006; Risucci et al., 2001; Risucci et al. 2000), with quality of laparoscopic surgery as measured by rating scales (Keehner et al, 2004; Schueneman et al, 1984; Wanzel et al, 2003; Wanzel et al. 2002), and with quality of laparoscopic surgery as measured by simulator training outcomes (Eyal and Tendick, 2001; Hedman et al., 2006). Additionally, Risucci (2002) found that surgeons score higher on Visualization tests than a comparable normative sample from the general population.

2. Spatial relations is the ability to quickly manipulate simple mental representations of a visuo-spatial nature. This factor is thought to be similar to Visualization, but with more emphasis on speed, in relatively simple tasks. Ritter et al. (2006) found a correlation between Spatial relations and both duration of training and number of trials on a flexible endoscope simulator task (colonoscopy). Westman et al. (2006), Haluck et al. (2002), and Eyal and Tendick (2001) all found a significant correlation between quality in a number of surgical simulator training tasks and Spatial relations. Westman et al. found this for a colonoscopy simulator task, Haluck et al. and Eyal and Tendick for a laparoscopy simulator task.

3. Speed of closure refers to the ability to match incomplete stimuli to memory representations of the corresponding complete stimuli. Both Wanzel et al. (2003, 2002) and Risucci et al. (2002, 2001, 2000) use Speed of closure tests in their research. Risucci et al. studied laparoscopic simulator training tasks, Wanzel et al. studied non-endoscopic procedures. Only in Risucci's 2001 study a low, but significant correlation between Speed of closure and speed on several simulator dexterity drills was found. This factor seems to contribute little to surgical skill.
4. Flexibility of closure is the ability to identify given patterns in a cluttered visual environment. Steele et al. (1992), and Gibbons et al. (1986) found a significant correlation between Flexibility of closure and ratings of both quality of anastomoses on the porcine model and operating room performance. Schueneman et al. (1984) used Flexibility of closure tests as well, but found no significant correlations with operating room performance as measured by rating scales. Such contradicting results make it hard to assess the contribution of Flexibility of closure to surgical skill and surgical learning.

5. Perceptual speed refers to the ability to quickly identify a given shape from a number of alternatives. Perceptual speed has not been included in surgical training studies yet, as far as we know.

Concluding, there is good evidence for the involvement of Visualization and Spatial relations in surgical training, and some evidence against the involvement of Speed of closure in such training. Flexibility of closure and Perceptual speed remain little researched in this context. Specifically for *colonoscopy* training (studied here) only one study is known to us that investigates the relation between achievement in such training and visuo-spatial ability (by proxy of a Spatial relations test). The present study aims to develop a more complete understanding of the involvement of the various aspects of visuo-spatial ability in the development of endoscopic skill. Surgical curricula in an age of simulator technology need such knowledge to optimize both efficiency and effectiveness.

2 Materials and Methods

2.1 Participants

Fifteen medical trainees, five male and ten female, participated in this study. None of the participants reported clinical experience in colonoscopy. All participants were between 21 and 29 years of age, with a mean age of 25. All reported normal or corrected to normal vision. Prior to signing up, potential participants were informed on the nature of the study and the activities involved. They were also informed that all gathered data would be processed anonymously. All participants signed an 'informed consent' form.

2.2 Study protocol

Prior to performing on the simulator, the participant filled out a demographics questionnaire. Participants' visuo-spatial abilities were assessed in two sessions by a specially assembled test-battery (as described in paragraph 2.3). Both test-battery and questionnaire were filled out in group sessions. In the next stage, participants individually received a general introduction into colonoscopy, VR endoscopy simulators, and how to utilize the colonoscopy simulator instruments by means of a video prior to performing the first session, to ensure all participants would have a comparable basic level of knowledge and understanding. After this introduction, initial performance in basic colonoscopy skills was assessed using the GI mentor II simulator. Finally, all participants received colonoscopy training on this same simulator. In total, the training consisted of four simulator sessions performed within one week. Time needed to conclude one session was on average 45 minutes.

2.3 Psychometric assessment

Visuo-spatial ability was tested during two psychometric assessment sessions. Each session included five different tests measuring the visuo-spatial ability factors of Visualization, Spatial relations, Flexibility of closure, and Perceptual speed. To measure these abilities, two tests for each factor were administered, on separate occasions. This was done to compensate for intra-individual factors that might influence test results (e.g. lack of sleep). The test battery was administered in groups, in the period preceding the simulator training sessions. Example items of representative tests measuring these factors are given in Figure 5-1. A complete list of the tests used in this study can be found in the appendix.

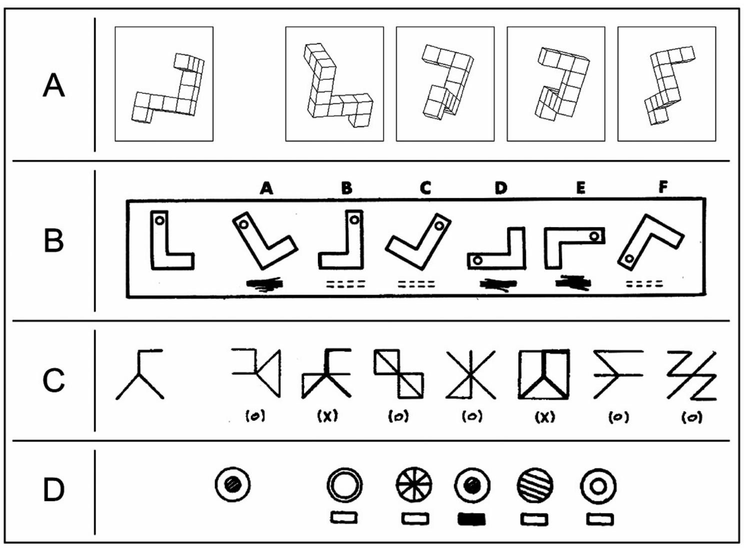


Figure 5-1. Example items of the four paper-and-pencil tests that were used to measure relevant factors of participants' visuo-spatial ability. All tests require the participant to identify a target figure shown to the left from a row of similar figures to the right. 'A' shows an example item from the Mental Rotation Test, measuring Visualization. 'B' shows an item from the Cards test, measuring Spatial relations. 'C', Hidden Objects measures Fluency of Closure. With items such as shown in 'D', Perceptual speed is measured.

2.4 Colonoscopy simulator training

Next, participants trained in flexible endoscope manipulation and navigation to the cecum (a pouch that marks the beginning of the large intestine) on the GI Mentor II simulator (see Figure 5-2A). Training consisted of four 45-minute sessions within one week (one per day). Each session involved two different tasks. The EndoBubble exercise (see Figure 5-2B) was combined with the task to reach the cecum in various VR-colonoscopy cases (VR stands for virtual reality, see Figure 5-2C) to provide training in, and objective assessment of, skills in basic camera navigation, instrument aiming, and bimanual instrument control.

In the EndoBubble exercise the participant navigated through a virtual tube as quickly as possible and popped as many balloons as possible with a virtual needle mounted on the tip of the flexible endoscope, without touching the wall. This task involved camera navigation, aiming, and bimanual instrument control in an abstracted environment. Performance measures for this task were total time, number of popped balloons, and number of times the wall was touched.

In the VR-colonoscopy exercises, the task was to navigate the camera through a virtual representation of a winding colon with peristaltic movement to the cecum as quickly as possible, with as little patient discomfort as possible. In this task, the participant also occasionally needed to apply torque to the endoscope shaft, or was confronted with looping of the colon. This system provides the following performance measures: total time, percentage of time the virtual patient was in pain (as given by the simulator software), percentage of time spent with a clear view (camera is aligned with motion path), and the number of times the camera lost its alignment with the motion path.

2.5 Data reduction

For both the EndoBubbles task and the VR-Colonoscopy task, ‘time on task’ was found to be the only useful training outcome measure. Other potentially interesting performance variables showed a ceiling effect, or where otherwise insufficiently differentiated. Consequently, only ‘time on task’ is used for the analysis reported in the results section.

The visuo-spatial test battery consisted of two tests for each of the five factors of interest in this study. For each individual, mean values of each of those five pairs of tests were calculated. No significant deviations from the normal distribution were found according to a Kolmogorov-Smirnov test, allowing the use of parametric tests.

