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Visuospatial ability factors and performance variables in laparoscopic simulator training

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ABSTRACT

Visuospatial ability has been shown to be important to several aspects of laparoscopic performance, including simulator training. Only a limited subset of visuospatial ability factors however has been investigated in such studies. Tests for different visuospatial ability factors differ in stimulus complexity, in their emphasis on identifying visual stimuli in a cluttered context, and in the demands they make on speed of processing. To help clarify the involvement of visuospatial ability factors in laparoscopic performance the current study investigated the role of four such factors in laparoscopic simulator performance. 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 visuospatial ability factors were measured. Learning curves were based on the simulator performance variables of (task) Duration, Motion efficiency, and Damage. The visuospatial ability factor Visualization impacted Damage and Motion efficiency. The factor Spatial relations impacted Damage. Visuospatial ability factors measuring the ability to mentally manipulate complex to moderately complex stimuli are more important than other visuospatial ability factors during basic laparoscopic simulator training. A finding relevant to theories of skill development is that the impact of Visualization on learning curves for Damage and Motion efficiency was most evident during early- and late (but not middle) training, which may be an indicator of a switch between different phases of skills learning. Learning curves and repeated measures analyses indicated damage control should be emphasized in laparoscopic skills training.

1. Introduction

1.1. General

Visuospatial ability is known to correlate positively with surgical skill both in simulator training- and in real-world-settings (Hegarty, Keehner, Cohen, Montello, & Lippa, 2007 provide an overview). While relevant to issues of career selection and adaptive training, the role of visuospatial ability in (developing) minimally invasive surgery skills is not well understood, in part due to a lack of sufficiently fine-grained measurements used for both visuospatial ability and surgical performance. By studying a more comprehensive selection of visuospatial ability factors and more aspects of laparoscopic skills during a basic laparoscopic skills simulator training course, we aim to provide appropriate detail to this discussion.

Also, we want to contribute to the discussion on the impact of cognitive abilities on skill acquisition. While Ackerman's influential model of skill acquisition holds that with automation of skill the contribution of cognitive abilities to skilled performance vanishes, Keehner and her colleagues found a lasting contribution of visuospatial ability to performance on a laparoscopic simulator task (Ackerman, 1988; Keehner, Lippa, Montello, Tendick, & Hegarty, 2006). Keehner et al. suggest that the processing of spatial content necessitated an ongoing involvement of visuospatial ability, as opposed to the expected diminishing effect of cognitive abilities on purely rule-based tasks that can be fully automated over time. Evidence for this however is limited at this point, and other studies (Keehner, Cohen, Hegarty, & Montello, 2004; Keehner, Tendick, et al., 2004) did not find such involvement.

1.2. Surgical simulator training

Simulator technology has rapidly become an important asset of surgery training (Dawson & Kaufman, 1998; Kneebone, 2003). Especially laparoscopic surgery, which requires considerable skill but is relatively easy to simulate, has proven to benefit from simulator training (Ahlberg et al., 2007; Eriksen & Grantcharov, 2005; Felsher et al., 2005; Grantcharov et al., 2004; Hyltander, Liljegren, Rhodin, & Lönroth, 2002; Van Dongen, Tournoij, van der Zee, Schijven, & Broeders, 2007).

During a laparoscopic procedure, a camera and laparoscopic instruments are introduced to the abdominal cavity through tiny incisions in

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the body wall that act as pivots. The camera is instrumental in providing the surgeon visual feedback on an external screen. Laparoscopic instruments consist of two handles, attached to a slender, hollow tube with the manipulative ends of the instrument extending from the other end of the tube, inside the body. These tools can be scissors, cauterization tools, or other. The virtual reality hardware used in the current study offers a close approximation to this set-up by providing similar manipulative instruments, held together by a movable pivot on an anchoring foothold. Visual feedback from the virtual patient's abdomen and the instruments is provided on an external monitor (Fig. 2). The LapSim software suite used in this study provides a broad range of laparoscopic exercises, ranging from simple exercises aimed at developing skill in manipulating laparoscopic instruments to simulations of full surgical procedures. Laparoscopic camera movement can be simulated by the software, adding the spatial challenge of having to adjust one's movements to misaligned visual feedback.

