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Spatial ability, experience, and skill in laparoscopic surgery

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Abstract

Background: Previous research showing correlations between spatial ability and surgical skills has used participants in relatively early stages of training. Research in skill acquisition has shown that the role of cognitive abilities can diminish as skills become increasingly automatic. In this study, we explored the role of spatial ability in laparoscopic surgical skills in two groups, one experienced and the other relatively inexperienced.

Methods: Subjects were recruited from two videoscopic courses: an advanced course for experienced surgeons and a laparoscopic urological surgery course attended by participants with relatively little laparoscopic experience. Three measures were obtained: spatial abilities, videoscopic experience, and operative skills.

Results: A significant correlation ($r = 0.393$) was found between spatial ability and skills in the lower experience group but not among the experienced surgeons ($r = 0.020$).

Conclusions: The results are consistent with the prediction that the importance of spatial ability in performance of laparoscopic skills should diminish with experience.

Keywords: Psychometrics; Spatial ability; Skill acquisition; Laparoscopic surgery

Previous research exploring the contributions of cognitive and perceptual motor abilities to technical skill in the operating room has found that one of the most important predictors of surgical skills is spatial ability. Spatial ability refers to a set of separable but related cognitive functions concerned with representing and processing spatial information, including visualization, spatial orientation, and speeded mental rotation or spatial relations. These processes have been comprehensively documented through standardized testing, and research has confirmed that such abilities vary significantly within the general population (for a recent review, see Hegarty and Waller [1]).

Using a comprehensive battery of psychometric tests, Schueneman et al [2] identified a cluster of tests that correlated in a factor they labeled complex visuospatial organization. Surgical residents' scores on this factor proved to be a more reliable predictor of operative skill than either psychomotor ability or personality factors [2]. Several studies have demonstrated a correlation between surgical skills and performance on the embedded figures test [3], which measures the ability to distinguish two-dimensional shapes within complex visual backgrounds [4–6]. Scores on tests of spatial relations [7] (which measure the ability to recognize a correspondence between two objects at differing spatial orientations) have been shown to predict the performance of surgical trainees on a microsurgery task [8]. More recently, a variety of spatial tests have been shown to predict learning of open [9] and laparoscopic [10,11] surgical skills, supporting the idea that spatial cognition contributes to operative expertise (but see Deary et al [12]).

A common element among these studies was the use of relatively inexperienced participants: residents, trainees, or participants in basic laparoscopic courses. The psychological literature indicates that the role of cognitive factors such as spatial ability can change substantially with experience. According to relevant theoretical approaches, human ac-

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tions are made possible by a hierarchy of control processes, ranging from high-level supervisory or executive processes, requiring a great deal of attentional resources (ie, conscious monitoring of performance), to lower-level, semiautomatic and fully automatic functions, requiring few, if any, attentional resources (ie, habitual, overlearned behaviors) [13]. If a task is novel or unfamiliar it relies on high-level attentional resources, but with sufficient practice performance becomes increasingly automatic, and even complex tasks can become somewhat proceduralized, thereby reducing cognitive load [13].

Given this framework, the role of higher-level cognition in the performance of complex tasks should reduce with the accumulation of experience, as the control mechanisms for the relevant skills become increasingly proceduralized. In line with this prediction, the correlation between cognitive abilities and performance has been shown to attenuate with practice, as the role of cognition gradually diminishes [14,15]. If these findings generalize to surgery, the relative importance of individual differences in spatial cognitive ability will diminish as a surgeon's experience increases.

On the basis of these assumptions, three testable hypotheses were generated for the present study. First, given the heavy spatial demands of minimally invasive techniques, it is possible that surgeons who choose to specialize in such methods self-select during training according to spatial ability. Although previous studies have found no evidence of such self-selection among surgeons (eg, Harris et al [16]), these have not explicitly examined videoscopic specialists. Thus, we predicted that the spatial abilities of laparoscopic surgeons would prove to be exceptional, relative to the general population.

Second, if spatial ability is an important factor for determining videoscopic operative skills, individual variations in this factor will be related to a surgeon's performance under minimally invasive conditions. Thus, our second prediction was that spatial ability would correlate positively with videoscopic operative skills.