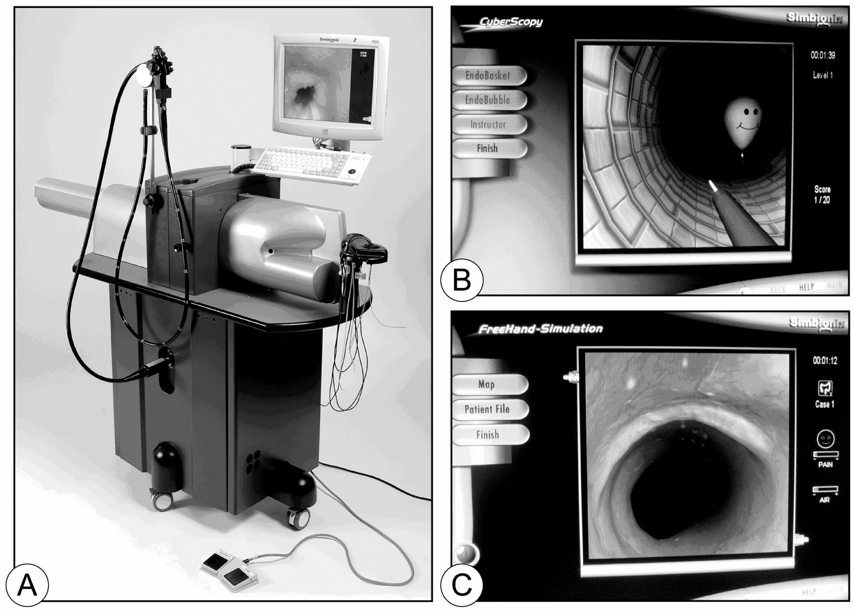


Figure 5-2. Overview and screenshots of the colonoscopy simulator training setup. Frame ‘A’ shows the simulator hardware. ‘B’ shows a scene of the EndoBubbles-task. Participants had to reach the end of the tunnel, and puncture all balloons on their way, without damaging the sides of the tunnel. ‘C’ shows an example of the VR-colonoscopy task. Participants navigated to the cecum and back again, as fast as possible, with as little discomfort as possible for the virtual patient.

3 Results

Means and standard deviations for Time on task are shown in Figure 5-3, for both colonoscopy simulator tasks. To verify the visually obvious learning effect, repeated measures ANOVAs were run for Time on task, for both simulator tasks. Session was used as repeating measure. The four cognitive ability factors described in section1.2 were used in these analyses as covariables, to assess the predicting value of these covariables on learning. Effects for both tasks were highly significant, F(1, 14) = 41.1, $p < .001$ for the EndoBubbles task, and F(1, 14) = 10.3, $p < .001$ for the VR-Colonoscopy task, confirming that participants became faster on both tasks. A significant between subjects effect for Visualization was also found for both tasks, F(1, 14) = 10.7, $p < .01$ for the EndoBubbles task, and F(1,14) = 8.6, p < .02 for the VR-Colonoscopy task.

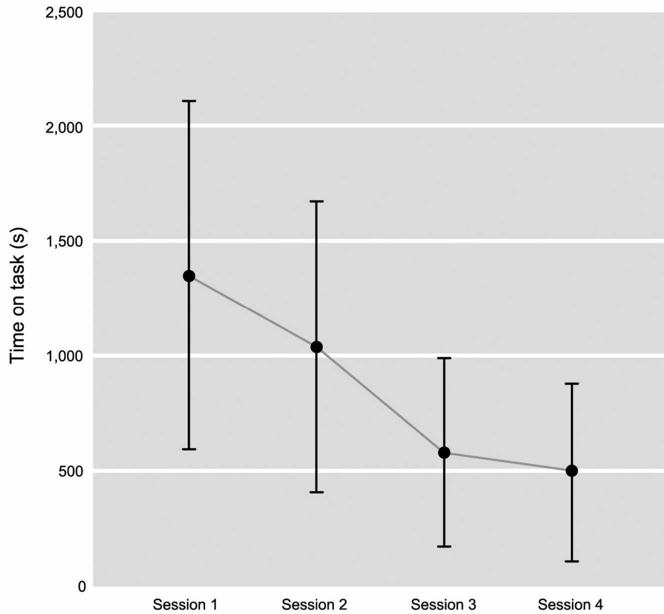
This means that for both tasks participants of high Visualization ability improved faster on Time on task compared to participants of low Visualization ability.

Additionally, to assess the effect of the four cognitive ability factors on Time on task, correlations were calculated for these variables (Table 5-1). Time on task was derived by taking the means of all sessions. For the EndoBubble task, only Visualization correlated significantly, and negatively, with Time on task (i.e., the better participants scored on the Visualization tests, the faster they performed the simulator tasks). For the VR-Colonoscopy task, again only Visualization correlated significantly, and negatively, with Time on task.

Table 5-1. Correlations between the four visuo-spatial ability factors and Time on task for both colonoscopy simulator training tasks.

Time on task	Visualization	Spatial relations	Speed of closure	Perceptual speed
		Participants (n = 15)		
EndoBubbles	-.61*	.25	-.18	-.03
VR-Colonoscopy	-.69**	-.30	-.31	.27

* significant at the .05 level; ** significant at the .01 level



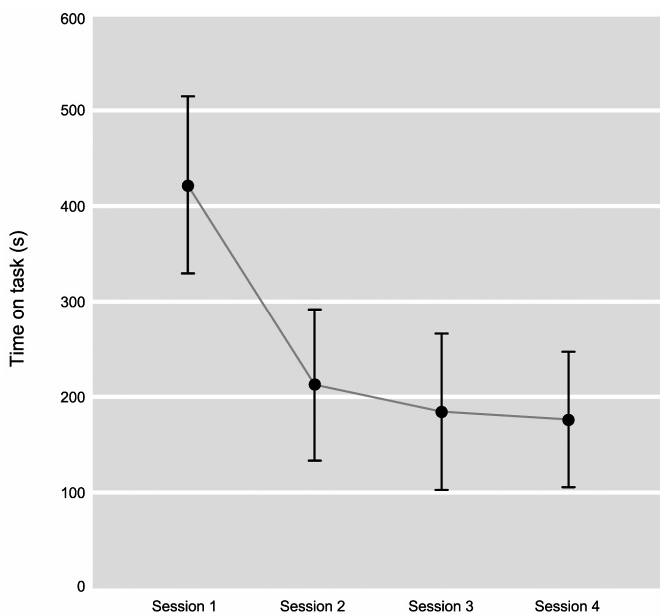


Figure 5-3 Means and standard deviations for Time on task, for all sessions of both simulated colonoscopy tasks. Top: VR-colonoscopy task, bottom: EndoBubbles task.

4 Discussion

Visualization, as measured by Vandenberg and Kuse's mental rotation test (Vandenberg and Kuse, 1978) and Guay's visualization of viewpoints test (Guay and Mc Daniels, 1976), was found to be important for performance on colonoscopy simulator training, in this study correlating with performance on the Time on task measure. Visualization also covaried with learning rate for both simulator training tasks, as assessed by a repeated measures analysis for Time on task. Stefanides et al. (2006) report a similar finding for two cognitive ability factors that are somewhat visuo-spatial in nature, but strictly speaking fall in the domains of Memory and Reasoning. The importance of the visuo-spatial factor of Visualization for colonoscopy learning rate represents a novel find, indicating fewer training sessions for high scorers on this ability to attain the same level of skill as low scorers. Given the relationship between Visualization and endoscopic proficiency (see section 1.2 of this chapter), this finding likely generalizes to learning rate in other endoscopic domains.

Contrasting Visualization to other visuo-spatial ability factors, the defining characteristic of Visualization is high stimulus complexity (Vandenberg and Kuse, 1978; Hegarty and Waller, 2005). The ability to mentally manipulate complex visuo-spatial structures is critical to early colonoscopy training performance. The specific cognitive speed and memory demands of other visuo-spatial factors are less involved in performance in this training. Future work in the construction of visuo-spatial tests aimed at predicting endoscopic performance should benefit from including requirements of stimulus complexity. Such requirements can also be instrumental in performing the task analyses necessary for designing and building endoscopic simulator training software.

A drawback of this study is that only early learning was studied, long term studies are needed to assess the role of visuo-spatial ability in different learning stages. In many professions that demand highly skilled visuo-motor performance, typically automation of these skills takes place over time, perhaps reducing the demands on the higher cognitive abilities of its practitioners (sports, music). Surgery differs in that there is a large degree of unpredictability with each new case. Automation will still take place, but the role of visuo-spatial ability is likely to stay important. This is corroborated by Keehner et al.(2006), in a study in which general reasoning demands taper off after early training, but visuo-spatial ability remains important.

An additional question is why we should be interested in visuo-spatial ability over other cognitive abilities in the context of surgical training. Surely endoscopic skills also demand high reasoning ability, memory ability, etc, from its practitioners! We would like to speculate that by the time students of medicine start their residencies, their prior education already pretty much has functioned as a filter for those other relevant abilities. In contrast, visuo-spatial ability only starts playing a major role during one's residency, but has up to that point pretty much flown 'under the radar', so to speak. If this were the case, a major improvement over current educational practice would be the inclusion early in the medical curriculum of assignments that can only be successfully concluded if visuo-spatial demands are met.

