Applied Ergonomics 116 (2024) 104210

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Optical angle and visuospatial ability affect basic laparoscopic simulator task performance

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ARTICLE INFO

Keywords:
Visuospatial ability
Laparoscopy
Training
Optical angle

ABSTRACT

Surgical trainees show decreased performance during laparoscopic surgery when the laparoscope (camera) is not aligned with their line of sight towards the operating area. In this study we investigate the influence of visuospatial ability on laparoscopic simulator performance under such non-zero optical angles. Novices were invited to participate in a laparoscopic training session. After completing a visuospatial ability assessment, they performed a simplified laparoscopic task on an in-house developed laparoscopic simulator under eight different optical angles ranging between 0° and 315° in steps of 45°. Data-analysis showed decreased performance under all non-zero optical angles for task duration (mean difference between 1506 and 5049 ms, standard error between 499 and 507, $p < .05$) and for accuracy under optical angles greater than ±45° (mean difference between 1.48 and 2.11, standard error 0.32, $p < .01$). Performance-zones were identified for various optical angle ranges and differed for task duration and accuracy. Participants of high visuospatial ability performed significantly better under non-zero angles for accuracy compared to participants of low visuospatial ability (mean difference 0.95, standard error 0.34, $p < .01$), except for the 180° optical angle (no difference).

Educational relevance

The results of this study demonstrated that psychomotor performance decreases when performing laparoscopic tasks (which are shown on a monitor) under a different angle than the line of vision of the surgeon towards the operating field. This decrease in performance was dependent on the visuospatial ability of the surgeon. Knowledge of this study can be used for future training design and for future procedure design of surgical procedures.

1. Introduction

To perform laparoscopic procedures, surgeons have to learn to operate under indirect vision, as the *laparoscope* (a thin, rigid, cylindrical instrument that contains a camera) is inserted through a small incision in the abdomen of the patient and the surgeon receives visual feedback on their actions through a monitor. In this setting, *line of sight* refers to the horizontal projection of the line connecting the surgeon to the operating area. Whenever possible, the monitor is placed in an extension of this line of sight. *Line of scope* refers to the horizontal projection of the line connecting the laparoscope to the operating field when the laparoscope has the operating area in view. The spatial challenge of working under indirect vision increases when the line of sight differs from the line of scope, i.e. when these two lines form a non-zero angle, the *optical angle* (Fig. 1). Previous research in laparoscopic training and the operating room showed decreasing performance and reaction time (measured in terms of task duration and error rates) and an increase in mental work load under increasing optical angles (Meng et al., 1996; Rhee et al., 2014; Ames et al., 2006; Swanstrom and Zheng, 2008; Zheng et al., 2003). The maximum optical angle of 180° however is a special case, with some previous studies in laparoscopic performance reporting the worst performance under an 180° optical angle (Meng et al., 1996; Rhee et al., 2014; Ames et al., 2006), and another showing better performance under an 180° optical angle compared to optical angles of ±90–135° (Klein et al., 2015). Surgical educators and cognitive psychologists alike are interested in the mitigating role of cognitive abilities in training and performance of spatially challenging psychomotor tasks. In this study we investigate how visuospatial ability modulates performance in laparoscopic training under different optical angles.

Because the capacity to mentally rotate improves with increasing

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https://doi.org/10.1016/j.apergo.2023.104210
Received 23 June 2023; Received in revised form 12 December 2023; Accepted 14 December 2023
Available online 28 December 2023

