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Visual gaze patterns reveal surgeons' ability to identify risk of bile duct injury during laparoscopic cholecystectomy

Running head: Visual gaze patterns in BDI detection

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ABSTRACT

Background: Bile duct injury is a serious surgical complication of laparoscopic cholecystectomy. The aim of this study was to identify using eye tracking technology distinct visual gaze patterns associated with promptly detecting bile duct injury risk during laparoscopic cholecystectomy.

Methods: Twenty-nine participants viewed a laparoscopic cholecystectomy that led to a serious bile duct injury ('BDI video') and an uneventful procedure ('control video') and reported when they perceived an error that could result in bile duct injury. Outcome parameters include fixation sequences on anatomical structures and eye tracking metrics. Surgeons were stratified into two groups based on performance and compared.

Results: The 'early detector' group displayed reduced common bile duct dwell time in the first half of the BDI video, as well as increased cystic duct dwell time and Calot's triangle glances count during Calot's triangle dissection in the control video. Machine learning based classification of fixation sequences demonstrated clear separability between early and late detector groups.

Conclusions: There are discernible differences in gaze patterns associated with early recognition of impending bile duct injury. The results could be transitioned into real time and used as an intraoperative early warning system and in an educational setting to improve surgical safety and performance.

Key words: orientation, laparoscopic cholecystectomy, bile duct injury

INTRODUCTION

Bile duct injuries (BDIs) are the main serious technical complication of laparoscopic cholecystectomy (LC), and persist as a significant challenge in hepatobiliary surgery. BDI can lead to serious sequelae such as biliary peritonitis or fistula and bile duct stenosis that can have a profoundly negative impact on prognosis and life expectancy,[1] as well as high rates of consequent litigation.[2] The laparoscopic approach is now the gold standard for the procedure of cholecystectomy. However, despite the known advantages conferred,[3] there may be increased risk of iatrogenic bile duct injury as compared with the open approach,[4] with an incidence of 0.3-2.7%.[5]

There is a body of research related to methods to decrease the risk of BDI in laparoscopic cholecystectomy, including the 'critical view of safety' (CVS) first described by Strasberg et al in 1995, whereby Calot's triangle is fully visualised by mobilising the neck of the gallbladder from the liver.[6] Other methods include landmark techniques and specific dissection techniques.[7] It has been suggested that up to 97% of intraoperative errors in laparoscopic cholecystectomy are as a result of visual perceptual illusion, [8] rather than lack of technical ability or knowledge and that 70 – 80% of BDIs stem from misidentification of biliary anatomy.[9] Given that as many as 90% of injuries are not diagnosed in the intraoperative period, this anatomical disorientation poses a major problem.[10] Although this suggests bile duct injuries should certainly be considered preventable, one study found that 70% of surgeons regard them as unavoidable.[11] Consequently, ongoing research into training and operative methods and tools to minimise these hazards would result in valuable reduction in patient morbidity and mortality.

The importance of identification of anatomical structures and spatial awareness in preventing bile duct injuries makes this area of research well suited to utilising eye-tracking technology. Our group have previously used eye-tracking technology to quantify visual attention strategies associated with successful orientation during laparoscopic cholecystectomy,[12] and have demonstrated that training novices in orientation strategies improves their ability to correctly orient during surgery.[13] To our knowledge, visual gaze patterns of surgeons in the context of a bile duct injury during laparoscopic cholecystectomy remains unexplored, and yet, its understanding may provide real-time hints of surgical underperformance, all the way from early training to the operating room.

The aim of this study was to determine visual gaze patterns for surgeons who can promptly identify an impending bile duct injury. We hypothesize that if surgeon's gaze patterns encode any information about their ability to recognise the mistake leading to a bile duct injury, then gaze patterns between early and late recognizers should be discriminable.

METHODS

Subjects

The study was approved by the West London National Research Ethics (NRES) committee. All subjects were provided with an information sheet and signed a consent form before participating in the study. A total of 29 surgeons (27 male, 2 female) were recruited to the study. Mean age was 39.3 years (range 31 – 57 years). Subjects had a mean laparoscopic cholecystectomy experience of 215 operations as primary surgeon (range 5 – 1000) and 235 as assistant surgeon (range 40 – 1000).

Participants recruited were surgeons working at one of two large London teaching hospitals (St Mary's Hospital, Paddington, and the Royal Free Hospital, Hampstead). Inclusion criteria was simply that surgeons must have performed or assisted at least 5 laparoscopic cholecystectomies. No exclusion or elimination criteria were defined.