6. Visuo-spatial Ability and Memory in Laparoscopic Simulator Training

Abstract

Visuo-spatial ability has been shown to be important to several aspects of laparoscopic performance, including simulator training. However, only a limited subset of visuo-spatial abilities has been used in such studies. Tests for different visuo-spatial ability factors differ greatly in stimulus complexity and the demands they make on speed of processing. To help clarify the involvement of visuo-spatial ability in laparoscopic performance the current study investigated the role of four visuo-spatial ability factors and two memory factors in different phases of surgical simulator training. Twenty four students participated in a two-month course, consisting of eight weekly, half-hour Laparoscopic simulator training sessions. Before the start of this course four visuo-spatial ability factors and two memory factors were measured. Simulator performance variables were (task) Duration, Motion efficiency, and Damage. Early learning (first three sessions) was characterized by significant improvements in all performance variables, while during late learning (last three sessions) only Duration continued to decrease. Late learning Damage fluctuated greatly. The involvement of visuo-spatial ability in laparoscopic training performance was found to be more complex than estimated before. The inconsistency of late learning Damage suggests an explicit damage criterion might be a well-advised addition for surgical simulator training, speed and efficiency being more natural goals in such settings.

Adapted from: Luursema, J. M., Verwey, W. B., & Burie, R. (Submitted). Visuo-spatial ability and Memory in Laparoscopic Simulator Training. *Medical Education*.

1 Introduction

1.1 General

Simulator technology is rapidly becoming an important asset of surgery training (Kneebone, 2003; Dawson and Kaufman, 1998). Especially laparoscopic surgery, which requires considerable skill but is relatively easy to simulate, has proven to benefit from simulator training.

A number of studies investigated the validity of surgical simulator training, and showed that performance measures derived from such simulators can differentiate between experienced surgeons and novices (Eriksen and Grantcharov, 2005; Felsher et al., 2005; van Dongen et al., 2007). More importantly, there is transfer from simulator training to performance in the operating room (Ahlberg et al., 2007; Grantcharov et al., 2004), and to surgical performance on live animal models (Hyltander et al., 2002).

A better understanding of the role cognitive abilities play in the development of surgical skills is likely to inform system design in this area. For instance, students of low visuo-spatial ability may benefit from learning materials that make a larger effort to visualize challenging anatomical information. Also, different phases in the development of surgical skill likely involve different cognitive abilities to a different degree. This is relevant to design aspects such as learner feedback, training schedule, the breakdown of training tasks, etcetera.

In a pioneering study, Keehner and her colleagues investigated the contributions of visuo-spatial ability and reasoning ability to learning a spatial skill using an angled laparoscope in a virtual reality training environment (Keehner et al., 2006). In theories of skill acquisition (Anderson, 1982; Fitts, 1964), increasing automation of skills over time is posited, from an initial phase that involves extensive cognitive control, through a phase where skill-related actions are collated in chunks to the final phase where the learned skills are fully automatic. Reasoning ability is thought to give a good indication of someone's general cognitive ability, and therefore should be a good indicator for early phase learning, but not for late phase learning. Confirming Keehner et al.'s expectations, reasoning ability only correlated with skill over the first couple of sessions. Surprisingly, in Keehner et al.'s study visuo-spatial ability remained important over all twelve training sessions. The authors explain this by assuming that some elements of the task under study do not automate, and necessitate an ongoing involvement of visuo-spatial ability.

The current study extends the paradigm of Keehner et al. for different laparoscopic training tasks, by using a more comprehensive battery of visuo-spatial ability tests, and by using duration, damage, and motion efficiency as performance measures, rather than only duration. This allows for more detailed inferences on what aspects of visuo-spatial ability contribute to which aspects of laparoscopic skill. Memory factors rather than reasoning ability were taken into account as an indicator of general cognitive ability. Rationale for this choice was the likeliness that memory, rather than reasoning ability would be involved in learning the procedural aspects of the tasks used in this study. Those tasks differ from real-world tasks in that there is no necessity to be aware of underlying (medical) factors that would complicate decision making during actual laparoscopic surgery.

1.2 Cognitive abilities

Where most of psychology is interested in the commonalities between people, research into cognitive abilities has been driven by an interest in individual differences. Factor-analytic research has enabled workers in this field to differentiate between several cognitive abilities, and to arrange those in a three-tiered, hierarchical model of general to specific cognitive abilities (Carroll, 1993). The top tier is represented by a single factor, g, or general intelligence, which is defined as the shared factor loadings of a number of second tier factors such as verbal intelligence, numerical ability, visuo-spatial ability, and memory. These second tier factors in turn are each composed of a number of third tier factors, e.g. visuo-spatial ability consists of the shared factor loadings of the factors Visualization, Spatial relations, Perceptual speed, Flexibility of closure, and Speed of closure. Third tier factors are the ones that are actually measured by validated tests, after which the higher level factors are derived from the resultant data.

Three sources of individual differences have caught the attention of researchers interested in the relation between individual differences and surgical performance; these are manual dexterity, personality, and visuo-spatial ability. Research in manual dexterity has so far not led to any evidence of involvement of this factor in surgical performance (Bann and Darzi, 2005). Personality factors such as extroversion have been shown to correlate with being a surgeon (McGreevy and Wiebe, 2002), yet it is unclear how this should inform surgical training, or practice. Visuo-spatial ability has been successfully linked to a variety of surgical and medical skills (A useful overview is published by Hegarty et al., 2007). Below, an introduction is provided into visuo-spatial ability in light of surgical training, leading to an outline of the current study.

1.3 Visuo-spatial ability

Visuo-spatial ability refers to the human cognitive ability to form, retrieve, and manipulate mental models of a visual and spatial nature (Lohman, 1979a). Carroll identifies five main factors that together form visuo-spatial ability (Carroll, 1993). These are Visualization, Spatial relations, Speed of closure, Flexibility of closure, and Perceptual speed.

1. *Visualization* is defined as the ability to manipulate complex mental representations of a visuo-spatial nature. Most research takes Visualization as a proxy for visuo-spatial ability as a whole. The relation between Visualization and surgical performance is therefore relatively well charted. Visualization correlates with speed for a number of surgical and laparoscopic tasks (Keehner et al., 2006; Risucci et al., 2001; Risucci et al., 2000). Visualization correlates also with surgical quality as measured by rating scales (Keehner et al., 2004; Schueneman et al., 1984; Wanzel et al., 2002; Wanzel et al., 2003), and with surgical quality as measured by simulator training outcomes (Eyal and Tendick, 2001; Hedman et al., 2006). Additionally, Risucci (2002) found that surgeons score higher on Visualization tests than a comparable normative sample from the general population.

2. *Spatial relations* indicates the ability to quickly manipulate simple mental representations of a visuo-spatial nature. Ritter et al. (2006) find a correlation between Spatial relations and both duration of training and number of trials (to criterion) on a flexible laparoscope simulator task. Westman et al. (2006), Haluck et al. (2002), and Eyal and Tendick (2001) all reported a significant correlation between surgical simulator performance and Spatial relations.

3. *Speed of closure* is defined as the ability to match incomplete stimuli to memory representations of the corresponding complete stimuli. Both Wanzel et al. (2002; 2003) and Risucci et al. (2001; 2000; 2002) use Speed of closure tests in their research. Only in Risucci's 2001 study a low, but significant correlation between Speed of closure and task-on-time on several simulator dexterity drills was found. This factor seems to contribute little to surgical skill.

4. *Flexibility of closure* indicates the ability to identify given patterns in a cluttered visual environment. Steele et al. (1992), and Gibbons et al. (1986) found a significant correlation between Flexibility of closure and quality of surgical procedures as measured by rating scales. Schueneman et al. (1984) used Flexibility of closure tests as well, but found no significant correlations. The contribution of Flexibility of closure to surgical skill is unclear but seems limited.

5. *Perceptual speed*, the ability to quickly identify a given shape from a number of alternatives, has not been included in surgical training studies yet, as far as we know. This is somewhat surprising since, given the time critical nature of surgery, Perceptual speed may well be an important cognitive ability for the surgical practitioner.

In addition to these visuo-spatial factors, Carroll discusses V*isual memory* as a memory factor. Visual memory is defined as the ability to correctly identify visual stimuli presented earlier from a mix of those earlier stimuli and novel ones. This classification is somewhat arbitrary since, as Carroll notes, tests for the factor of Visual memory tend to have a high loading on the visuo-spatial factors Visualization and Spatial relations. Visual memory is therefore included in the current discussion on visuo-spatial ability. Indeed, Haluck et al. (2002) found a significant correlation of a Visual memory test with a performance measure in an Endotower simulation task, but Wanzel et al. (2002) found no significant correlation. Little is known yet as to the contribution of Visual memory to learning surgical skills.

Concluding, there is good evidence for the involvement of Visualization and Spatial relations in surgical performance, and some evidence against the involvement of Speed of closure in such performance. Fluency of closure, Perceptual speed, and Visual memory are little researched in this context. The present study aims to remedy this by assessing correlations between performance on two surgical simulator tasks and the third-tier visuo-spatial ability factors Visualization, Spatial relations, Flexibility of Closure, and Perceptual speed. Speed of closure was excluded in light of the negative findings in the literature.