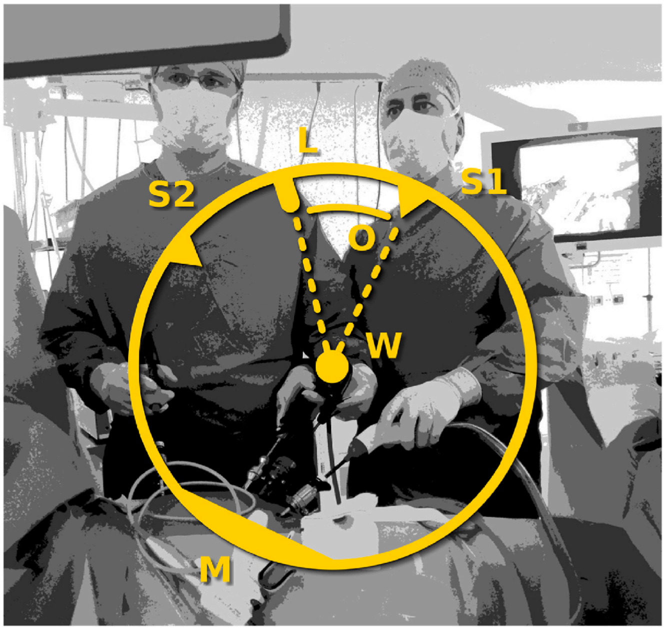

Fig. 1. A side view of a laparoscopic procedure in the operating room with a corresponding schematic top-down view in yellow to show the variables relevant to the challenges of laparoscopic indirect vision and optical angle (the angle between the line of scope and the line of sight). O = optical angle, S1 = operating surgeon 1, S2 = assisting surgeon 2, L = Laparoscope, W = operating area, M = monitor, L-W = line of scope, S1–W = line of sight. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

visuospatial ability (Shepard and Metzler, 1971), visuospatial ability likely influences surgical performance under non-zero optical angles. Visuospatial ability refers to the ability to mentally apprehend, encode, rotate, and manipulate three-dimensional objects (Lohman, 1979). Visuospatial ability is important in predicting success in various psychomotor skills such as piloting aircrafts, mechanical drawing (Humphreys and Lubinski, 1996; Quasha and Likert, 1937), and academically in mathematics and science (Hegarty et al., 2007). High visuospatial ability also correlates with better performance in minimally invasive surgery, as an earlier meta-analysis demonstrated improved laparoscopic performance for novices and more experienced surgeons with higher spatial ability (optical angle however was not taken into account as a separate variable) (Kramp et al., 2016). Also, visuospatial ability predicted surgical skill acquisition rate and can probably be used as criterion for assessing candidates for surgical training (Maan et al., 2012).

Earlier studies either investigated the effect of non-zero optical angles on surgical performance, or how visuospatial ability modulated surgical performance under a zero degrees optical angle. As far as we know, we are the first to report a study investigating the effect of both these variables on performance in a laparoscopic task. For practical reasons of training course design and instrument placement in the operating room, we wanted to know whether different optical angles with similar performance levels can be grouped into *zones of performance* for speed or accuracy. Speed and accuracy are associated with different training goals, accuracy being the more relevant proxy measure for clinical safety. Based on previous research we hypothesized that an increasing optical angle would result in a decrease in performance until an optical angle of 180°, after which it would similarly improve until 360°. As discussed above, performance at the 180° optical angle itself may be better than performance at the angles immediately before or after it, which would represent an exception to this pattern. A larger optical angle requires more mental rotation, which is performed faster and with less error by people of high visuospatial ability (Shepard and Metzler, 1971). Therefore we expected that this association between optical angle and performance would be affected by level of visuospatial ability, where performance for participants with low visuospatial ability would deteriorate more when switching from the 0° optical angle to the non-zero optical angles compared to participants with high visuospatial ability. If these hypotheses would be correct the results of this study would be a step towards individualized training programs that focus on training with non-zero optical angles in participants with reduced visuospatial ability, and visuospatial ability could be used as a selection criterion for admission to residency programs. Additionally, the results of this study could help indicate which non-zero optical angles should be avoided.

2. Materials and methods

2.1. Subjects

This study was performed at the University of Twente, The Netherlands. Participants were students of the bachelor's program in Psychology. This group was selected to represent a demographic similar to medical students but without medical or laparoscopic experience, to maximize the effect of individual differences in visuospatial ability and minimize the effects of relevant experience. Students could sign up for this study via a digital environment developed for participant recruitment (Sona Systems®). Participation as a subject in research studies is mandatory for students of Psychology at the University of Twente, who earn study credits for their time. The study protocol was not submitted to an ethical board, as this was not required for this type of research under Dutch law at the time of data collection (WMO, 2015). Based on a meta-analysis of Kramp et al. (2016), who found a medium to strong correlation between surgical performance in the operating room and visuospatial ability ($r = 0.50$) (Kramp et al., 2016), we expected an effect size between 0.5 and 0.8. To detect the lower limit of this expected effect size (0.5) power calculations with use of G*Power (Faul et al., 2009) revealed that a total of 28 participants were needed to achieve a power of 0.8 with an α error probability of 0.05.