Experimental design

During the experiment, subjects were shown 2 recorded videos of laparoscopic cholecystectomies lasting approximately 3 minutes. Subjects were informed of the aim of the experiment to study gaze patterns of surgeons in recognising the risk of bile duct injury, but not explicitly told whether either of the videos featured a bile duct injury. The sequence of viewing the videos was randomised 50:50 between all participants. Video 1 featured a laparoscopic cholecystectomy that ended with a serious bile duct injury (see 'BDI video'). The injury was the classical misidentification of the common bile duct for the cystic duct with complete transection of the common bile duct. The first dissection occurred at 8 seconds, the first obvious error in the dissection that may result in a bile duct injury was at 18 seconds (when the surgeon grasps the bile duct much below the gallbladder) and the transection of the bile duct occurred at 1 minute 57 seconds. Video 2 consisted of a standard laparoscopic cholecystectomy with no injuries (see 'Control video'). The participants were asked to log, by pressing on the keypad, when they first identified any error that if carried forward was likely to result in a bile duct injury, or any error that had already resulted in a bile duct injury. There were no interruptions or feedback given to subjects at any time during or after the experiment.

The objective was to identify those subjects who were able to recognise an impending bile duct injury in the BDI video early on, and subsequent to grouping into early and late detectors, evaluate the existence of significant and sustained differences in their visual gaze patterns, both in the case of the BDI and control videos.

Eye-tracking

Gaze tracking was performed using an SMI REDn remote eye-tracking system (SensoMotoric Instruments, Berlin, Germany) that was mounted just below the video monitor. This is an infrared video-based binocular eye-tracking system recording the position of gaze in the work plane (screen) at 30 Hz. Images are real-time digitized and processed using 3D eye-model algorithms. Before each recording, subjects viewed multiple moving dots on the screen as a calibration process, allowing, across the screen plane, a gaze position accuracy of 0.4° and spatial resolution of 0.05°. The data were analysed using proprietary software (BeGaze, SMI, Berlin, Germany) and bespoken scripts developed by our group over the years in MATLAB (Mathworks, UK).

Assessment

Multiple areas of interest (AOIs) were selected for each of the two videos, delimiting the various significant organs and structures. The following 13 AOIs were identified: right hand instrument (RHI), liver, gallbladder, common bile duct, cystic duct, cystic artery, hepatic duct, hepatic artery, duodenum, Rouviere's sulcus, Calot's triangle, hepatoduodenal ligament, cystic artery.

Using the BeGaze software, these AOIs were dynamically mapped, enabling the computation of the following eye tracking metrics for each participant: dwell time (sum of fixations and saccades), dwell time %, fixation count, fixation time [ms], fixation time %, average fixation duration [ms] glances count, and revisits. A fixation corresponds to when gaze does not move further than 30 pixels for a minimum of 80 milliseconds. Saccades are defined as the rapid movement between fixation points. In order to normalise the dwell time per AOI, the dwell time was divided by the relative square coverage occupied by that structure within a given time period (dwell time/AOI coverage). This is frequently used as a surrogate for attention allocation.[12-17]

Analysis

Data were analysed across each quartile of the videos and across each video as a whole. For the BDI video, participants were grouped according to how quickly they were able to identify the risk of a bile duct injury, defined by when they first pressed on the keypad. Eye tracking metrics for both videos were compared across these groups with respect to the different AOIs.

Comparisons between individual nonparametric variables were done using the Mann-Whitney *U* test. Correlations of continuous variables were determined by nonparametric linear regression. Analyses were performed using statistical software (SPSS v24.0, IBM corporation, USA). Differences were considered statistically significant at $P < 0.05$.

An automated classification of surgeons based on their gaze patterns to identify the risk was done using an approach previously employed by our group to profile eye tracking data and executed using bespoke analysis software.[12-17] In particular, subjects' dynamically labelled fixation data was processed using a probabilistic hidden Markov model,[17] a model which represents an underpinning generative process responsible for a given sequence of observations. The model output were descriptors of the exhibited gaze pattern. Statistical differences for associated models were computed as surrogate for pairwise difference between AOI-tagged fixation sequences using the log probability of a certain sequence being generated by the descriptive model of another sequence, permitting behavioural analysis of gaze patterns.

RESULTS

Figure 1 illustrates the times at which the different participants recognised the risk of bile duct injury as the BDI video was played. The results show a cluster of participants (n=15) who detected the risk of BDI within the first 30 seconds of the video, while the remaining participants detected the risk at some time after the half-way point (n=12), or not at all (n=2). Therefore, we separated the participants into two groups: those who detected the risk of BDI in the first half of the BDI video ('Early Detectors' or Group 'ED'; ***n = 15***) and those who detected the risk of BDI in the second half of the BDI video or did not detect the risk at all ('Late Detectors' or Group 'LD'; ***n =14*****).**

Demographics

There was no significant difference in age (39.00 [IQR 11] vs 37.50 [IQR 6]; U = 85.5, P = 0.400) or experience in laparoscopic cholecystectomy (150.00 [IQR 249] vs 100.00 [IQR 154]; U = 97.0, P = 0.747) between Group ED and LD.