In addition the third-tier memory factor Memory span was tested, in order to learn about this factor's involvement in different phases of the simulator training process. Involvement of memory (measured by Memory span and Visual memory tests) was expected early in training, reflecting the demands of not yet automated skills in performing a high level, complex task (Fitts, 1964; Perlow et al., 1997). Visuo-spatial factors were expected to stay important throughout training, reflecting content specific task demands (Keehner et al., 2006).

2 Method

2.1 Participants

Twenty four students of the Technical Medicine programme at the University of Twente participated in this study, nineteen female and five male. All were either twenty one or twenty two years of age, and inexperienced with any form of Laparoscopic technique. All reported normal or corrected to normal vision. Participation was a required part of the curriculum. An informed consent form was signed by all participants.

2.2 Procedure

Prior to the simulator training sessions, subjects participated in two group sessions to assess their cognitive abilities thought relevant to surgical training and practice, as outlined in the introduction. During the first of these hour-long sessions, paper-and-pencil tests for the cognitive abilities of Visualization, Spatial relations, Fluency of closure, Perceptual speed, Visual memory, and Memory span were administered. A demographics questionnaire was also part of the first session. During the second session, different tests for the same six abilities were administered. The mean of each pair of tests for a specific cognitive ability was taken as an indicator for that ability. Sample items of tests representing each factor are shown in Figure 6-1. Not shown in this figure is a representative item from the Memory span tests, those tests being auditory in nature. For each item of these tests, a list of five to thirteen numbers or letters is said out aloud, at a pace of one symbol per second. Then the experimenter says 'start' after which the participants need to write down the complete string of symbols, in the correct order. A complete list of the tests used to assess these abilities can be found in appendix.

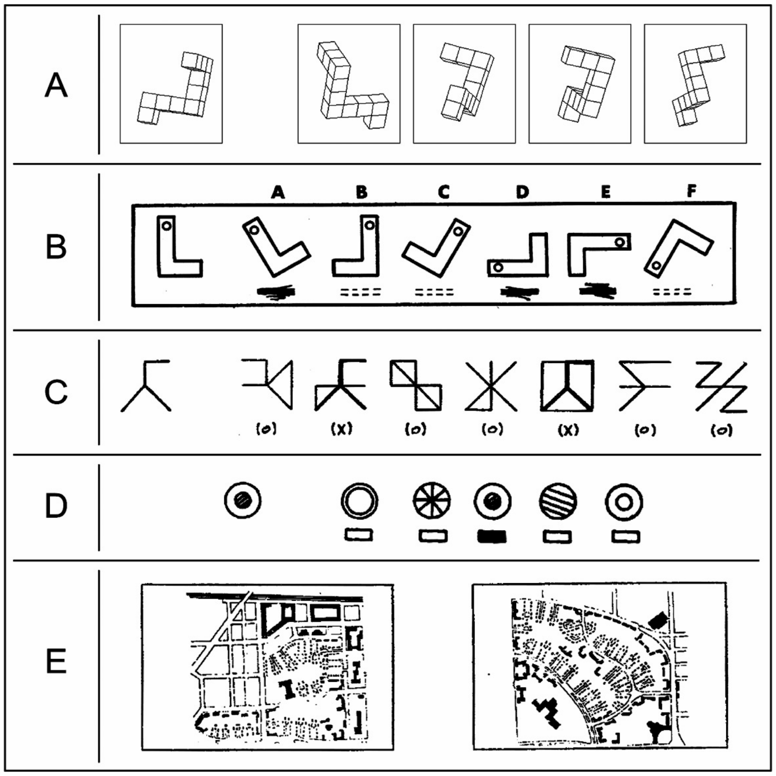


Figure 6-1. Sample items of five of the ten paper-and-pencil tests that were used to measure the four visuo-spatial ability factors and single memory factor. 'A' shows an example item from the Mental Rotation Test, measuring Visualization. Subjects mark two objects from a row of four that show the identical, but rotated, item shown to the left. 'B' shows an item from the similar Cards test, measuring Spatial relation. 'C', Hidden Objects, employs a similar procedure. Here the subjects have to mark those figures that contain the example figure at the left. Fluency of closure is the name of the factor measured by this test. With items such as shown in 'D', Perceptual speed is measured. 'E', measuring Visual memory, shows two map-like pictures. Subjects study a series of sixteen pictures similar to these, and are then presented with a new paper showing again sixteen map-like pictures. Participants mark the pictures that they already studied in the memorization phase.

The actual simulator training sessions took place over a time span of two months, during which each participant engaged in eight weekly, half-hour long training sessions. Two standard exercises that come with the LapSim laparoscopic simulator training hardware were selected for the current study; *Grasping*, and *Instrument Navigation*. They were selected for their generic nature, and for the convenience of offering the same task alternately for both left and right hand, thus offering a similar challenge for both left handed and right handed participants. Grasping and Instrument Navigation were offered in two levels of difficulty. The simulator setup is shown in Figure 6-2.

During the Grasping exercise both hands operate a virtual grasping tool, with a green tip for the right hand tool, and a red tip for the left hand tool. Target objects in this exercise are small blood vessel-like structures of limited length that appear one at a time, and that need to be pulled from their abdominal cavity-like embedding. The structures are colour-coded red or green, to indicate the grasper that needs to be used. After successful removal of the vessel it needs to be transported to a spherical goal object.

Figure 6-2. The LapSim laparoscopic simulator used in the experiment.

Touching of the two objects makes the vessel disappear, and a new vessel appears elsewhere. The difficult task version includes rotated camera angles and smaller targets.

Instrument Navigation comes with identical left- and right hand tools, the tool being a blunt ‘probing device’. Again the instrument tip is colour coded green for the right hand instrument, and red for the left hand instrument. Target spheres appear colour coded to indicate the tool that needs to be used to touch this object. After successful contact is established the target object disappears, and a new target object appears elsewhere. To create the difficult version of this task, rotated camera angles, camera movement, and smaller targets were included.

2.3 Apparatus

The experimental training set-up consisted of Immersion’s VLI hardware, connected to a Pentium 4 CPU 3.00 GHz, 504 MB RAM computer running Windows XP. A 19” TFT monitor provided visual feedback to the participant (Figure 6-2). Surgical Science’s LapSim v.3.0.10 was used as training software.

2.4 Data reduction

Participants trained individually on a LapSim laparoscopic simulator, on two different tasks, each in an ‘easy’ and a ‘difficult’ version. The ‘easy’ versions of the tasks proved too simple and performance was always maximal. Therefore these were dropped from further analyses. Consequently, only data for the difficult versions of Grasping and Instrument navigation were retained for analysis.

For each task, a number of performance variables was logged. Correlations were calculated for the performance variables of each task and session, and all performance variables were pooled into three compound performance variables on basis of their mutual correlations (variables were pooled when correlations were .6 or more across all sessions). This led to the compound performance variables Duration, Damage, and Motion efficiency. The compound Damage variable was calculated from the simulator-supplied variables ‘Tissue damage’ and ‘Maximum damage’. No information was supplied by the manufacturer on how these two damage variables are derived from participants’ performance. Motion efficiency was calculated from ‘Instrument path length’ and ‘Instrument angular path’, for both the left- and the right hand. Duration represents the addition of 'Left hand time' and 'Right hand time'. The basic performance variables underlying Damage and Motion efficiency were in different units of measurement. Therefore, clustering was achieved by the following four steps: (1) Same variables for all sessions were collated to single variables overarching all eight sessions (e.g., the variables ‘Tissue damage week 1-8’ and ‘Maximum damage week 1-8’ became ‘Tissue damage all’ and ‘Maximum damage all’). (2) The resultant variables were transformed to z-scores. (3) The z-scores of the relevant performance variables were averaged (e.g., the mean of the z-values for ‘Tissue damage all’ and ‘Maximum damage all’ was taken to derive as single ‘Damage all’ variable), and (4) the resulting three variables were split back to session-by-session variables (e.g., ‘Damage all’ was split into ‘Damage week 1', 'Damage week 2', ..., 'Damage week 8'’). In this way, differences in both means and variances between sessions were retained.

This reduction procedure was executed for both the Grasping- and the Instrument manipulation task, resulting in a pair of similar performance variables. The mean of each pair was used in the statistical analysis (e.g. ‘Damage Grasping’ + ‘Damage Instrument navigation’; divided by two makes ‘Damage’).

If a participant scored an extreme value (>3SD) on any of the three simulator training variables, this led to removal of all data for that participant on the indicated task, for the session where the extreme value was scored. If extreme values for a specific task were scored on three or more consecutive sessions, data from all sessions for this task were removed for that participant. Only one participant consistently scored extreme values in this last manner (and for all tasks). Consequently, all data for this participant were removed from the dataset. The procedure outlined in this paragraph led to a data loss of five percent. The analyses presented in section 3 are based on data from the resulting 23 participants.

