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INNOVATION

Influence of 3D laparoscopic surgery on surgeon's visual pattern and mental workload

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ABSTRACT

Previous studies have found that surgeons perform better in three-dimensional (3D) surgery than in two-dimensional (2D) surgery. However, no comparative studies have revealed the impact of 3D laparoscopic surgery on the surgeon's vision. To explore the effect of laparoscopic surgeons' depth perception during 3D laparoscopic surgery, 10 participants were recruited and performed 4 sets comparative simulated laparoscopic procedures in a virtual simulator, and eye movement signals were acquired, which were used to characteristics the visual differences. Fixation rate and saccade speed were used to characterise the influence of moderating variables for visual characteristics. The results from the data showed significant differences in eye movement behaviour. Compared with 2D laparoscopic surgery, surgeons have more average fixation rate (p-values = 0.001, 0.000, 0.003 and 0.015, respectively) and faster saccade speed (p-values = 0.037, 0.003, 0.073 and 0.105, respectively) in 3D laparoscopic surgery. The results of this study showed that surgeons had more efficient visual search in 3D laparoscopic surgery. At the same time, the results also indicated that surgeon's mental workload in 3D laparoscopic surgery was low. The relevant conclusions of this paper revealed the advantages of 3D laparoscopic surgery through visual efficiency.

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1. Introduction

At present, laparoscopic surgery is a preference to diagnosis and treatment for many diseases. When using a 2D laparoscope, the surgeon, especially a novice surgeon, often is confronted with inefficiency or even operation error because of the lack of depth perception and spatial orientation [1]. As an improvement of 2D laparoscopic surgery, 3D laparoscopy devices are increasingly being used in clinical practice. A large number of studies have shown that surgeons of primary experience in 3D usually get better performance than 2D, which is manifested in shorter operation practice and lower error rate [2]. The biggest difference between design and implementation is that the 3D laparoscopic lens with dual cameras can enable surgeons to form depth perception.

Current clinical comparative studies on 2D and 3D usually focus on the comparison of surgical results, operation time and other indicators. Systematic review and meta-analysis on its prospect found that, 3D laparoscopy was superior to 2D laparoscopy in terms of surgical time, perioperative complication sand hospital stay [3–5]. Research show that 3D displays offer large improvements over 2D displays in precision of depth judgements. It is worth mentioning that recent study attributed the probable cause on memory and visual search in naturalistic 2D and 3D environments [6]. Participants' memory for global spatial context is helpful in making search more efficient.

Eye movement behaviours, as an index that can characterise the surgeon's mental workload state, has been widely used in related researches [7–9]. The collection of eye movement signals has the characteristics of convenience, non-invasive, sensitive characterisation and so on. For instance, eye movements of neurosurgeons could be gathered as analysis target when they using a surgical microscope in a recent study [10]. The study found that eye movement patterns were correlated with skill levels, whereas the surgeon with more expertise is associated with greater eye control, stability, and focussing. Using eye movement signals to study 3D scenes is also a research

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field that attracts more attention [3,5]. Heo et al. quantitative measurement of eyestrain on 3D stereoscopic display, and they found the degree of change of stereoscopic disparity (CSD) causes more eye movements variety than other factors [11].

Previous studies of our team also show that eye movement signals can be used as an effective tool to study laparoscopic surgeons' mental workload and skills in the operating room [9]. To provide the true reappearance for 2D and 3D laparoscopy surgical scene in vision and touch for the participants, laparoscopic virtual reality simulators are usually employed. Some studies have suggested that virtual simulators may be more reliable and convenient, and peg transfer, ball pick-and-drop, cutting and suturing are commonly simulation procedures [12].

2. Methods

2.1. Participants

The procedures of this study were carried out in accordance with approved guidelines. The Ethics Committee of Tongji Medical College, Huazhong University of Science and Technology approved this study (IORG No: IORG0003571). For a more realistic and appropriate experimental environment, this study had been performed in a real laparoscopic operating room in Wuhan Union hospital and the lighting conditions and other requirements for an operating environment were in strict compliance with related standards as in our previous paper [9]. All participants have completed informed consent. According to the requirements of the experiment, 10 male laparoscopic surgeons with enough laparoscopic surgery experience were recruited. The participants ranged from 28 to 35 years (mean age = 30.9, SD = 2.6).

2.2. Experimental platform and tasks

The experiment was executed with a laparoscopic training box, which was the most popular simulation device for laparoscopic surgery and was supported by 2D/3D laparoscopy for providing operating image. Scenarios of performing 3D laparoscopic simulated tasks were shown in Figure 1.