2.2. Apparatus

An in-house designed simulator box was built with a round, rotatable camera lid (Fig. 2A and B). The round lid of this box was 270 mm in diameter, the dimensions of the box were 390x390x190 mm. The camera was a mini CMOS CCTV security camera with a 640x480 pixel resolution, wired with an RCA connector to a standard 22 inch LCD monitor. We opted for analog connectivity to avoid the latency of USB cameras. The camera was mounted on the edge of the underside of the lid and pointed to the center of the floor of the box, which was the location where the tasks had to be completed. This configuration allowed us to keep the experimental task in focus, while systematically varying the optical angle. The camera image was presented at a monitor in front of the participant and over the working area, a configuration that is typical for laparoscopic surgery. The tasks were performed with a modified laparoscopic single-use Maryland grasper from Johnson and Johnson, in which the grasping end was replaced by a capacitive touch pen for operating the touch sensitive screen of a tablet (Fig. 2C). OpenSesame 3.0.7 was used to program the tasks on the Samsung Galaxy Note 10.1 GT-N8000 touchscreen tablet running Android 4.1.2. To test visuospatial ability, participants completed the Mental Rotations Test (Vandenberg and Kuse, 1978) and the Surface Development Test (Ekstrom and Harman, 1976), two standard tests to assess visuospatial ability most commonly used in medical learning and training studies. These tests were digitized with the use of OpenSesame 3.0.7 and performed on a desktop PC running Windows 7. Data was analyzed by using SPSS Statistics for Windows, Version 25.0 (IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp).

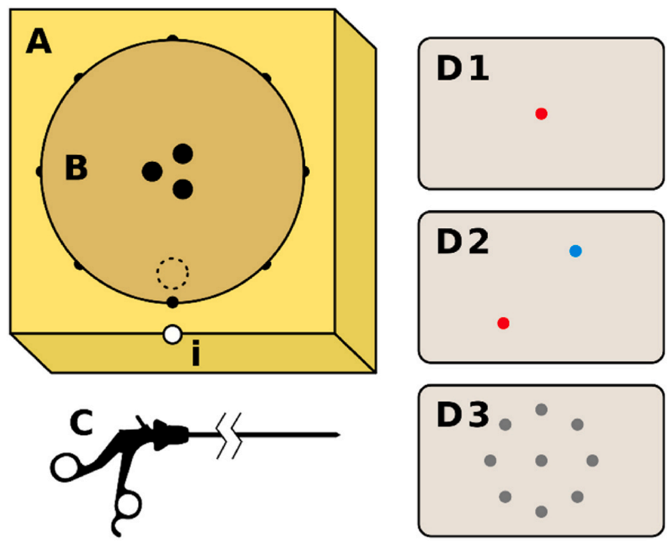

Fig. 2. Schematic representation of the experimental task setup. Tasks were performed in a simulator box (A) with a camera (dotted circle) attached to the underside of a rotatable lid (B). The camera was aimed at the center of the floor of the box where a tablet was located. By rotation of the lid the angle of this camera towards the tablet could be altered. Participants inserted a customized laparoscopic instrument that was altered to end in a capacitive stylus instead of a grasper (C) through a laparoscopic port, i.e. a small opening on the front of the box (i) with which they could operate the tablet. To initiate a task, the participant had to tap a red fixation target on a tablet which was located inside the simulator box (D1). This was followed by the actual task of hitting the two differently colored target areas positioned in opposition from each other (D2). For each camera position, eight pairs of targets needed to be tapped as shown in D3. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3. Task and procedure

The participants performed the same series of tasks in the simulator box under eight different optical angles. Participants used a laparoscopic stylus to tap targets on a tablet which was located on the bottom of the simulator box. To initiate a task, participants were instructed to tap and hold a red fixation target on the middle of the screen (Fig. 2D1), to standardize the starting point of the stylus and its distance to the targets. After the fixation target disappeared, two differently colored (red and blue), circular target areas appeared in opposition of each other (Fig. 2D2). This marked the start of the actual task, in which participants had to first tap the red target and then the blue target. The circular targets were of a standardized size, with a diameter of 17 mm. These targets were positioned at opposite ends of the tablet screen, ensuring a consistent distance of 80 mm between the centers of the two targets. For programming reasons, the target areas sensitive to clicking had to be square (17 × 17 mm) and were consequently slightly larger than the visible targets. When the target area was touched by the stylus it counted as a hit, but if the touchscreen was touched anywhere else than the target it counted as a miss. An audio signal informed the participant whether their attempt was successful or not. After this, the next task would start with a differently located pair of opposite dots (the location of the eight opposite pairs is indicated in Fig. 2D3). The order of appearance of a total of eight of such pairs of targets was randomized for each of the eight optical angles of the experiment.