None of the derived variables (the Duration, Damage, and Motion efficiency variables for the surgical simulator training tasks and the Visualization, Spatial relations, Fluency of closure, Perceptual speed, Visual memory, and Memory span variables resulting from the cognitive abilities test battery) did not significantly deviate from the normal distribution, as assessed by the Kolmogorov-Smirnov-1 test, implying that variances analyses can be used.

3 Results

To assess training effects, a repeated-measures ANOVA was done separately for all three performance variables, over all eight sessions. Significant changes across blocks were observed for all three variables [Duration $F(7, 16) = 118.2$, $p < .01$; Motion efficiency $F(7, 16) = 38.2$, $p < .01$; and Damage $F(7, 16) = 8.7$, $p < .01$]. Learning was observed for Duration and Motion efficiency (respectively shorter and more efficient), Damage lessened over the first three sessions, but then increased and diminished again over the resulting five sessions (Figure 6-3).

To analyse the relationship of cognitive abilities with performance on the simulator training outcome variables, repeated measures ANCOVAs were performed separately for the *early learning* and *late learning* phases of each performance variable, with cognitive abilities as covariates. The first three training sessions were labelled *early learning*, the last three sessions were labelled *late learning*. Thus, 6 repeated measures ANCOVAs were performed, each spanning three sessions and each involving six covariates.

Early learning phases for all performance variables involved significant changes, in the direction of shorter duration, greater motion efficiency, and less damage respectively. A significant late learning change was only found for Duration, towards shorter duration (Figure 6-3). Involvement of cognitive abilities was only found for early learning Damage and early learning Motion efficiency. Memory span covaried with early learning for Damage and Motion efficiency, the latter covaried furthermore with Visualization and Perceptual speed (Table 6-1). Duration did not covary with any cognitive ability factor, although a tendency in that direction was found for Visualization and early learning phase Duration ($F = 2.37$, $p = .06$, single tailed). Higher cognitive ability always coincided with better performance.

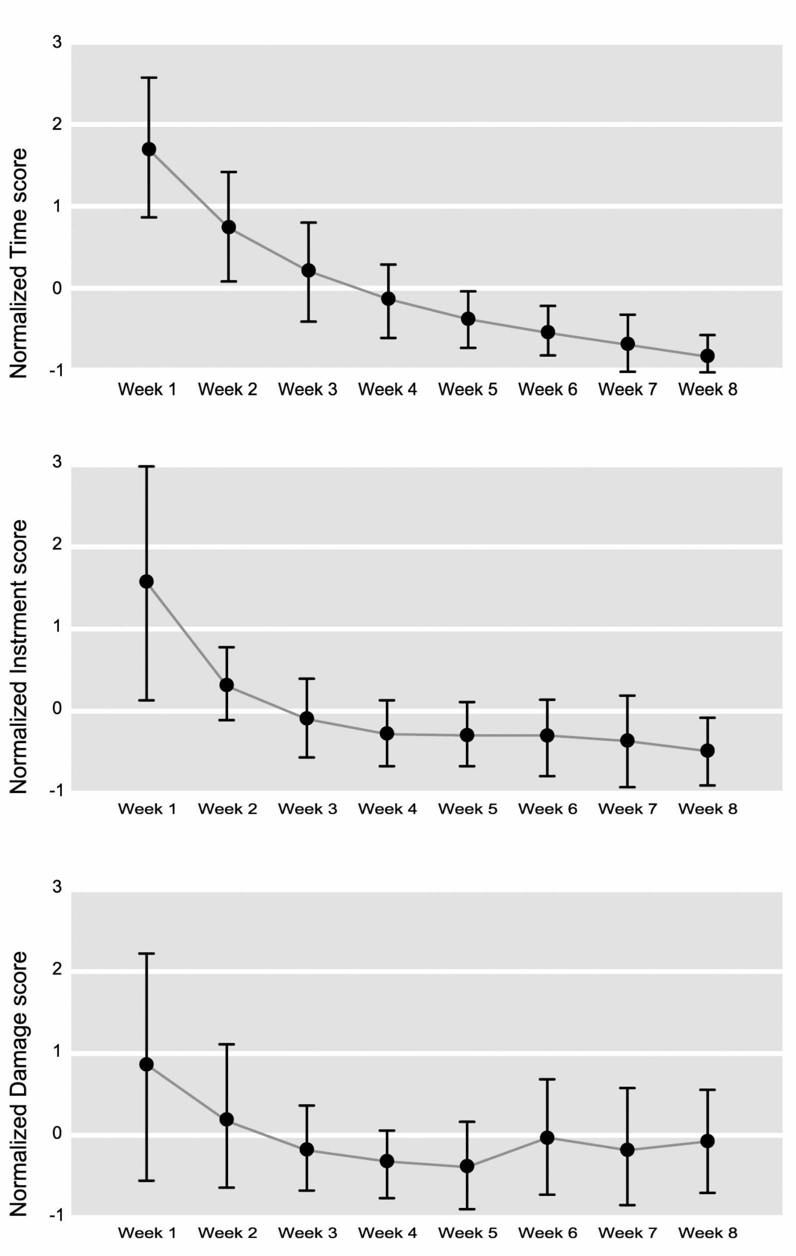


Figure 6-3. Learning curves of the three performance measures for the simulator training in terms of z-scores (see 'Method' section).

4 Discussion & conclusions

4.1 Discussion

The current study investigated the contribution of visuo-spatial ability and memory to performance in both early- and late surgical simulator training. Three performance variables (Duration, Motion efficiency, and Damage) were correlated with four visuo-spatial ability factors (Visualization, Spatial relations, Fluency of closure, and Perceptual speed) and two memory factors (Memory span and Visual memory). The results for each of these performance variables will be discussed below.

Participants improved both during early training Duration (first three sessions) and late training Duration (last three sessions). In contrast to Keehner et al's (2006) results, who found Duration and Visualization to be correlated throughout training in a long term laparoscopic training paradigm, no involvement of visuo-spatial ability on Duration was found in the current study, although a tendency towards such involvement was noted for Visualization in early training Duration. Our study might have been insufficiently powered to duplicate Keehner et al.'s results.

Table 6-1 Repeated measures ANCOVA for all performance variables, split in early learning (first three sessions of eight) and late learning phases (last three sessions of eight), with cognitive abilities as covariables (in bold, single-tailed). Only significant results are shown.

Source	***df/df Error***	***F***	***p***
	Duration early learning (n = 23)		
Duration early learning	2/15	79.02	.00
	Motion efficiency early learning (n = 23)		
Motion efficiency early learning	2/15	40.31	.00
Visualization	2/15	4.49	.02
Perceptual speed	2/15	3.63	.02
Memory span	2/15	5.23	.01
	Damage early learning (n = 23)		
Damage early learning	2/15	9.00	.00
Memory span	2/15	3.14	.03
	Duration late learning (n = 23)		
Duration late learning	2/15	7.25	.00

Only early training Motion efficiency reached significance. Early Motion efficiency covaried with Memory span, Visualization, and Perceptual speed. The early involvement of Memory span likely reflects the demands of not yet automated skills in performing a high level, complex task (Fitts, 1964; Perlow et al., 1997). The involvement of both Visualization and Perceptual speed, but not Spatial relations or Fluency of closure remains somewhat enigmatic. As contributing factors to visuo-spatial ability, Visualization is thought to emphasize an ability to mentally manipulate complex visuo-spatial stimuli, whereas Perceptual speed emphasizes the ability to mentally manipulate simple visuo-spatial with speed (Carroll, 1993). Spatial relations and Fluency of closure fall in between on this speed-complexity continuum.

If both speed and complexity are important factors in motion efficiency, one would expect more visuo-spatial factors to reach significance, notably Spatial relations, since this factor is thought to be very similar to Visualization, mainly differing in stimulus complexity (Carroll, 1993). That this is not the case might point towards the contribution of yet unknown variable(s). Our understanding would greatly benefit from research that aims to better control the performance variables inherent to laparoscopic training tasks, trading ecological validity for experimental control. Especially visuo-spatial stimulus complexity is not well understood, and the benefits of a better understanding would extend beyond laparoscopic training to training in general.

Early training Damage reached significance, and covaried with Memory span, but not with any other cognitive ability. The involvement of Memory span likely reflects the procedural demands of early training, demands that diminish during later training phases. After an initial phase with diminishing damage, damage values started to fluctuate in a seemingly random manner over the remaining sessions. Simulated patients are very complacent, not likely to return with complications, and obviously not capable of suffering. Therefore, damage in simulated patients might be assessed differently by trainees than damage in real patients. An explicit damage criterion for simulator training would remedy this.