A major benefit of the use of simulators in laparoscopic training is the possibility to quantify performance, which facilitates an assessment of the involvement of cognitive abilities in developing and practicing laparoscopic skills. A better understanding of this involvement may lead to adaptive training courses for students of different cognitive ability profiles, and/or to the design and implementation of specific admission tests for those career tracks that are critically dependent on specific cognitive abilities.

1.3. Cognitive abilities

Psychometric research into individual differences has enabled a differentiation 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 reasoning ability, visuospatial ability, and memory. These second tier factors in turn are each composed of a number of third tier factors that are actually measured by intelligence tests, after which the higher level factors are derived from the resultant data.

Other individual differences with a cognitive dimension, such as decision-making abilities were not adopted in this study. While relevant in the context of performance in the operating room, they were thought to be of limited predictive value in a basic laparoscopy course, where real-world complexities are strongly reduced to allow focus on technical skills development.

1.4. Visuospatial ability

Visuospatial ability refers to the human cognitive ability to form, retrieve, and manipulate mental models of a visual and spatial nature (Lohman, 1979a). Visuospatial ability has been successfully linked to a variety of surgical and medical skills (an overview is published by Hegarty et al., 2007). Visuospatial ability is interesting over other cognitive abilities for two reasons: first, contrary to other cognitive ability factors, visuospatial ability has not been selected for during the academic phase of the medical curriculum, and thus may largely account for differences in performance in medical procedures with a spatial emphasis (Luursema, Buzink, Verwey, & Jakomiwicz, 2010); second, there is some evidence that whereas general cognitive ability is especially important during early learning, visuospatial ability remains important throughout training, due to non-automating task specific aspects of laparoscopic tasks (Keehner et al., 2006).

Carroll identifies five third-tier factors that together form visuospatial ability (Carroll, 1993). These are Visualization, Spatial relations, Speed of closure, Flexibility of closure, and Perceptual speed. Below, these visuospatial ability factors are discussed in light of surgical training, leading to an outline of the current study.

1. *Visualization* is the ability to manipulate complex mental representations of a visuospatial nature. Mental manipulations required in Visualization tests can be quite elaborate, and require rotation of complex spatial shapes, folding, perspective taking, or others. The relationship between Visualization and surgical performance is relatively well charted, and positive (e.g. Hedman et al., 2006; Keehner et al., 2006; Luursema et al., 2010; Risucci, Geiss, Gellman, Pinard, & Rosser, 2001; Schueneman, Pickleman, Hesslein, & Freeark, 1984; Wanzel et al., 2003).
2. *Spatial relations* indicates the ability to quickly manipulate simple mental representations of a visuospatial nature (often requiring mental rotation). Tests for Spatial relations generally correlate positively with surgical simulator performance (e.g. Eyal & Tendick, 2001; Haluck et al., 2002; Ritter, McClusky, Gallagher, Enochsson, & Smith, 2006).
3. *Speed of closure* is defined as the ability to identify partly obscured spatial forms which are not specified to the learner in advance. Tests for Speed of closure are used in Wanzel, Hamstra, Anastakis, Matsumoto, and Cusimano (2002), Wanzel et al. (2003), Risucci et al. (2001), Risucci, Geiss, Gellman, Pinard, and Rosser (2000) and Risucci (2002). Only in Risucci's 2001 study a low, but significant correlation between Speed of closure and task-on-time on simulator dexterity drills was found. This factor seems to contribute little to surgical skill.
4. *Flexibility of closure* indicates the ability to identify spatial forms that are specified to the learner in advance in a cluttered visual environment. Correlations with surgical performance for this factor differ. Tests for this factor show positive correlations with surgical performance in some research (Gibbons, Baker, & Skinner, 1986; Steele, Walder, & Herbert, 1992) but not in others (Luursema et al., 2010; Schueneman et al., 1984).
5. *Perceptual speed*, the ability to quickly identify a given shape from a number of alternatives, has only been used in one earlier study, as far as we know (Luursema et al., 2010). The authors found no involvement for Perceptual speed on execution time and high-level error variables in two colonoscopy simulator training tasks.