After a trial run under the 0° optical angle to allow students to familiarize themselves with the apparatus and the procedure, the above-mentioned laparoscopic series of tasks was performed under 8 different optical angles (of 0°, 45°, 90°, 135°, 180°, −135°, −90°, and −45°). Under these different optical angles participants would see and do the same tasks, however seen from a different angle. Therefore, the representation of movements from the participant on the screen deviates increasingly from what the participant expects to see. Participants were instructed to adjust the camera to the requested angle by lifting, rotating, and repositioning the lid of the simulator box, which would reposition the camera fixed to the underside of this lid. A visual aid was incorporated on the box and the lid to guide the positioning (participants could match small half circles on the box with a small half circle on the lid to form a full circle). The order of the blocks and of the trials within the blocks were randomized in order to compensate for learning effects. Participants were asked to perform to the best of their ability on both accuracy and duration, but to prioritize accuracy.

These tasks were performed during a single 60-min session. Every participant was individually supervised during this entire session. At the start of the session but before performing the tasks, the participant was informed about the study and was given the opportunity to ask questions, after which an informed consent form was signed. After this, participants completed digitized versions of the Mental Rotations Test (Vandenberg and Kuse, 1978) and the Surface Development Test (Ekstrom and Harman, 1976), two standard tests to assess visuospatial ability most commonly used in medical learning and training studies.

2.4. Data preparation

The number of targets hit (accuracy) and the time needed to tap all 8 pairs of targets (duration) were automatically recorded for every individual optical angle by the Open Sesame script running on the tablet. We did not expect differences between the left or right optical angles, i.e. between −45° and 45°, −90° and 90° or −135° and 135°. To confirm this, we performed TOST procedures to assess the differences between the left and right optical angles, with a predefined smallest absolute difference of interest set at 1 s for duration and 1 point in score for accuracy. The choice of a smallest absolute difference of interest in the TOST procedures was informed by a small pilot study conducted prior to the main experiment. One point for accuracy and 1 s for duration emerged as meaningful and detectable units in our study's context. The TOST procedure demonstrated equivalence for both accuracy and duration. To improve statistical reliability, these optical angles were therefore clustered into a single outcome measure for 45°, 90°, and 135° by averaging the scores of the left and right optical angles, which was done separately for accuracy and duration. To investigate the influence of visuospatial ability on performance without taking into account the effect of the optical angle, we calculated grand totals for accuracy and duration by adding the averaged values for all eight optical angles, separately for accuracy and duration.

To evaluate the effect of visuospatial ability on task performance, a visuospatial ability score was calculated for each participant. The number of correct answers for both visuospatial tests were first scored for each participant. Both the Mental Rotation Test and the Surface Development Test measure the same visuospatial ability factor (i.e., *Visualization*, 'The ability to apprehend a spatial form, object, or scene and match it with another spatial object, form, or scene with the requirement to rotate it (one or more times) in two or three dimensions.' (Carroll, 1993)). Both tests have good reliability scores of respectively .83 and .90 (Vandenberg and Kuse, 1978; Ekstrom and Harman, 1976). The results of both tests were normalized and averaged to improve robustness.

A 'decrease in performance' variable between the 0° optical angle and the optical angle with the worst performance (assessed per individual participant) was calculated post-hoc after analyzing performance to assess if performance of participants with low visuospatial ability decreased more with a non-zero angle compared to participants with high visuospatial ability.

2.5. Statistical analysis

Shapiro-Wilk tests were used to determine if data followed a normal distribution. For most variables this was not the case and non-parametric tests were used to analyze the data.

The statistical analysis employed a linear mixed-effects model, with optical angle and visuospatial ability as fixed effects, and participants included as random effects. Given the discrete and predetermined nature of the optical angles tested (i.e., 0°, 45°, 90°, 135°, 180°, −135°, −90°, and −45°), we opted to treat optical angle and visuospatial ability as fixed effects to explore their direct influence on laparoscopic performance. Including participants as random effects was deemed essential to account for individual variability and enhance the robustness of our findings.

Hence, the model employed in our analysis was as follows:

$\text{Performance}_{ij} = \beta_0 + \beta_1 \times \text{Optical Angle}_{ij} + \beta_2 \times \text{Visuospatial Ability}_i + \gamma_{0i} + \epsilon_{ij}$

Where:

Performance_{ij} = Performance (duration or score) of subject i at optical angle j.

$\text{Optical Angle}_{ij}$ = The optical angle during a specific measurement or observation for individual i.

$\text{Visuospatial Ability}_i$ = Visuospatial ability of individual i.

Coefficients β_0, β_1 and β_2 = Coefficients representing the intercept, the effect of optical angle, and the effect of visuospatial ability, respectively (fixed effects).