4.2 Conclusions

In Keehner's study (2006), only Duration was used as a measure for surgical quality. The results of the current study show a more complex picture of the relationship between visuo-spatial ability and surgical performance in that different performance variables in laparoscopic surgery training correlate with different visuo-spatial ability factors. A broader range of surgical training tasks need to be studied with respect to the involvement of visuo-spatial ability. The results of such studies will help us understand the individual and environmental variables involved in high quality laparoscopic performance, which in turn can inform learning environment design and admission criteria for surgical curricula.

7. Summary, Discussion, and Conclusion

1 Introduction

Medical training is in transition. As described in chapter 1, electronic learning environments such as virtual anatomical learning environments and endoscopic simulators are catalysts in this change. Individual differences in cognitive abilities (most notably visuo-spatial ability) are involved in the development of both anatomical knowledge and surgical skill. Aiming to help understand and optimize this new situation the following questions guided the research described in this thesis:
1) How does visuo-spatial ability interact with computer implemented stereopsis and dynamic exploration in the domain of virtual anatomical learning?
2) How do the different components of visuo-spatial ability correlate with different endoscopic simulator performance measures such as Duration, Motion efficiency and Damage, in different learning stages?
Summaries and discussions are provided separately for the research resulting from those questions, starting with the virtual anatomical learning studies. The chapter ends with a general conclusion.

2 Virtual anatomical learning

2.1 Summary

Three studies are reported in this thesis investigating the effects of stereopsis, dynamic exploration, and visuo-spatial ability on virtual anatomical learning. Stereopsis and dynamic exploration are features associated with traditional anatomical learning through dissection. These features can be implemented in virtual learning environments, but such implementation comes at extra costs, both in hardware and in software development. Since the cognitive ability of visuo-spatial ability is involved in visuo-spatial learning (such as anatomical learning) we thought it useful and interesting to measure this ability in our participants. People of differing visuo-spatial ability might be affected differently by computer-implemented stereopsis and dynamic exploration.

All three studies were designed similarly: first relevant individual differences (such as visuo-spatial ability) were measured, then participants studied virtual anatomy in one of two conditions, and lastly their knowledge was assessed in two tests of a visuo-spatial nature. Participants were assigned to a condition based on their visuo-spatial ability scores.

In the first of these studies, one condition involved a combination of computer involved stereopsis and dynamic exploration, and the other condition involved no stereopsis and very limited interactivity. Overall, participants benefitted from the stereopsis + dynamic exploration condition. This was mainly caused by participants of low visuo-spatial ability performing on par with their high visuo-spatial peers in this condition.

The second study contrasted a condition with computer-implemented stereopsis with a non-stereoptic condition. The same 3D anatomical reconstruction was studied as in the first experiment, only now in an autorotating version (no dynamic exploration). Again, over all conditions visuo-spatial ability correlated anatomical learning. A benefit from the stereoptic condition was found for one of the post tests, confirming that stereopsis is partly responsible for the beneficial effect of the combined stereopsis/ dynamic exploration condition of the first experiment. Contrasting to the first study, no significant interaction effect was found for visuo-spatial ability and experimental condition.

The third study explored the role of dynamic exploration in virtual anatomical learning, and to this end a yoked study design was adopted. This means that for the study phase, pairs were formed of equal visuo-spatial ability. One member of the pair dynamically explored virtual anatomy, while the other member of the pair passively watched the active member's explorations (on a separate screen, to minimize changes of participants being aware of being in a different study condition). Similar to the second (stereopsis) study, visuo-spatial ability correlated with post test scores. Additionally, a slight benefit of the active condition was found for the identification post test scores. Again, no significant interaction effect was found for visuo-spatial ability and experimental condition.

2.2 Discussion

As a general conclusion, these experiments confirm that high visuo-spatial ability leads to better anatomical learning (as found for virtual anatomical learning by Garg et al., 1999, 2001, 2002; and for traditional anatomical learning by Rochford, 1985). In the first anatomical learning study, a combination of computer implemented stereopsis and dynamic exploration actually led participants of low visuo-spatial ability to perform on par with their high visuo-spatial counterparts. For students of low visuo-spatial ability, a combination of computer implemented stereopsis and dynamic exploration leads to better learning than either of those alone. This is likely caused by this condition's similarity to real world object manipulation, where stereopsis and prehension are functionally coupled (Servos et al. 1992; Bradshaw et al., 2004). For people of high visuo-spatial ability it didn't matter whether they studied with stereopsis and dynamic exploration or not, as the reduced condition offered enough information for them to form an adequate mental model.

A limitation of the anatomical learning studies reported in this thesis is their low ecological validity. The virtual anatomical learning task used here was designed (simplified) for participants naive to human anatomy, and was not part of a specific medical course or curriculum. To find out whether people of low visuo-spatial ability can be sufficiently supported to perform on par with their high visuo-spatial counterparts in a visuo-spatially demanding professional setting, the type of studies outlined above would need to be repeated with learning materials similar to those used in anatomy departments, with actual medical students, and post-tests similar to real-world tasks, involving visuo-spatial knowledge of anatomy (interpreting CT-imaging or ultrasound images would make a great candidate). If such studies support the notion that initial high quality learning of anatomical information is sufficient for real-world performance, then people of low visuo-spatial ability could continue to be included in the relevant curricula. Provided of course they get enough opportunity to form an appropriate visuo-spatial model of the (patient specific) anatomy they are going to encounter.

Finally, it must be noted that visuo-spatial ability was assessed by the Mental Rotation Test (Vandenberg and Kuse, 1978; Peters, 1995), which measures the visuo-spatial factor of Visualization, which is only one of five factors together forming visuo-spatial ability. This test was used as a proxy for visuo-spatial ability to conform to most research in this area that also tends to use Visualization as a proxy for visuo-spatial ability. This makes it easier to compare our results to other research. The factor Visualization measures the ability to manage visuo-spatial complexity, whereas other visuo-spatial factors are more involved in pattern recognition or perceptual speed. Whether such other visuo-spatial ability factors impact (virtual) anatomical learning remains at present unknown, but is an empirical question.

Hence, the present research shows that in virtual learning environments that aim to teach a visuo-spatial understanding of challenging anatomical concepts, people of low visuo-spatial ability benefit from a combination of computer-implemented stereopsis and dynamic exploration.

3 Endoscopic simulator training

3.1 Summary

The last two empirical chapters of this thesis investigate how cognitive abilities correlate with the development of endoscopic skill. Insight in this relation represents a step towards 1) predicting an individual's capacity for surgical performance; 2) optimizing transfer from the training situation to the professional situation; and 3) designing adaptive training courses that accommodate a broad range of students of differing cognitive abilities. Endoscopic skill was represented by virtual colonoscopy in the study described in chapter five and by virtual laparoscopy in chapter six's study. In colonoscopy, a flexible endoscope is introduced into the anus for procedures relating to the colon. Laparoscopy is characterized by inflating the abdomen and introducing surgical instruments and a scope through tiny incisions in the body wall. Cognitive abilities measured in both studies were four visuo-spatial ability factors (Visualization, Spatial relations, Fluency of closure, and Perceptual speed). For the laparoscopy study, two additional memory factors were measured (Memory span and Visual memory). In both studies, these cognitive abilities were measured in two, one-hour group sessions. All participants consequently enrolled the simulator training sessions (four 45-minute sessions in the colonoscopy study, seven 35-minute sessions in the laparoscopy study).

In the colonoscopy study analysis, Duration (a time on task measure) was used as the only simulator performance measure. The visuo-spatial factor of Visualization was found to be important for Duration in colonoscopy simulator training. Novel was the finding that Visualization also covaried with learning *rate*.

In the laparoscopy study, the first three sessions were taken to represent early training; the last three sessions represented late training. Three performance variables (Duration, Motion efficiency, and Damage) were derived from the simulator data, leading to a total of six performance variables being assessed in repeated measures ANCOVAs; these were Duration early, Duration late, Motion efficiency early, Motion efficiency late, Damage early, and Damage late. Covariables were four visuo-spatial ability factors (Visualization, Spatial relations, Fluency of closure, and Perceptual speed) and two memory factors (Memory span and Visual memory). Four performance variables showed significant (and positive) changes during practice; these were Duration early, Duration late, Motion efficiency early, and Damage early. Of these four variables only two covaried with any cognitive ability; namely 1) early Motion efficiency covaried with Visualization, Perceptual speed, and Memory span, and 2) early Damage covaried with Memory span. Better performance always covaried with higher cognitive ability scores. Of the non-significant performance variables, late Damage values started to fluctuate in a seemingly random manner over the remaining sessions, and late Motion Efficiency was characterized by slight, non-significant changes.

3.2 Discussion

No easily generalizable picture of the involvement of visuo-spatial ability factors in endoscopic training appears from the last two studies summarized above. Overall, the involvement of cognitive ability factors during early training likely reflects the cognitive demands of skills not yet automated for performing a high level, complex task (Fitts, 1964; Perlow et al., 1997).