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. Flexibility of closure and Perceptual speed are little researched in this context, although Luursema et al. (2010) found no involvement of these factors on a colonoscopy simulator task. The present study extends the latter research to the laparoscopic domain, and improves upon it by including a larger number of learners, recording eight instead of four training sessions, and by using more detailed performance measures. The current study took into account task duration, motion efficiency and damage, whereas the colonoscopy study only used a duration measure and two indirect measures related to quality of task execution. We assessed the relationship between the above three performance measures on two surgical simulator tasks, and the third-tier visuospatial ability factors of Visualization, Spatial relations, Flexibility of Closure, and Perceptual speed. Speed of closure was excluded in light of the negative findings in the literature. In line with previous findings, Visualization and Spatial relations were expected to positively impact performance. No specific hypotheses were formulated as to the impact of the visuospatial ability factors of Flexibility of closure and Perceptual speed.

2. Method

2.1. Participants

Twenty four students of the Technical Medicine program at the University of Twente participated in the basic laparoscopic skills simulator training course that generated the data used in this study, nineteen female and five male. The department of Technical Medicine trains medical professionals who specialize in creating and evaluating novel applications for existing technology to improve clinical practice. 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 to this course was a required part of the curriculum. An informed consent form was signed voluntarily by all participants.

2.2. Procedure

Prior to the simulator training sessions, subjects were tested twice for four visuospatial ability factors. During the first of these hour-long sessions, paper-and-pencil tests for the cognitive abilities of Visualization, Spatial relations, Flexibility of closure, and Perceptual speed were administered. A demographics questionnaire was also part of the first session. During the second session, different paper-and-pencil tests for the same four ability factors were administered. The mean of each pair of tests for a specific cognitive ability factor was taken as an indicator for that factor. Sample items of tests representing each factor are shown in Fig. 1. A complete list of the tests used to assess these abilities is given in Appendix A.

The actual simulator training sessions took place over a time span of two months, during which each learner engaged individually in eight weekly, half-hour training sessions. The goal of this basic laparoscopic training course was to familiarize the learners with the laparoscopic instruments to develop the basic technical skills needed for eventual training in actual laparoscopic procedures. This limits the scope of this study, leaving out the actual decision-making processes of real-world laparoscopic surgery. Two standard exercises that come with the LapSim laparoscopic simulator training software 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 hands, thus offering a similar challenge for both left handed and right handed learners in training both the dominant- and non-dominant hands. A third exercise (named *Coordination*) offers different tasks for the left versus the right hand, and (while part of the course) was not selected for analysis. The Grasping and Instrument Navigation exercises were offered at two levels of difficulty, once during each training session. The simulator set-up is shown in Fig. 2.

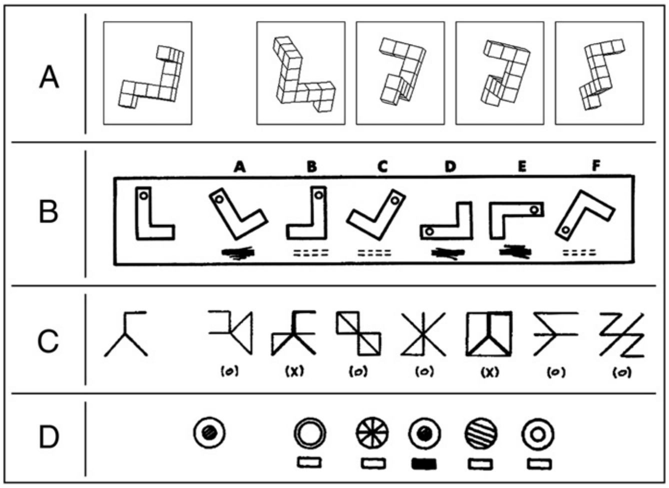

Fig. 1. Sample items of four of the eight paper-and-pencil tests that were used to measure the four visuospatial ability factors and the memory factor Visual memory. ‘A’ shows an example item from the Mental Rotation Test, measuring Visualization. Participants are required to mark the two objects from a row of four that show the identical, but rotated, item shown at utmost left. ‘B’ shows an item from the similar Cards test, measuring Spatial relations. Items such as shown next to ‘C’, from the Hidden Objects test, measure the Flexibility of closure ability factor. Participants have to mark those figures that contain the example figure at the left. With items such as shown in ‘D’, Perceptual speed is measured. Participants have to match the utmost left item to one of five items to its right.