The four tasks were carried out as follows. Task one (Peg transfer): 12 small columns are erected on a plastic rigid plate, and 6 small columns on the left side are covered with foam triangular prism, and 6 small circles on the right side are empty. It is required to use the left-hand grip to clamp the prism in turn, transfer to the right-hand grip, and then put it on the symmetrical right small cylinder by the right-hand grip. After the transfer of the six prisms, it is moved back to the left side of the cylinder and back to the initial position. Task two (precise positioning): a rigid cylinder is erected with 10 small columns with a concave top. The participants are required to use the left and right hands to place the five small balls on the grooves, then replace the left and right hands and move the small balls from the grooves to the initial position. Task three (stitching): stitching with a needle holder with a 15-cm stitch, stitching and knots at the mark's position, and completing one surgical knot after three stitches. Task four (pattern cutting): the A4 print paper is printed with a black circular line with a

Figure 1. Scenarios of performing 3D laparoscopic simulated tasks.

diameter 10 cm, which requires precise cutting along the print line. This project mainly exercises the precision of cutting skills.

2.3. Workload assessment protocol

2.3.1. Data analysis

Ten participants performed the dual tasks including four simulated laparoscopic procedures in the same set of conditions, which allowed a within-subject comparison. Data were analysed using SPSS version 19.0 and GraphPad Prism 8.0. Considering the small number of samples, the data set was first analysed by Q–Q graph, and the results showed that the data set meets the requirements for analyse. Descriptive statistics are presented as the mean and SD. Differences of eye movement of under 2D/3D laparoscopic visual mode were identified using paired sample *t*-test. A in superscript denotes significant differences ($p < 0.05$).

2.3.2. Eye-tracking data

According to previous studies, dynamic visual search pattern and changes in attention characteristics can be evaluated by participants' eye movements, particularly pupil dilatation [13–15]. The Tobii Glasses 2 Eye Tracker (Tobii Technology, Danderyd, Sweden) was used as an eye-tracking instrument in our study. Before starting the procedure, the participants were equipped with the eye tracker and were asked to stare at black dots printed on a paper card for the calibration process. The physiological parameters of the participants' eyes were recorded during the calibration process.

Laparoscopic surgery requires a high degree of attention, and therefore, eye movement is more able to reflect the physiological state of the surgeon and surgical conditions. Here, fixation rate, saccade speed and saccade duration distribution were analysed as the focal index to measure mental workload during operation.

3. Results

The Descriptive statistics about overall experimental performances are shown in Table 1. Participants with intermediate laparoscopic surgery experience showed significant differences in two different types of experiments. Experiment duration, turnover and scores in four 3D simulation experiment were obviously better than in 2D. Take Peg transfer (task 1) as an example, participants finished faster ($p = 0.02$), had fewer mistakes ($p = 0.032$) and higher score ($p = 0.032$) in 3D simulation experiment.

In the experiment, we used fixation rate and saccade speed to characterise the dynamic visual search efficiency of the participants. The experimental results are presented in Tables 2 and 3, respectively. Compared with 2D laparoscopic surgery, surgeons in 3D laparoscopic surgery have significant more average fixation rate ($p = 0.001$, 0.000, 0.003 and 0.015, respectively) and faster saccade speed ($p = 0.037$, 0.003, 0.073 and 0.105, respectively), with significant difference in tasks 1 and 2.

Another interesting comparison result is shown in Figure 2 in the form of a clustered histogram. In the case of an exponential distribution, the saccade duration distributions in the two visual modes are different in certain intervals.

Table 1. Overall comparison results between 2D and 3D laparoscopic simulation experiments.

	2D	3D	*p*
Peg transfer			
Duration	99.6 ± 24.9	72.2 ± 12.5	0.02[a]
Turnover	2.3 ± 1.8	1.2 ± 1.7	0.032[a]
Score	88.5 ± 8.8	94.0 ± 8.4	0.032[a]
Precise positioning			
Duration	143.4 ± 33.6	101.8 ± 23.1	0.02[a]
Turnover	2.7 ± 2.1	1.3 ± 1.2	0.039[a]
Score	86.0 ± 9.9	94.0 ± 6.1	0.013[a]
Stitching			
Duration	269.9 ± 67.1	230.2 ± 62.8	0.08
Turnover	5.7 ± 1.4	3.6 ± 2.4	0.03[a]
Score	72.5 ± 8.2	82.0 ± 11.8	0.003[a]
Pattern cutting			
Duration	271.2 ± 61.8	265.4 ± 53.5	0.132
Turnover	7.7 ± 1.8	5.4 ± 2.0	0.02[a]
Score	60 ± 7.8	73.5 ± 9.4	0.000[a]

[a]denotes significant differences ($p < 0.05$).

Table 2. Average fixation rate of 10 participants under laparoscopic 2D/3D simulation experiment (N/M).