When looking at more specific issues like the endoscopic performance measure Duration, used in both studies, none of the acquired cognitive ability factors correlate with Duration in the long-term laparoscopy study, yet Visualization correlates with Duration in the colonoscopy study. Add to this Keehner et al.'s 2006 finding that Visualization correlates with Duration throughout a long term study investigating the role of general reasoning and visuo-spatial ability on angled laparoscope training, and a confusing picture appears indeed. Evidently not all endoscopic tasks place the same demands on the visuo-spatial ability. Future work would benefit from a literature review including a task analysis of the different endoscopic tasks, and the different visuo-spatial ability tests used in earlier research.

Alternatively, our studies may not have been sufficiently powered to find stable effects. Availability of medical personnel is a common problem in this type of study that aims for practical relevance. Ideally a combination of studies with a large number of (non-medical) participants should identify patterns that consequently can be confirmed by studies like the ones reported in chapter five and six of this thesis.

The involvement of both Visualization and Perceptual speed, but not other visuo-spatial factors such as Spatial relations in early Motion efficiency (in the laparoscopy study) is another unexpected finding. As contributing factors to visuo-spatial ability, Visualization is thought to emphasize the ability to mentally manipulate complex visuo-spatial stimuli, whereas Perceptual speed emphasizes the ability to solve simple visuo-spatial tasks under speeded conditions (Carroll, 1993). If both speed and complexity are important factors in early Motion efficiency, one would expect Spatial relations to reach significance too, since this factor is thought to be very similar to Visualization, mainly differing in the speed-complexity trade-off associated with its stimuli (Carroll, 1993). Other variables besides speed and complexity likely play a role in the differentiation between the visuo-spatial ability factors discussed above. Additionally, visuo-spatial stimulus complexity is not well understood, and both theoretical and experimental work is needed to remedy this situation.

4 General conclusion

Understanding the role of cognitive abilities in medicine can be instrumental in helping the field of medical education make the transition from the current situation to a situation where the challenges of implementing electronic media are met, and where the new possibilities of those media are exploited to its fullest. This statement holds for topics as diverse as the study of medical core knowledge (e.g. anatomy), to training highly specific skills (such as endoscopic surgery skills). For the virtual study of anatomy the contribution might lie in providing guidelines for adaptive support systems that help students in learning visuo-spatially challenging concepts. For endoscopic training a better understanding of the role cognitive abilities play in training will help make the transition from the traditional master-apprentice model to a field where evidence-based training is the gold standard. Predicting individual skill level and optimizing maximum positive transfer from the training situation to the working environment are examples of the benefits such knowledge may bring. Professionals trained in electronic learning environments such as endoscopic simulators will not only be proficient in their skills mastery, but will also become part of a new tradition that emphasizes quantification of performance. This has potential benefits beyond the training situation to the professional situation as well, helping to establish a culture of greater transparency and accountability. This is an important step towards a new type of professional that monitors their own level of skill and understanding, and for whom the need for developing meta-cognition and to engage in life-long learning is self-evident instead of an educational novelty. It has been, and continuous to be, a joy for me to serve in this transition.

8. Nederlandse Samenvatting

1 Introductie

De wijze van opleiden van medici is aan het veranderen. Eén van de katalysatoren van deze verandering is het toenemende gebruik van elektronische leermiddelen, zoals het gebruik van simulator technologie bij het trainen van chirurgen, of het gebruik van elektronische leeromgevingen bij anatomisch leren. Het hoofddoel van dit proefschrift is om deze nieuwe situatie te helpen begrijpen, en daarmee een stap te zetten naar het optimaliseren van deze nieuwe manier van medisch opleiden. De rol van visueel ruimtelijk voorstellingsvermogen in dit leren staat centraal bij de experimenten waar dit proefschrift verslag van doet. Visueel ruimtelijk voorstellingsvermogen is de vaardigheid visuele en ruimtelijke informatie op te slaan in het geheugen, en deze informatie weer terug te kunnen halen en mentaal te kunnen manipuleren.

De eerste drie empirische hoofdstukken doen verslag van een serie experimenten naar de samenhang tussen stereopsis, dynamische exploratie, en visueel ruimtelijk voorstellingsvermogen bij het leren van virtueel nagemaakte buikorganen. Stereopsis verwijst naar het zien van ruimtelijke diepte door het vergelijken van de iets verschillende informatie die door onze twee ogen binnenkomt. Van dynamische exploratie is sprake als men interactief en real-time het aanzicht van een voorwerp kan manipuleren (als dit bijvoorbeeld via een computer gepresenteerd wordt). In de twee daaropvolgende empirische hoofdstukken staat de relatie tussen visueel ruimtelijk voorstellingsvermogen en de ontwikkeling van endoscopische vaardigheden centraal. Endoscopie is een verzamelterm voor die minimaal invasieve chirurgische technieken waarbij een camera gemonteerd aan het uiteinde van een (al dan niet flexibele) buis het lichaam wordt ingebracht. Hieronder worden eerst de drie anatomische studies samengevat en besproken, en daarna worden de twee endoscopische studies samengevat en besproken. Een algemene conclusie besluit deze samenvatting.

2 Virtueel anatomisch leren en visueel ruimtelijk voorstellingsvermogen

De studie die wordt gepresenteerd in hoofdstuk twee onderzoekt of een combinatie van stereopsis en dynamische exploratie virtueel anatomisch leren bevordert, en of deelnemers met een laag visueel ruimtelijk voorstellingsvermogen hier meer baat bij hebben dan deelnemers met een hoog visueel ruimtelijk voorstellingsvermogen.

Deelnemers zonder diepgaande kennis van de menselijke anatomie kregen een leertaak voorgeschoteld waarin een aantal anatomische onderdelen van de buik bestudeerd werd. De deelnemers werden verdeeld in twee groepen van gelijke samenstelling met betrekking tot visueel ruimtelijk voorstellingsvermogen. Er waren twee varianten van de studiefase, één waarin de deelnemers de anatomie konden bestuderen met behulp van een combinatie van stereopsis en dynamische exploratie, en een tweede variant zonder deze features. Elke groep kreeg slechts één van de twee varianten van de studiefase aangeboden. Na de studiefase werden alle deelnemers getest op visueel ruimtelijke kennis van de aangeboden anatomie met behulp van twee speciaal ontwikkelde tests. Hoog visueel ruimtelijk voorstellingsvermogen hing samen met betere prestaties op de tests. Deelnemers met een laag visueel ruimtelijk voorstellingsvermogen hadden meer baat van de studiefase conditie met stereopsis en dynamische exploratie. Zij presteerden dan op hetzelfde nivo als de deelnemers met een hoog visueel ruimtelijk voorstellingsvermogen.

In hoofdstuk drie wordt verslag gedaan van een studie met als doel uit te zoeken of stereopsis verantwoordelijk is voor de positieve bijdrage van de stereopsis + dynamische exploratie conditie zoals gerapporteerd in hoofdstuk twee. In een soortgelijk onderzoek werden twee condities van een studiefase vergeleken door anatomische kennis te meten met twee tests. In één conditie werd de anatomie stereoptisch aangeboden, in de andere niet. Hoog visueel ruimtelijk voorstellingsvermogen correleerde met hoge test scores, en een voordeel van de stereoptische conditie voor performance op een van beide tests werd gevonden. Er werden geen interacties van visueel ruimtelijk voorstellingsvermogen en conditie gevonden.

Hoofdstuk vier doet verslag van het derde experiment in deze serie, met als doel de bijdrage van dynamische exploratie aan virtueel anatomisch leren te onderzoeken. Deelnemers werden getest in paren van gelijk visueel ruimtelijk voorstellingsvermogen. Tijdens de studiefase kon een helft van het paar actief de virtuele anatomie manipuleren. De andere deelnemer keek op een afzonderlijk scherm naar de manipulaties van de actieve deelnemer. Dezelfde tests werden weer gebruikt om kennis van de bestudeerde anatomie te meten. Dynamische exploratie leverde een kleine, maar significante positieve bijdrage aan anatomisch leren.

Over het geheel genomen bevestigen deze experimenten dat een goed visueel ruimtelijk voorstellingsvermogen samenhangt met een goed anatomisch leervermogen. Meer specifiek laten deze experimenten zien dat een combinatie van stereopsis en dynamische exploratie in de virtuele anatomische leeromgeving tot beter virtueel anatomisch leren leidt, en dat de combinatie van deze eigenschappen beter werkt dan elk van beide alleen. In zulke condities presteren mensen met een laag visueel ruimtelijk voorstellingsvermogen op hetzelfde nivo als mensen met een hoog visueel ruimtelijk voorstellingsvermogen. Dit hangt waarschijnlijk samen met het feit dat in de dagelijkse leefomgeving stereopsis en de motorische aspecten van het manipuleren van voorwerpen een gekoppeld systeem vormen bij het leren kennen van nieuwe voorwerpen. De koppeling van computer geïmplementeerde stereopsis en dynamische exploratie benadert de omstandigheden van dit leren beter dan een virtuele leersituatie zonder deze kenmerken.