Coefficient γ_{0i} = Random intercept for individual i (random effect).

Coefficient ϵ_{ij} = Residual error term.

We compared the main effects of optical angle and visuospatial ability, with Bonferroni corrections for multiplicity. Additionally, when no difference was found in performance under two specific optical angles, TOST procedures were performed to test for equivalence, with a predefined smallest absolute difference of interest of 1 s for duration and 1 point for accuracy.

Mann Whitney U tests were used to compare high and low visuospatial ability groups for the decrease in performance variable between the 0° angle and the non-zero optical angles. For all tests a p value equal to- or below 0.05 was considered significant.

3. Results

3.1. Participants

A total of 37 students participated in the experimental session. However, due to software problems data from only 33 participants were analyzed. Of the participants analyzed, 20 participants were male and 13 participants were female. Age ranged from 19 to 33 years. Mean age was 22.9 years with a standard deviation of 3.2 years. One participant was left-handed. None of the participants reported previous experience with laparoscopy or uncorrected substandard visual acuity. The participants were post-hoc divided in a low visuospatial ability group (n = 17) and a high visuospatial ability group (n = 16) by a mean split (Table 1).

3.2. Duration

TOST procedures confirmed equivalence for task duration (mean differences of −1.33s and 0.67s, $p < .01$) between opposite right and left optical angles. To improve statistical reliability, these optical angles were therefore clustered into a single outcome measure for 45°, 90°, and 135° by averaging the scores of the left and right optical angles.

Table 1
Characteristics of all participants and of the two groups of low- and high visuospatial ability.

	Total	Low visuospatial ability	High visuospatial ability
Participants	33	17	16
Mean age	22.9	23.1	22.6
Female/Male	13/20	8/9	4/12

Participants performed significantly faster under the 0° optical angle task compared to all non-zero optical angles (mean difference between 1506 and 5049 ms, standard error between 499 and 507, $p < .05$) (Fig. 3A). Performance under the 45° optical angle was significantly faster compared to the optical angles of 90°, 135° and 180° (mean difference between 1581 and 3543 ms, standard error between 495 and 496, $p < .05$). Task duration under an 180° optical angle was significantly shorter than duration under 90° and 135° (mean difference between 1759 and 1962 ms, standard error between 499 and 503, $p < .01$). Task duration under optical angles of 90° and 135° did not differ significantly from each other. TOST procedures did not demonstrate equivalence between 90° and 135° (mean duration 90° = 8128 ms, mean duration 135° = 7925 ms, maximum $p = .15$ with $t = -1.48$). Therefore, it was not possible to cluster performance of different optical angles in performance zones for duration.

3.3. Task accuracy

TOST procedures confirmed equivalence for accuracy scores (mean differences of 0.69 and −1.31, $p < .05$) between opposite right and left optical angles. To improve statistical reliability, these optical angles were therefore clustered into a single outcome measure for 45°, 90°, and 135° by averaging the scores of the left and right optical angles. The results demonstrated that a 0° optical angle did not differ significantly for accuracy compared to the 45° optical angle, but showed significantly higher accuracy compared to the 90°, 135° and 180° optical angles (Fig. 3B) (mean difference between 1.48 and 2.11, standard error 0.32, $p < .01$). There were no significant differences in accuracy between the optical angles of 90°, 135° and 180°. TOST procedures demonstrated equivalence between 0° and 45° (mean differences of −0.88 and 1.12, $p < .01$), 90°–135° (mean differences of −0.56 and 1.44, $p < .01$) and 90°–180° (mean differences of −1.21 and 0.79, $p < .01$)." No equivalence could be demonstrated between the 135° optical angle and 180° (mean score 135° = 4.86, mean score 180° = 5.49, maximum $p = .21$ with $t = 1.30$). Based on these results optical angles were clustered in three performance-zones (Fig. 4).

3.4. Influence of visuospatial ability

Performance in duration and accuracy for both groups of low and high visuospatial ability under each optical angle is visualized in Fig. 3. There was no significant difference between the low and high visuospatial ability group for total task duration across the trials (mean difference −236 ms, standard error 847, $p = .78$). For the individual optical angles also no differences in duration were found between the low and high visuospatial ability group (Table 2).

When comparing total session accuracy score between the two groups, the results demonstrated a significant difference, where accuracy was higher for the group of high visuospatial ability (mean difference 0.95, standard error 0.34, $p < .01$). When comparing accuracy between the groups for every optical angle individually, the results did not demonstrate a significant difference between the two groups under the 0° and 180° optical angle (Table 2). Under all the other optical angles (45°, 90° and 135°) there was a significant difference in accuracy between the two groups, with the high visuospatial group outperforming the low visuospatial group.