Third, if the effects of higher-level cognitive functions are moderated by practice, the relative importance of spatial abilities should differ according to the experience level of the surgeon. Thus, the correlation between spatial abilities and operative skills will be higher among relative novices than among experienced surgeons.

In the present study we examined the relationship between spatial skills, videoscopic experience, and surgical performance. Measures were taken of spatial visualization ability and videoscopic experience among surgeons, and these were correlated with surgical skills rated in vivo during minimally invasive techniques.

Methods

Two groups of surgeons attending videoscopic training courses at the University of California, San Francisco (UCSF), were recruited over a period of 9 months. Forty-eight surgeons (42 male, 6 female) attended a 2.5 day advanced videoscopic surgery course for general surgeons. Forty-five surgeons (42 male, 3 female) attended a 1.5-day introductory laparoscopic urologic surgery course. Consent was obtained from all participants in this research, which was carried out under the cognizance of the UCSF Committee on Human Research. Three measures were obtained for all participants: spatial abilities, videoscopic experience, and operative skills.

Spatial abilities were measured with a timed paper-and-pencil visualization test (paper folding [17]). This standardized measure requires subjects to visualize a sheet of paper folding in various directions, and to reason about the final locations of holes punched through all layers of the sheet while it is folded.

Participants were asked to estimate their experience performing relevant laparoscopic procedures listed on a questionnaire. To produce an estimate of experience for correlation analyses, the total number of procedures was summed for each participant in each group, without any adjustment for the relative difficulty of the procedures. A log transform was then applied to the sum, as justified by the power law relationship in learning curves [18].

Table 1
Videoscopic surgery performance rating form

1.	Understands the principles of use of instruments
2.	Handles laparoscope in an effective manner
3.	Handles tissues in a manner to minimize damage or the potential for damage
4.	Movements planned appropriately before executing
5.	Movements executed effectively and efficiently
6.	Uses two hands in a coordinated fashion
7.	When in role of surgeon, shows ability to utilize and give appropriate direction to assistants
8.	When in role of assistant, shows ability to understand and anticipate flow of operation
9.	Able to acquire new skills
10.	Rate the overall performance of this participant

Instructors were asked to rate the participant's performance in each category, irrespective of training level. Performance was on a scale of 1 to 7 in which 1 was poor, 4 was average, and 7 was excellent.

Validation of skills questionnaire

Operative skills were measured using a questionnaire devised for the study (Table 1). It comprised 10 questions designed to address differing aspects of operative skill on a 7-point global rating scale. The structure of the questionnaire followed a model previously developed and validated for open surgical skills assessment by Martin et al [19]. The skills ratings were conducted by course instructors, who observed the participants working under videoscopic conditions in live animals over 2 half-days. In the majority of cases (74 of 93 participants), two ratings were obtained from different instructors for each participant.

Table 2
Performance on three measures for both experimental groups

Measure	Advanced course	Urology course
Videoscopic experience, median (range)	302 (63–1,020)*	13 (0–105)
Operative skill rating, mean (SD)	4.63 (0.76)†	4.13 (0.93)
Spatial ability, mean (SD)	10.45 (3.49)	9.83 (3.98)

* $P < 0.001$, Mann-Whitney U test (two-tailed).
† $P < 0.005$, independent samples t test (two-tailed).

The questionnaire was assessed for reliability using standard measures. Questions 1 to 9 measured differing aspects of videoscopic skills, and question 10 measured overall performance. The aggregate scores from questions 1 to 9 correlated highly with scores on question 10 (n = 93, r = 0.947, $P < 0.001$), implying that the final item appropriately summarized the surgeons' overall performances. Cronbach's alpha was 0.98, indicating high internal consistency and implying that the 10 questions measured closely related skills. In view of this indication of internal reliability, an aggregate score representing the overall skill level of each participant was calculated (mean rating across all questions and raters), and this was used in the statistical analyses.

Inter-rater reliability was determined by correlating the scores from the two raters of each participant in the cases where two separate ratings were obtained. The intraclass correlation (average measure, one-way random effects model) confirmed that statistically significant inter-rater agreement was achieved (n = 74, $r = 0.467$, $P < 0.005$).