	Peg transfer	Precise positioning	Stitching	Pattern cutting
2D	46.07 ± 14.42	35.6 ± 8.1	15.08 ± 8.18	23.59 ± 8.72
3D	58.4 ± 13.89	43.21 ± 11.9	27.86 ± 8.93	29.06 ± 12.27
p	0.001[a]	0.000[a]	0.003[a]	0.015[a]

[a]denotes significant differences ($p < 0.05$)

Table 3. Average saccade speed of ten subjects under laparoscopic 2D/3D simulation experiment.

	Peg transfer	Precise positioning	Stitching	Precision cutting
2D	2.52 ± 0.55	2.26 ± 0.46	2.22 ± 0.59	1.82 ± 0.53
3D	2.99 ± 0.69	2.96 ± 0.48	2.72 ± 0.80	2.14 ± 0.89
t	−2.45	−4.04	−2.03	−1.80
p	0.037[a]	0.003[a]	0.073	0.105

[a]denotes significant differences ($p < 0.05$)

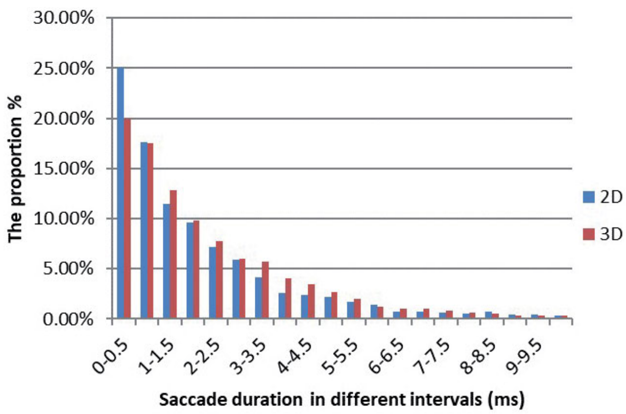

Figure 2. Proportion of saccades of different durations.

4. Discussion

The choice of surgical approach is a key issue in the operating room. At present, there are enough researches to explore 2D/3D laparoscopic technology. In a study published in 2012, Storz et al. [2] took part in the 2D/3D laparoscopic comparative study by using the medical student group and the expert group, and the experimental task was five common laparoscopic basic skill operations. The research results showed that in 80% (4/5) of the experimental tasks, the time and error rate for the participants to complete the experiment in the 3D experimental environment were significantly better than that in the 2D environment.

The studies of comparison of 3D and 2D endoscopy using eye tracking signals were implemented in recent years. A study implemented by Anschuetz et al. in 2019 evaluated the attention of the surgeon with fixation duration and blink rate [16]. They found that the fixation duration of the consultants' eye movements was shorter associated with 3D vision. This result is basically consistent with that of our study, but there is no significant difference between 3- vs 2-dimensional endoscopy in our study. A large number of studies have used fixation times, saccade time and saccade distance to explore movement visual search features of mobilisation, including fixation times and fixation times characteristics of participants' visual search and decision making in task situations. The reaction time is closely related to the accuracy and the distance of eye jump reflects the vision of participants' spatial characteristics of search, which is the main plus for participants to obtain effective information working mechanism. These metrics can be used to compare surgeons' visual search patterns and provide a reproducible framework for the analysis of gaze tracking in the 3D environment [17].

In our study, the performance, eye movement analysis and subjective scale of 2D/3D laparoscopic surgeons confirmed that 3D laparoscopic surgery can effectively influence eye movement mode and visual search mode. After analysing the data, it was found that the average scan rate and fixation rate of 3D laparoscopy were significantly higher than 2D laparoscopy, and the short scan rate of 3D laparoscopy was less. All these indicators show that in 3D scene, laparoscopic surgeons' eye movement activities are more active and visual search efficiency is higher. These conclusions are consistent with the expected research expectations. In 2002, a study using the eye movement index website homepage usability [18], the subjects' average fixation duration of four websites homepage was 520.50, 479.67, 399.42 and 458.67 ms, respectively, and the researchers believed that although there was no significant difference between the average fixation duration and the total fixation duration, they had the ability to reflect the usability and visual efficiency. Similar studies on average fixation time and total fixation time are also discussed from different aspects [19,20]. In addition, it can be found that the average fixation time in this study is significantly higher than the average fixation time in the web browsing mentioned above, which is caused by the large difference of eye movement indicators in different behaviours.

The difference between the results of this study and the expected results is that there is no statistical difference in the average scanning range under 2D/3D. This is not consistent with the existing conclusions in other research fields. It is generally believed that when the visual search efficiency is high, the span from the previous fixation point to the next fixation point will be larger, and there is no need to do too much fixation activity for the adjacent area of the target. This is mainly because the nature of laparoscopic surgery determines its refinement attribute, so the surgeon's more special eye movement mode also comes.

5. Conclusions

After analysis of surgeons' eye tracking signals during 3D laparoscopic surgery indicated that surgeon's visual pattern had advantage. In addition, surgeon confront with lower mental workload during 3D surgery. Our study is the first to address the surgeon's dynamic visual search capability between 2D and 3D laparoscopic surgery, using eye tracking signals. This study reveals an important reason for the performance difference of junior laparoscopic surgeon in operating room.