To investigate if visuospatial ability modulates the effect of optical angle, we compared difference in accuracy (delta accuracy) and difference in duration (delta duration) between the 0° optical angle and the optical angle with the worst performance for the high- and low visuospatial ability groups. We found no differences in delta duration ($z = -0.216$, $p = .829$). For delta accuracy however we did find such an effect, performance breakdown appeared significantly higher for the low visuospatial ability group ($z = -2.36$, $p = .02$).

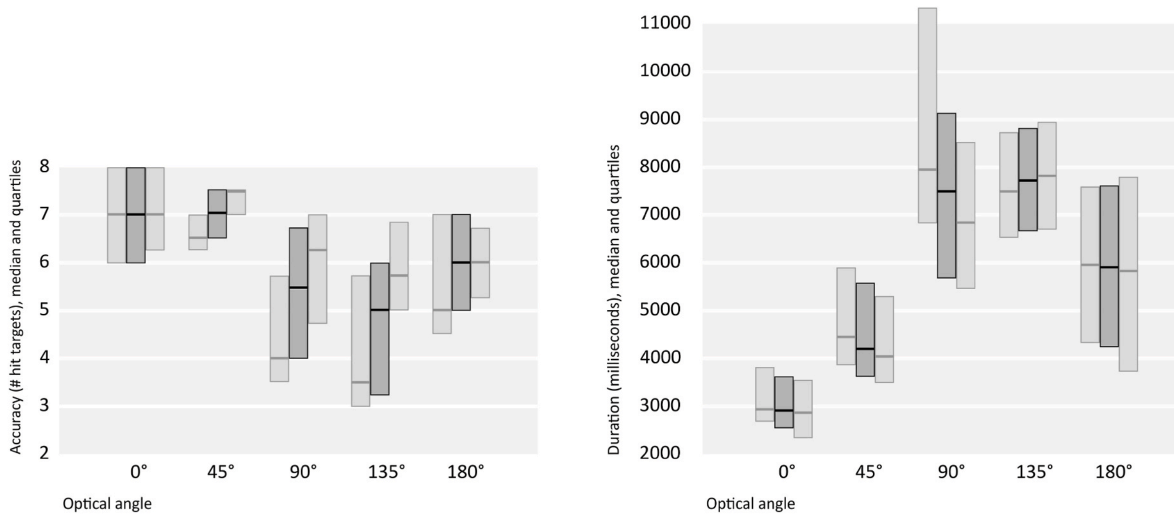

Fig. 3. Task performance under systematically varied optical angles. In each cluster of boxes, left boxes represents performance of the group of the low visuospatial ability, and right boxes the group of high visuospatial ability. Middle boxes represent performance of both groups combined. (left) Accuracy under varying optical angles. (right) Task duration under systematically varied optical angles.

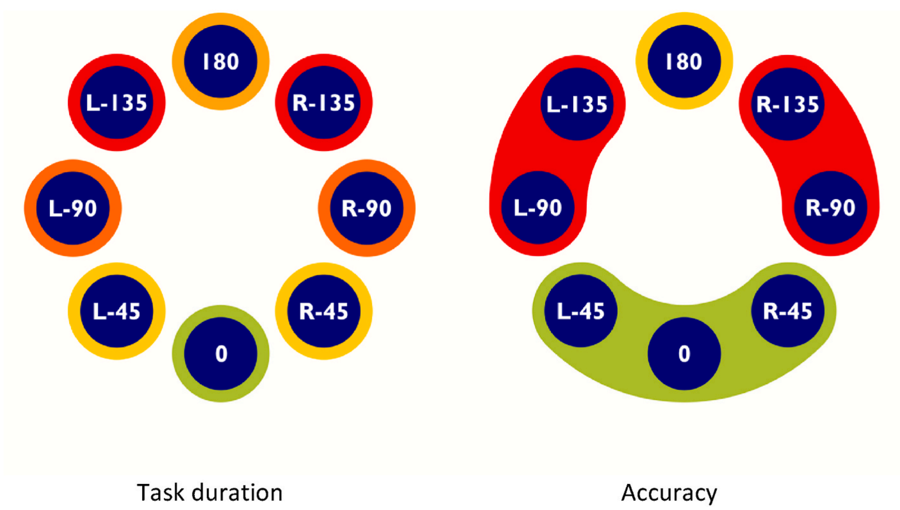

Fig. 4. *Performance-zones were defined for accuracy but not duration, based on performance under different optical angles. Performance degrades under increasing optical angles, with the exception of the 180° angle, which sits between the 90°-135° and 45° clusters in terms of performance for both duration and accuracy.*

Table 2
Linear mixed models for duration and accuracy between the groups of low visuospatial and high visuospatial ability for every optical angle individually. * = significant at or below the .01 level.