Results

Table 2 shows average scores on the three measures (videoscopic experience, operative skill, and spatial ability). The advanced course participants reported substantial experience with laparoscopic cholecystectomy (median 300 operations; range 50 to 1,000) but less experience with other laparoscopic procedures (median 20.5; range 0 to 329). The urology course participants reported their experience as primary surgeons in specified operative procedures, as primary surgeon in any diagnostic procedures, and as assistant. Even when experience in these categories was totaled, their experience was significantly lower than the advanced group. The two groups differed significantly in operative skill ratings, but not in spatial ability.

The surgeons' paper folding scores were compared with the published test norms from a college student population [17]. The surgeons' scores (mean 10.14, SD = 3.73) were somewhat lower than the normative scores (mean 13.8, SD = 4.5). In the urology course (lower experience) group, spatial ability was a significant predictor of videoscopic skill ($r = 0.39$, $P < 0.01$; Fig. 1a). By contrast, among the advanced course (high experience) group, there was no significant correlation between these two factors (Fig. 1b).

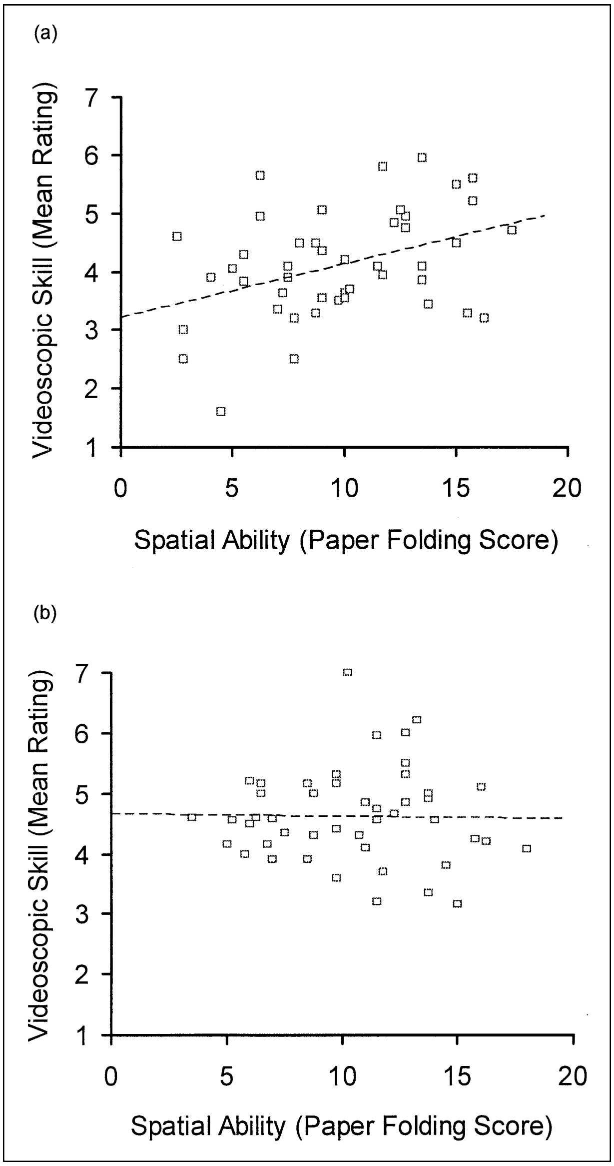

Fig. 1. Relationship between spatial ability (paper folding score) and videoscopic skill (mean rating) among the two groups of surgeons: (**a**) Urology course (lower experience group); (**b**) Advanced course (higher experience group).

A significant correlation between videoscopic experience and operative skill was found only in the advanced group ($r = 0.31$, $P < 0.05$).

Comments

Both groups in this study had scores on the paper folding test that were comparable with, and in fact slightly lower than, published norms. This finding is consistent with previous studies, which have found surgeons' spatial abilities to be similar to or lower than those of medical students [20] or trainees in other medical specialties [16,21]. These studies and the present effort have found a wide range of spatial ability among surgeons, suggesting that the hypothesis that surgeons are a spatially exceptional population is false. Surgeons' lower mean scores when compared with published norms could be explained by age differences. Although participants' ages were not recorded in the present study, they were clearly older than the college population from which norms were established. Performance on the paper folding test decreases by about 0.5 to 1.5 standard deviations over the lifespan, even in professions that are spatially demanding such as architecture or engineering [22].