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Author contributions

J.Y.Z. contributed to the conception and design of the study, and wrote the main manuscript text. B.P.W. and Z.H.S. reviewed the experiments and analysed the data. J.Y.Z. and J.L. participated in the acquisition of data and statistical analysis. F.L. and J.L. reviewed the manuscript.

Disclosure statement

The authors declare no competing financial interests. No funding bodies played any role in the study design, data collection and analysis, decision to publish or preparation of this manuscript.

Data availability statement

The datasets during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

[1] Cicione A, Autorino R, Laguna MP, et al. Three-dimensional technology facilitates surgical performance of novice laparoscopy surgeons: a quantitative assessment on a porcine kidney model. Urology. 2015;85(6):1252–1256.

[2] Storz P, Buess GF, Kunert W, et al. 3D HD versus 2D HD: surgical task efficiency in standardised phantom tasks. Surg Endosc. 2012;26(5):1454–1460.

[3] Cheng J, Gao J, Shuai X, et al. Two-dimensional versus three-dimensional laparoscopy in surgical efficacy: a systematic review and meta-analysis. Oncotarget. 2016;7(43):70979–70990.

[4] Fergo C, Burcharth J, Pommergaard H-C, et al. Three-dimensional laparoscopy vs 2-dimensional laparoscopy with high-definition technology for abdominal surgery: a systematic review. Am J Surg. 2017;213(1):159–170.

[5] Komaei I, Navarra G, Curro G. Three-dimensional versus two-dimensional laparoscopic cholecystectomy: a systematic review. J Laparoendosc Adv Surg Tech A. 2017;27(8):790–794.

[6] Li C, Aivar M, Kit D, et al. Memory and visual search in naturalistic 2D and 3D environments. J Vis. 2016;16(8):9.

[7] Tien G, Zheng B, Atkins MS. Quantifying surgeons' vigilance during laparoscopic operations using eyegaze tracking. Stud Health Technol Inform. 2011;163:658–662.

[8] Chetwood ASA, Kwok K-W, Sun L-W, et al. Collaborative eye tracking: a potential training tool in laparoscopic surgery. Surg Endosc. 2012;26(7):2003–2009.

[9] Zhang J-Y, Liu S-L, Feng Q-M, et al. Correlative evaluation of mental and physical workload of laparoscopic surgeons based on surface electromyography and eye-tracking signals. Sci Rep. 2017;7(1):11095.

[10] Eivazi S, Bednarik R, Leinonen V, et al. Embedding an eye tracker into a surgical microscope: requirements, design, and implementation. IEEE Sensors J. 2016;16(7):2070–2078.

[11] Heo H, Lee WO, Shin KY, et al. Quantitative measurement of eyestrain on 3D stereoscopic display considering the eye foveation model and edge information. Sensors. 2014;14(5):8577–8604.

[12] Lee G, Lee T, Dexter D, et al. Methodological infrastructure in surgical ergonomics: a review of tasks, models, and measurement systems. Surg Innov. 2007;14(3):153–167.

[13] Granholm E, Steinhauer SR. Pupillometric measures of cognitive and emotional processes. Int J Psychophysiol. 2004;52(1):1–6.

[14] Erol Barkana D, Acik A, Duru DG, et al. Improvement of design of a surgical interface using an eye tracking device. Theor Biol Med Model. 2014;11(1):S4.

[15] Smink DS, Peyre SE, Soybel DI, et al. Utilization of a cognitive task analysis for laparoscopic appendectomy to identify differentiated intraoperative teaching objectives. Am J Surg. 2012;203(4):540–545.

[16] Anschuetz L, Niederhauser L, Wimmer W, et al. Comparison of 3-vs 2-dimensional endoscopy using eye tracking and assessment of cognitive load among surgeons performing endoscopic ear surgery. JAMA Otolaryngol Head Neck Surg. 2019;145(9):838–845.

[17] Helbren E, Halligan S, Phillips P, et al. Towards a framework for analysis of eye-tracking studies in the three dimensional environment: a study of visual search by experienced readers of endoluminal CT colonography. Br J Radiol. 2014;87(1037):20130614.

[18] Cowen L, Ball LJS, Delin J. An eye movement analysis of web page usability. London: Springer; 2001.

[19] Goldberg JH, Kotval XP. Computer interface evaluation using eye movements: methods and constructs. Int J Ind Ergon. 1999;24(6):631–645.

[20] Goldberg JH, Stimson MJ, Lewenstein M, et al. Eye tracking in web search tasks:design implications. Paper presented at the Eye Tracking Research & Application Symposium, ETRA 2002; 2002 March 25–27; New Orleans, LA.