Duration	0°	45°	90°	135°	180°
Estimate effect	131.93	484.53	1624.88	−485.78	−236.04
Standard error	308.89	394.62	999.59	733.54	846.68
t value	0.427	1.23	1.63	−0.66	−0.28
p value	0.67	0.23	0.12	0.51	0.78
Accuracy	0°	45°	90°	135°	180°
Estimate effect	−0.06	−0.96	−1.41	−1.90	−0.39
Standard error	0.34	0.30	0.53	0.50	0.56
t value	−0.18	−3.20	−2.64	−3.80	−0.70
p value	0.86	**<.01***	**0.01***	**<.01***	0.48

4. Discussion

Participants showed increased performance degradation for both duration and accuracy when the optical angle deviated further from zero, with the exception of the 180° optical angle (where performance was between those of the 45° and 90° angle). Optical angles that did not differ significantly from each other and were statistically equivalent were clustered in performance zones, which could only be done for accuracy, as performance in duration was not equivalent between any optical angle. Low visuospatial ability increased the negative effect of optical angle on accuracy, except for the 0° and 180° optical angles.

Some previous studies described an increase in task duration with increasing optical angle (Meng et al., 1996; Rhee et al., 2014; Ames et al., 2006). Rhee et al. reported a linear trend between task duration and an increase in optical angle, however all three studies omitted a direct comparison between the 180° angle to other optical angles. Klein and colleagues did study performance under a wider range of optical angles, and our results confirmed their results (Klein et al., 2015). They found that the 180° optical angle was an exception to the linear trend between an increasing optical angle and increasing task duration. An explanation for this finding could be that under a camera alignment of 180° the fulcrum effect is no longer present (Dunnican et al., 2010). Inverted image condition under an 180° optical angle therefore may facilitate learning among novices due to a natural and expected representation of movement (Crothers et al., 1999). Previous research in psychomotor tasks performance under different visual perspectives without a fulcrum effect however also demonstrated better performance under an 180° optical angle compared to a 90° and 135° optical angle (Cunningham, 1989; Kim et al., 1987). This is in line with the idea that different strategies can be adopted for spatial problems (Schultz, 1991; Kozhevnikov and Hegarty, 2001). Two strategies suggested (Schultz, 1991) consist of mental rotation of either the working field or subject movement (mental self-movement) (Schultz, 1991). The third strategy he suggested is an analytic strategy which does not require mental rotation, but uses key features of a spatial problem. An analytic strategy previously suggested is that a reversed direction of movement is used under an 180° optical angle compared to a 0° optical angle (mirroring) (Cunningham, 1989), thus mental rotation is no longer needed. This interpretation is supported by the finding that performance under 180° is not affected by visuospatial ability. The performance zones we identified are also in line with the idea of strategy selection, as earlier results (Kozhevnikov and Hegarty, 2001) suggested an object rotation strategy (mentally rotating an object) between the 45–70° optical angles but a perspective taking strategy (imagining your body in a different position relative to the object) for 90–150° optical angles (Kozhevnikov and Hegarty, 2001). In their study, perspective taking but not object rotation was associated with visuospatial ability. It would be interesting to research whether our low-angle performances zones correspond with an object rotation strategy and our high-angle performance zones with a perspective taking strategy. Training specific visuospatial problem-solving strategies may support the acquisition of a wide range of visuospatial challenging skills.

A previous meta-analysis by Kramp et al. showed an overall significant correlation between laparoscopic skills and VSA (Kramp et al., 2016). Cochrane Q tests showed substantial heterogeneity in the results of the used studies in this meta-analysis, as not all studies demonstrated a significant correlation between visuospatial ability and laparoscopic performance. In this meta-analysis optical angle was not taken into account as a separate variable. The studies included in this meta-analysis used varying methodology to assess the impact of camera angle, and camera angles differed between studies. The heterogeneity of these earlier studies as to the impact of visuospatial ability on laparoscopic performance could be explained by our finding that this impact depends on optical angle.