Voor de anatomische stimuli uit deze studies leidde een combinatie van stereopsis en dynamische exploratie waarschijnlijk tot een betere opslag in het geheugen, waardoor het terughalen en mentaal manipuleren van deze informatie makkelijker werd voor deelnemers met een laag visueel ruimtelijk voorstellingsvermogen. Voor mensen met een hoog visueel ruimtelijk voorstellingsvermogen maakte de aanwezigheid van stereopsis en dynamische exploratie niet veel verschil, omdat zij zich blijkbaar op basis van de gereduceerde informatie al een mentaal model van voldoende kwaliteit konden vormen.

In virtuele leeromgevingen die als doel hebben een visueel ruimtelijk begrip van ingewikkelde anatomische concepten over te brengen hebben mensen met een laag visueel ruimtelijk voorstellingsvermogen baat bij een combinatie van computer geïmplementeerde stereopsis en dynamische exploratie.

Aansluitend op eerder werk naar de samenhang tussen visueel ruimtelijk voorstellingsvermogen en anatomisch leren werd in deze drie experimenten visueel ruimtelijk voorstellingsvermogen getest met behulp van een test die strikt genomen een subset van visueel ruimtelijk voorstellingsvermogen meet, namelijk de factor Visualisatie. Deze factor is vooral gevoelig voor visueel ruimtelijke complexiteit. Andere visueel ruimtelijke factoren zijn meer betrokken bij patroon herkenning of perceptuele snelheid. Of zulke visueel ruimtelijke factoren betrokken zijn bij (virtueel) anatomisch leren is onbekend, maar is in principe een empirische vraag.

Voor de studies naar de samenhang tussen visueel ruimtelijk voorstellingsvermogen en endoscopische vaardigheid werd een breder palet aan visueel ruimtelijke factoren getest.

3 Visueel ruimtelijk voorstellingsvermogen en endoscopische simulator training

In hoofdstuk vijf wordt verslag gedaan van een studie waarin een groep medische studenten deelnamen aan een colonoscopie simulator trainingscursus van vier sessies. Colonoscopie is een techniek waarbij een flexibele endoscoop ingebracht wordt in de dikke darm via de anus. Tijdens elke sessie werden steeds varianten op dezelfde twee taken aangeboden. De deelnemers werden getest op vier van de vijf factoren waar visueel ruimtelijk voorstellingsvermogen uit bestaat. De tijd die nodig was om een oefening af te ronden werd gebruikt als prestatiemaat. Deelnemers werden beter op de simulatortaken, en de visueel ruimtelijke factor Visualisatie (die vooral gevoelig is voor de complexiteit van visueel ruimtelijke stimuli) correleerde met prestatie. Visualisatie correleerde ook met de snelheid van de *toename* van de prestatie van de deelnemers.

Hoofdstuk zes beschrijft een lange-termijn studie waarin een groep medische studenten deelnam aan een laparoscopische simulator trainingscursus van acht sessies, verspreid over twee maanden. Bij laparoscopische ingrepen worden instrumenten en een endoscoop door kleine incisies in een met gas gevulde buik ingebracht. Alle deelnemers werden getest op vier factoren voor visueel ruimtelijk voorstellingsvermogen en twee geheugenfactoren. Drie maten voor simulator prestatie werden gebruikt, namelijk tijd om de oefening te doen, de efficiëntie van de bewegingen, en schade. Deelnemers verbeterden op alle prestatievariabelen. Daarna werden de eerste drie trainingssessies afzonderlijk van de laatste drie trainingssessies geanalyseerd. Voor de eerste drie sessies werden voor alle prestatie variabelen significante verbeteringen gevonden. Voor de laatste drie sessies was dat alleen bij de tijdsvariabele het geval. Van de visueel ruimtelijke factoren voorspelden alleen Visualisatie en Perceptuele snelheid prestatie op bewegingsefficiëntie. De geheugenfactor Geheugen reikwijdte voorspelde prestatie op bewegingsefficiëntie en schade tijdens de eerste drie sessies.

Het is lastig om uit de resultaten van deze studies een eenduidig beeld te krijgen van de samenhang tussen visueel ruimtelijk voorstellingsvermogen en (de ontwikkeling van) endoscopische vaardigheid. Heel algemeen gesproken lijkt de betrokkenheid van verschillende cognitieve vaardigheden vroeg in het trainingstraject vooral een bevestiging te zijn van het idee dat zulke vaardigheden van belang zijn op het moment dat de aan te leren, complexe taak nog niet geautomatiseerd is. Op een gedetailleerder nivo lijkt het erop dat verschillende prestatiematen van endoscopische taken samenhangen met verschillende cognitieve vaardigheidsfactoren. Daarbij in aanmerking genomen dat een prestatiemaat bij de ene taak niet noodzakelijkerwijs hetzelfde onderliggende construct meet als dezelfde prestatiemaat bij een andere taak, lijkt het erop dat gedetailleerde analyses van endoscopische taken; van de prestatiematen voor zulke taken; en van de visueel ruimtelijke factoren die ermee samenhangen, nodig zijn om gerichter experimenten te kunnen ontwerpen. De factor Visualisatie blijkt meer dan andere visueel ruimtelijke factoren samen te hangen met endoscopische vaardigheid. Van die factor is bekend dat deze vooral visueel ruimtelijke complexiteit meet. Helaas wordt visueel ruimtelijke complexiteit niet goed begrepen, en is ook op dat gebied meer werk nodig om tot een goed begrip van de ontwikkeling van endoscopische vaardigheden te komen.

Als er uiteindelijk vanuit een beter begrip van visueel ruimtelijke complexiteit gewerkt kan worden, wordt het niet alleen mogelijk cognitieve vaardigheidstests te ontwerpen die beter aansluiten op de beroepspraktijk, maar kan er ook gerichter gewerkt worden bij het ontwerpen en bouwen van simulatoren voor endoscopische vaardigheidstraining. De voordelen van een beter begrip van visueel ruimtelijke complexiteit strekken verder dan endoscopische training tot alle gebieden waar studenten complexe vaardigheden aanleren om te kunnen werken in een visueel ruimtelijk complexe werkelijkheid.

4 Algemene conclusie

Een goed begrip van de rol van cognitieve vaardigheden in de geneeskunde is essentieel om de overgang te kunnen maken van de huidige opleidingssituatie naar een situatie waar aan de uitdagingen van het implementeren van elektronische media is voldaan, en waar de mogelijkheden van deze media ten volle worden gebruikt. Dit geldt voor zulke uiteenlopende onderwerpen als de studie van medische basiskennis zoals de kennis van anatomie, tot het trainen van zeer specifieke vaardigheden zoals vaardigheid in de verschillende endoscopische technieken. Voor virtueel anatomisch leren kan dit bijvoorbeeld liggen in het afleiden van richtlijnen voor adaptieve ondersteuning die de student helpt bij het leren van visueel ruimtelijk complexe concepten. Voor training in endoscopische technieken kan zulke kennis instrumentaal zijn bij de overgang van het meester-gezel systeem van trainen naar een situatie waar 'evidence-based' training de gouden standaard is. Het kunnen voorspellen van iemands uiteindelijke nivo van vaardigheid en het optimaliseren van positieve transfer van de trainingssituatie naar de operatie kamer zijn hier voorbeelden van. Een gevolg van een juiste psychologische en onderwijskundige implementatie van deze nieuwe leermiddelen zal een generatie medische professionals zijn voor wie kwantitatief inzicht in de eigen vaardigheden een essentiële voorwaarde vormt voor een veilige en transparante beroepsuitoefening. Het was, en is, mij een groot genoegen een rol te kunnen spelen in deze overgang.

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10. Appendix

List of tests used in the research described in chapters five and six. The first four visuo-spatial ability factors of Visualization, Spatial relations, Flexibility of closure, and Perceptual speed were used in both the colonoscopy study and the laparoscopy study. The additional memory factors of Visual memory and Memory span were only used in the laparoscopy study.

Visualization

Mental rotation test (Vandenberg and Kuse, 1978)
Guay's visualization of viewpoints (Guay and Mc Daniels, 1976, adapted version described in Eliot & Macfarlane-Smith, 1983)

Spatial relations

Figures (Thurstone, 1936)
Cards (Thurstone, 1936)

Flexibility of closure

Hidden figures test (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)
Hidden patterns test (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)

Perceptual speed

Number comparison test (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)
Identical pictures test (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)

Visual memory

Shape memory test (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)
Map memory (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)

Memory span

Auditory memory span numbers (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)
Auditory memory span letters (Kit of factor-referenced cognitive tests, Ekstrom et al., 1976)