In the lower experience group attending the urology course, a significant correlation was found between scores on the paper folding test and operative skills. No such relationship was found among the higher experience group attending the advanced course. This result is consistent with the findings of skill acquisition researchers [14,15], who have shown that cognitive abilities such as spatial ability are important during the initial phase of learning a new skill, but less important in later phases in which skills become increasingly proceduralized [13].

With a median of only 13 procedures experience, participants in the urologic surgery course were clearly in the early phase of developing their laparoscopic skills. Similarly, all previous correlation studies examining the role of spatial ability in open [2,4–6,8,9,12] or laparoscopic [10,11] surgery have used residents, trainees, or participants in basic laparoscopic courses. With the exception of Deary et al [12], these studies demonstrated significant correlations between spatial ability and surgical skill. Participants in our advanced laparoscopic surgery course, however, had substantial laparoscopic experience with a median of more than 300 procedures. To our knowledge, this is the first study to examine the role of spatial ability in the skill of such an experienced group. In contrast to the urology group, there was no correlation between spatial ability and performance in this group, despite the similar setting and experimental conditions of the two courses.

The advantages of the course setting included the ability to sample a broad community of practicing surgeons and test their laparoscopic skills in an animate laboratory. However, the courses were not an ideal environment for experiments. Course participants were not a random sample of a population of surgeons. The duration of the courses limited the time for instructors to observe participants. Consequently, our inter-rater reliability was not as high as some previous studies using similar checklists [19,23], limiting the range of correlation that could then be observed with other measures. While we acknowledge that the skills rating checklist was a subjective measure, this type of approach is commonly used and has been previously validated [19]. There was only time in the course schedules to give one ability test, but the test we chose (paper folding) is a well-recognized measure of complex visualization ability that has shown high correlations with skills demanding of visualization [17]. Despite the limitations of the experiments, the results depicted in Fig. 1b demonstrate that even experienced surgeons with low spatial ability could achieve acceptable skill rankings. This is evidence of the reduced importance of spatial ability with experience.

The possibility of using tests of spatial ability as part of a battery to assess the aptitude of medical students for success in surgery has been discussed frequently [21,24,25]. Our results and those in the skill acquisition literature suggest that this should be approached with caution. Different abilities may be called upon at different stages of skill development. Most of the variance in skills ratings was not accounted for by either spatial ability or experience, indicating that other abilities could substantially influence achieved skill. While the importance of cognitive abilities diminishes with practice, the role of perceptual and motor abilities has been shown to increase over time [14,15]. Thus a greater effect of motor skills might be expected among experienced surgeons, relative to those with less experience. Future studies should examine the basis of skill not only during training but also at later stages of experience, ideally using a longitudinal paradigm to track developmental changes in this relationship. Tests of complex visualization ability such as paper folding tend to correlate with general intelligence (g), so it is desirable to also apply tests of general intelligence to be able to distinguish the specific contribution of spatial ability.

If some with lower spatial ability are slower to learn new skills, but nevertheless capable of achieving acceptable levels of skill in laparoscopic surgery, then a key question is whether their learning can be accelerated by focused training outside the operating room. Wanzel et al [9] found that although lower spatial residents were poorer initially in learning a Z-plasty procedure, with practice and feedback they achieved a level of competence comparable with that of persons with better spatial ability. Although there has not been a lot of research on teaching spatially demanding skills, the results so far are encouraging [26]. For example, Gerson et al [27] describe a curriculum that was successful in improving three-dimensional visualization skills among freshman engineering students through the use of visual aids and computer exercises. The use of bench models and virtual environments (or virtual reality) is being explored for training laparoscopic skills, and early results have shown transfer to performance in the operating room [28,29]. Research is necessary to elucidate the role of individual differences in abilities and optimize training to accommodate differences.

This research and previous efforts have studied skills in relatively structured settings. The role of cognitive factors in skilled performance will be greater in complex or unfamiliar situations [14], such as those encountered in the operating room. Spatial ability has been shown to be important in mechanical reasoning [30]. Research is necessary to determine its role in reasoning in surgical problem solving. Although it is inherently difficult to perform controlled studies in the operating room, it will be possible in simulation in virtual environments, just as pilot performance is studied in aircraft simulators [31].

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