In this study, students were instructed to prioritize accuracy over duration as this corresponds to actual surgery. In surgery, like in other fields, there is a trade-off between duration and accuracy (Chien et al., 2010) and this could explain the differences between the performance zones for task duration and accuracy. We found significant better performance on accuracy for participants with high visuospatial ability, however equal performance on task duration. This might imply that accuracy is more affected by visuospatial ability. As task duration has often been used as the main performance result in studies on surgical performance development, this could mean that the impact of visuospatial ability on surgical performance is underestimated.

4.2. Limitations

The results of this research are based on simulated laparoscopy with strongly simplified exercises. Actual surgery differs in many ways, including task complexity, complexity of the environment, and professional experience of the practitioner. To be relevant to laparoscopic surgery, more work is needed to confirm our findings in environments of greater ecological validity, such as the surgical skills lab and the operating room.

Further limiting the ecological validity of our study is the choice for non-medical students as participants. This was done to utilize a similar demographic as medical students, but without confounding variables such as differences in laparoscopic experience.

The performance zones as defined in this study will need additional verification, as factors such as ecological validity and power of the study may greatly impact the specifics of such zones. However, the support of different visuospatial task execution strategies corresponding to our performance zones (Kozhevnikov and Hegarty, 2001) suggests this is a valuable path to explore.

4.3. Impact

Current training programs are often focused on training laparoscopic skills under a 0° optical angle. Implementing non-zero optical angle training could move part of the learning back from the operating room to the skills lab. The modulation of performance under non-zero and non-180° optical angles by visuospatial ability can inform adaptive training design, for example by more extensive training for these angles for trainees of low visuospatial ability. Another option to stop the negative effects of non-zero optical angles is to prevent the use of such angles. This could possibly be achieved by adapting the procedure design or investing more time peri-procedural to create a laparoscopic port for a 0° optical angle.

The concept of different performance zones as demonstrated in this study can be used as an aid for future studies about laparoscopic skills development and the optical angle. Performance zones could be used to optimize *trocar*- and team placement. The trocar is the port of entry for the laparoscopic instruments and camera, placed through the skin of the patient's abdomen. During a laparoscopic procedure the introduction of an extra trocar is sometimes considered to obtain a better view of the operating field. The concept of performance zones can help guide extra trocar placement in terms of a trade-off between visibility of the surgical anatomy and performance penalty.

4.4. Future research

For practical purposes, the results of this study need to be extended to the medical domain, for instance in similar studies with medical students/surgeons located in the skills lab or the operating room. For example, are similar performance zones present in such setting? It is also important to learn more about the learning curves for different optical angles and their interaction with visuospatial ability. Is there a lasting performance penalty for difficult optical angles and people of low visuospatial ability? What kind of training effort is needed to perform comfortably under which optical angle? Answering these questions will help us implement adaptive training in which course design and duration depends on individual abilities, competencies and experience (Zahabi and Abdul Razak, 2020; Bergeron, 2008; Metzler-Baddeley and Baddeley, 2009). Other questions to be answered in future research have to do with transfer of skills, e.g. to which degree does training a task under a specific optical angle transfer to performance under adjacent angles? Does training one skill under a specific optical angle provide an advantage for learning the next skill under that angle? It would also be useful to learn more about the possible strategies which are used to cope with different optical angles and how these strategies can be used to increase training efficiency. For example, are some strategies more effective or efficient than others? Is it useful to guide learners of different visuospatial ability towards different visuospatial problem solving strategies?

4.5. Conclusions

Performance on a simplified laparoscopic task degrades with increasing optical angle, with the exception of the 180° optical angle. Optical angles can be grouped in performance zones, which differ for task duration and accuracy. High visuospatial ability was linked to better performance for accuracy under all optical angles other than the 0° and 180° optical angle. Visuospatial ability did not impact task duration.

Ethics approval and consent to participate

All methods were carried out in accordance with relevant guidelines and regulations. In compliance to Dutch legislation this study design was not submitted to an ethical board. As covered in the Medical Research Involving Human Subjects Act (WMO) stated in Article 1(2) and defined by the Central Committee on Research Involving Human Subjects this study protocol is not defined as medical/scientific research as it primarily investigates skills acquisition and does not answer direct questions in the field of illness and health, but is therefore defined as a non-MWO study for which ethical assessment is not obliged. For the processing and storage of participant information voluntary informed consent was obtained from all participating students, in compliance with national (Dutch) and European privacy law referred to in article 32 of Regulation (EU) 2016/679 "Processing of personal data".

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Julian Ebelhauser for his involvement in data collection and initial analysis of this study as a master student in the Department of Cognitive Psychology and Ergonomics of Twente University. His master-thesis is based on this dataset and initial analysis.

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