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 color-coded red or green, to indicate whether the right-hand grasper or the left-hand grasper needs to be used. After successful removal of the vessel it needs to be transported to a spherical goal object. Touching of the two objects makes the vessel disappear, and a new vessel appears elsewhere. The hard task version simulated rotated camera angles (further distorting the already misaligned co-location between visual feedback and actual instrument position) 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 color coded green for the right hand instrument, and red for the left hand instrument. Target spheres appear, which are color coded to indicate whether the right-hand or the left-hand tool 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 hard version of this task, rotated camera angles, and smaller targets were included. Additionally, the virtual camera changed position during the task.

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 in. TFT monitor provided visual feedback to the learner (Fig. 2). Surgical Science's LapSim v.3.0.10 was used as training software.

2.4. Data reduction

Two different LapSim exercises were selected for this study, each in an easy and a hard version. The easy versions of the tasks proved very simple for our learners, and were considered as warming-up exercises. These versions were dropped from further analysis, and only data for the hard versions of Grasping and Instrument navigation were analyzed. Extreme values (>3 SD) were removed from the dataset, leading among others to the removal of one learner who consistently and extremely underperformed. This led to a data loss of 5%. The analyses presented below are based on data from the remaining 23 learners. After removal of the extreme values, no significant deviations of the normal distribution were found for any of the low-level variables, excluding any floor effects (as assessed by the Kolmogorov–Smirnov-1 test).

Data from the low-level variables for each learner and each exercise recorded by the LapSim were normalized and averaged into three performance variables. The performance variable ‘Damage’ was thus derived from the values for ‘the number of instances damage was inflicted on virtual tissue during the task’ and ‘the damage in millimeters resulting from a task's most severe accident’. The performance variable ‘Motion efficiency’ was similarly derived from the values for ‘total instrument path length in millimeters’ and ‘the instrument angular path in arc degrees during a task’, for both the left and the right hands. Low values for these latter low-level variables are thought to indicate efficient and effective motions. The performance variable ‘Duration’ was derived by combining and normalizing the values for ‘left hand time’ and ‘right hand time’ (in seconds) for solving all the items of an exercise. This reduction procedure was executed for both the Grasping- and the Instrument manipulation task, resulting in pairs of similar performance variables for both tasks. The

Fig. 2. The LapSim™ laparoscopic simulator used in the experiment.

mean of each pair was used in the statistical analysis reported in the Results section.

The four visuospatial ability factors were similarly derived by normalizing and averaging values for the pairs of individual tests to assess that factor. None of the three resulting performance- and four visuospatial ability variables deviated significantly from the normal distribution, again assessed by the Kolmogorov–Smirnov-1 test, allowing parametric variance testing.

3. Results

The current study aims to add to the knowledge of the relation between visuospatial ability and the development of laparoscopic skills. We expected the visuospatial ability factors of Visualization and Spatial relations to positively impact laparoscopic learning, and did not formulate any hypothesis as to the effect of the visuospatial factors of Flexibility of closure and Perceptual speed. Repeated measures analyses were used to assess the impact of visuospatial ability factors on the development of laparoscopic skill. To provide more detail to this discussion, correlations and learning curves for the three laparoscopic performance variables are included.

To assess training effects and the relationship of visuospatial ability factors with this training, repeated-measures ANCOVAs were performed separately for the three performance variables, over all eight sessions, with the four visuospatial ability factors as covariates (Table 1). Since Mauchly's test indicated that sphericity could not be assumed for the data, the Greenhouse–Geisser degrees-of-freedom correction was applied. Significant changes were found for all three variables. Learning was observed for Duration and Motion efficiency (respectively shorter and more efficient), Damage lessened over the first four sessions, but then increased and diminished again over the remaining four sessions (Fig. 3).

The visuospatial ability factor of Visualization, indicative of the ability to mentally manipulate complex visuospatial material, was found to significantly impact all performance variables, with a medium effect size for Damage, a small effect size for Motion efficiency, and a negligible effect size for Duration. The factor of Spatial relations, involved in the speeded mental manipulation of somewhat simpler visuospatial material, was significant to Damage (medium effect size) and Motion efficiency (but at a negligible effect size). Perceptual

Table 1
Repeated measures ANCOVAs for all performance variables, over all eight training sessions, with cognitive ability factors as covariates.

Source	F	df/df error	p	η^2
Duration (n = 23)				
Session	131.65	3.04/54.74	.00	.94
Visualization	4.01	3.04/54.74	.01	.03
Spatial relations	2.19	3.04/54.74	.10	.02
Flexibility of closure	.12	3.04/54.74	.95	.00
Perceptual speed	1.96	3.04/54.74	.13	.01
Motion efficiency (n = 23)				
Session	46.28	2.01/36.22	.00	.78
Visualization	5.64	2.01/36.22	.01	.12
Spatial relations	3.47	2.01/36.22	.04	.07
Flexibility of closure	.69	2.01/36.22	.51	.01
Perceptual speed	3.23	2.01/36.22	.05	.07
Damage (n = 23)				
Session	9.32	3.00/54.05	.00	.51
Visualization	3.18	3.00/54.05	.03	.34
Spatial relations	3.55	3.00/54.05	.02	.40
Flexibility of closure	.80	3.00/54.05	.50	.09
Perceptual speed	1.33	3.00/54.05	.27	.14

Note. Degrees of freedom values are Greenhouse–Geisser corrected, since sphericity for the data could not be established.

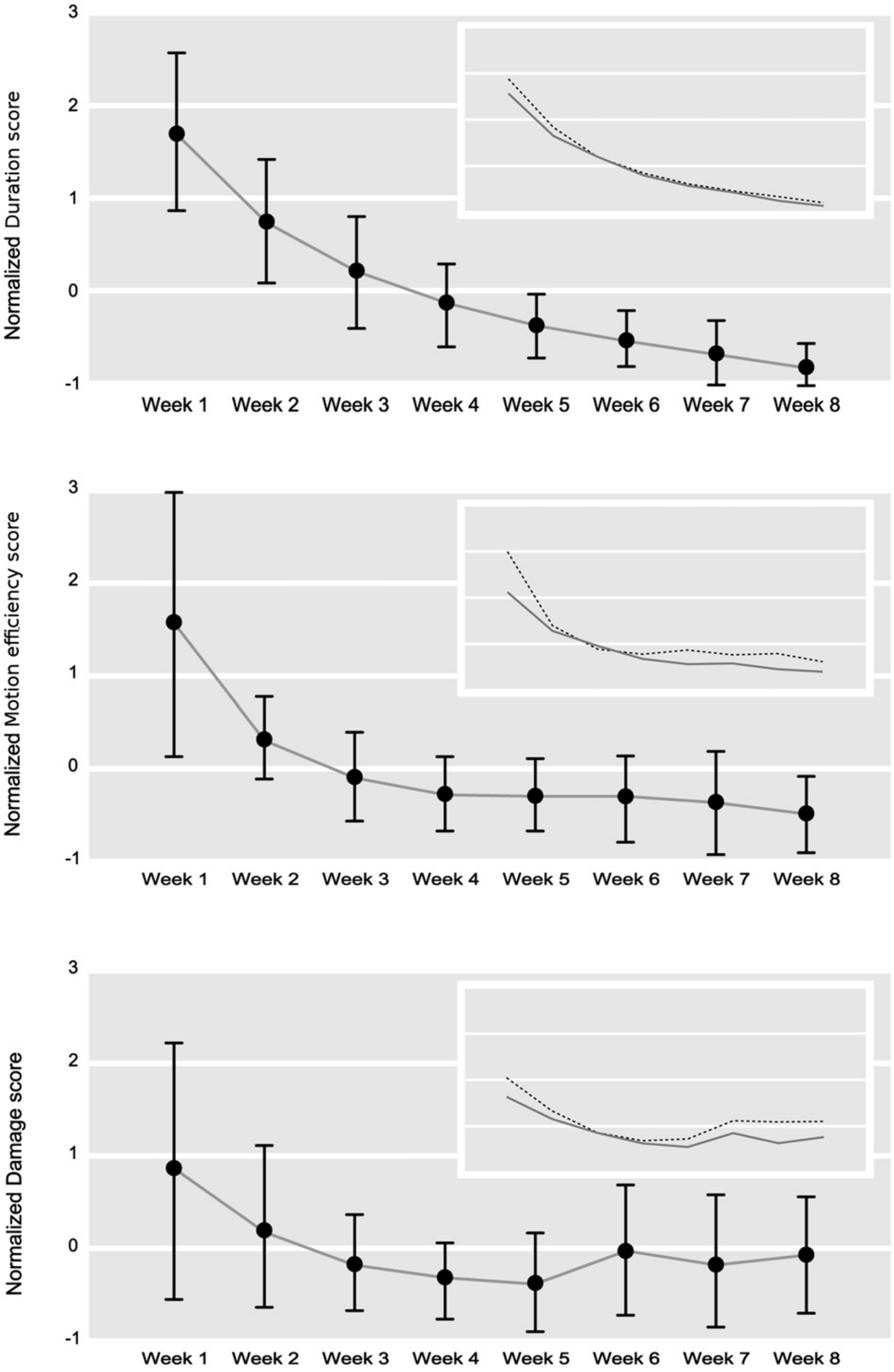

Fig. 3. Normalized learning curves of the three simulator performance measures used in this study. The vertical bars show session means and standard deviations. The insets show learning curves for the same group, split in a low Visualization subgroup (n = 12), and a high Visualization subgroup (n = 11). The high Visualization subgroup is the better performing one.

speed, responsible for speeded matching of very simple visual stimuli, significantly impacted Motion efficiency, but with a negligible effect size. The Flexibility of closure factor (an indicator for the ability to recognize visual information in a visually cluttered environment) was not involved in any of the current laparoscopic performance measures. In Fig. 3 insets are provided that show learning curves for subgroups of high- versus low-Visualization ability, this being the most relevant visuospatial ability factor emerging from this study. However, correlations between the three performance measures and Visualization on a week-by-week basis rendered no significant outcomes.

Finally, correlations for all three performance measures over all sessions showed Motion efficiency to correlate highly with both Damage ($r = .714$, $p < .00$) and Duration ($r = .736$, $p < .00$). Duration correlated only moderately with Damage ($r = .380$, $p < .00$).

4. Discussion

The current study investigated the contribution of visuospatial ability to laparoscopic simulator training. Specifically, the effect of four visuospatial ability factors (Visualization, Spatial relations, Flexibility of closure, and Perceptual speed) on three performance variables

(Duration, Motion efficiency, and Damage) was analyzed. Visualization impacted performance on Damage and Motion efficiency, and Spatial relations impacted performance on Damage, suggesting that the ability to mentally manipulate complex to moderately complex visual stimuli is key to those aspects of laparoscopic skills development (Table 1). Most likely, people of high Visualization and Spatial relations ability are better at compensating the misalignment between visual feedback and instrument position inherent in laparoscopic surgery simulation, which would facilitate the reduction of unnecessary and adverse movement over the course of the training program.

Flexibility of closure did not influence any of the performance variables. Combined with the known lack of involvement of the Speed of closure factor in this kind of training, this leads us to believe that the ability to match or recognize stimuli in a visually cluttered environment is not very relevant to the development of laparoscopic skill, at least in the tasks studied so far. Laparoscopic simulator tasks however are much more clearly delineated and stereotyped than real-world laparoscopic surgery, so studies investigating the ecological validity of Flexibility of closure and Speed of closure in real world settings are still needed, although good construct validity for the basic LapSim laparoscopic surgery tasks has been established by showing that these tasks distinguish between professional groups of differing laparoscopic experience level (e. g., Eriksen & Grantcharov, 2005; Van Dongen et al., 2007).

Perceptual speed significantly impacted Motion efficiency, but at marginal effect size. Perceptual speed being a factor that emphasizes speed over complexity, this reinforces the conclusion that the ability to mentally manipulate complex visuospatial stimuli is central to those visuospatial ability factors that contribute to laparoscopic simulator performance.

A limitation to the Visualization and Spatial relations tests used in this study is that three out of four are mental rotation tests, the fourth being a perspective taking test. Visualization tests that are designed to depend on other potentially relevant mental manipulations (e.g. paper folding tests, which are readily available), and visuospatial tests that offer such stimuli on different relevant complexity ranges (not so readily available) should be instrumental to research into the role of visuospatial complexity in laparoscopic skill development (and other medical skills characterized by indirect visual feedback on one's actions).

Although high Visualization in our study was associated with larger improvements in Damage and Motion efficiency, no significant correlations were found between Visualization and any of the performance variables on a week-by-week basis. However, looking at subgroup learning curves split for Visualization, interestingly for Motion efficiency and Damage these curves first converge, and then diverge again, suggesting that early, procedural learning ends at similar levels for all learners, after which late, optimization type learning is characterized by a longer lasting benefit for learners of high Visualization ability. Although additional post-hoc statistical testing (a MANOVA for high- and low Visualization groups × performance data) did not result in significant effects, this possibility should be explored further in research designed for this purpose. This is relevant to the interpretation of existing literature in this field, for the methodology of future studies, and for medical training in general (e.g. in personnel selection or adaptive training design). Especially intriguing is the 'return of Visualization' during the optimization phase. If this is a more than incidental observation, the 'vanishing of Visualization' could be used as a marker to identify learning phases in training settings with a large visuospatial component, relevant to optimizing transfer.

Training (the Session variable) was found to be more important to performance improvement than Visualization ability (Table 1 and Fig. 3), especially for Duration and Motion efficiency. This may partly be an artifact of the large improvements during the first three sessions, thought to indicate early procedural learning. Late, optimization-type learning shows less pronounced improvements associated with training, but does show better Motion efficiency and Damage performance for the high Visualization group. Whether the performance difference between high- and low Visualization learners warrants using Visualization ability as a selection criterion for admission to a career track involving minimally invasive procedures is at present hard to say, as we are not aware of studies relating exact differences in simulator performance to relevant real-world laparoscopic outcome measures. Comparing real-world damage with simulator damage would be especially relevant, both given the relatively large effect of Visualization on Damage and the obvious importance of real-world damage on patient outcomes.

The effect of Session on Damage was significant but relatively weak, compared to the effect of Session on Motion efficiency or Duration (Table 1). It is also the only performance variable to show an inconsistent learning curve, where after an initial five-session improvement streak, seemingly random changes occur (Fig. 3). Despite its real-world importance, it may not be the major focus of the learners. 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. This concern is amplified by the moderate correlation of Damage and Duration, which may indicate different training strategies. Students may differ in their preferred Duration/Damage tradeoff, in other words, some students may be rushing. If this is the case, a Duration/Damage ratio might be a valid measure of conscientiousness, a personality trait known to distinguish surgeons positively from a normative population (Hoffman, Coons, & Kuo, 2010; McGreevy & Wiebe, 2002). Follow-up studies that correlate conscientiousness to such a derived performance measure would be very welcome, and have the potential to add an objective measure for conscientiousness to the existing methods. Practically, emphasizing damage control over speed in training instructions, and using explicit damage criteria for simulator training are recommended.

Appendix A

Tests used in the present study to assess the visuospatial ability factors Visualization, Spatial relations, Flexibility of closure, and Perceptual speed.

Visualization

Mental rotation test (Vandenberg & Kuse, 1978).

Guay's visualization of viewpoints (Guay & Mc Daniels, 1976, modified by Lippa, Hegarty, & Montello, 2002).

Spatial relations

Figures (Thurstone, 1936).

Cards (Thurstone, 1936).

Flexibility of closure

Hidden figures test (kit of factor-referenced cognitive tests, Ekstrom, French, Harman, & Dermen, 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).

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