Bile duct injury video

In the first half of the BDI video, Group ED had reduced CBD dwell time [ms] (U = 152.0, P = 0.041), reduced CBD normalised dwell time [ms/% coverage] (U = 152.0, P = 0.041), reduced CBD dwell time [%] (U = 152.0, P = 0.041), reduced CBD fixation time [ms] (U = 152.0, P = 0.037), and reduced CBD fixation time [%] (U = 153.0, P = 0.037). In the final quarter of the BDI video, Group ED had increased liver glances count (U = 53.0, P = 0.023) and increased liver revisits (U = 51.0, P = 0.018). Across the whole BDI video, Group ED had reduced CBD fixation time [ms] (U = 150.5, P = 0.046) and reduced CBD fixation time % (U = 150.5, P = 0.046). Table 1 shows the data for these findings, while Table 2 shows the normalised dwell times for each of the AOIs in the first half of the BDI video.

Group ED had an increased blink count compared with Group LD across the whole BDI video (35 [IQR 22] vs 17 [IQR 19]; U = 57.5, P = 0.037) and specifically in the second half of the BDI video (17 [IQR 14] vs 9 [IQR 10]; U = 56.5, P = 0.033).

Figures 2B and 2C show heat maps during the dissection of Calot's triangle in the bile duct injury video for Group ED and Group LD respectively. This shows the relative dwell time on different anatomical regions and is a direct visual representation of the discernible differences in gaze patterns between the two groups. Figure 2D shows the similarity-based profiling using hidden Markov models (HMM). Points which are closer in space exhibit similar behaviour, and the results should two very distinct clusters with clear separability between Group ED and Group LD.

Control video

In viewing the video of a normal laparoscopic cholecystectomy, Group ED had, in the third quarter of the video, increased cystic duct dwell time [ms] (U = 54.0, P = 0.026), increased cystic duct normalised dwell time [ms/% coverage] (U = 54.0, P = 0.026), increased cystic duct dwell time [%] (U = 54.0, P = 0.026), increased cystic duct fixation time [ms] (U = 55.5, P = 0.029) and increased cystic duct fixation time [%] (U = 55.5, P = 0.029). There was also increased Calot's triangle glances count (U = 51.5, P = 0.018), increased Calot's triangle revisits (U = 53.5, P = 0.023) and increased Calot's triangle fixation count (U = 58.5, P = 0.041) in the third quarter. This quarter corresponds to the Calot's triangle dissection, and the data are shown in Table 1. Table 2 shows the normalised dwell times for each of the AOIs in the third quarter of the control video.

There was no significant difference in blink count or other basic eye tracking parameters between Groups ED and LD while viewing the control video.

Figures 3B and 3C show heat maps during the dissection of Calot's triangle in the control video for Group ED and Group LD respectively. This is a direct visual representation of the discernible differences in gaze patterns between the two groups. The red areas in the figures correspond with increased average dwell time on these anatomical regions.

Figure 3D shows the similarity-based profiling using hidden Markov models (HMM). Similar to the BDI video plot, this shows two very distinct clusters with clear separability between Group ED and Group LD.

DISCUSSION

This study presents the first evaluation of surgeon gaze behaviour in the context of bile duct injury, comparing surgeons based on their ability to detect the risk of bile duct injury. Much of the published work on bile duct injuries in laparoscopic cholecystectomy emphasises the importance of clear identification of biliary anatomy before dividing any structure. However, a surgeon should not divide a structure without identifying it, and likewise would not divide the bile duct if they knew it was the common duct.[18] Thus, a critical contributory factor in being mistakenly persuaded that the structure being transected is the correct one is the underestimation of risk, which is why we used the endpoint of time taken to detect the risk of bile duct injury to divide our subjects into two groups. Our results here have shown that there are discernible visual gaze patterns that are associated with the early detection of the risk of bile duct injury.

When examining AOI metrics in the BDI video, Group ED had increased dwell time on the right hand instrument during the first quarter of the video. This may be due to focussed attention at the site of dissection during the initial stages of the operation. Group ED also displayed reduced fixation times and dwell times on the common bile duct, particularly in the first half of the BDI video. This may suggest visual attention was distributed more to surrounding anatomical landmarks rather than the common bile duct in those able to successfully identify the risk of BDI. In the final quarter of the BDI video, Group ED also displayed increased liver glances and revisits compared with Group LD, which may reflect an attempt to re-establish what was perceived as a possible loss of orientation in the video from this group of participants, who were better aware of the incorrect surgical approach.

When examining AOI metrics in the control video, in the third quarter Group ED had increased fixation times and dwell times on the cystic duct. In addition, there were increased glances, revisits and fixation count on Calot's triangle. Importantly, this third quarter of the video contains the beginning and completion of the dissection of the two windows of Calot's triangle. Identification of Calot's triangle is the key component in obtaining the Critical View of Safety (CVS). This strongly suggests that increased attention during this imperative stage of laparoscopic cholecystectomy is conducive to better risk identification. Crucially, these results demonstrate that the two groups of participants are consistently different in their approach even when viewing a normal laparoscopic cholecystectomy, suggesting there are key differences in orientation strategies that account for the differences in injury risk assessment.

By using hidden Markov modelling for analysis of these data, we were able to represent visual behaviour patterns as captured by a fixation sequence as a point in a plane or 2D plot. We demonstrated clear separability of participants grouped according to how quickly they were able to detect the risk of bile duct injury. Significantly, the separability of these two groups using Markovian modelling was consistent while viewing a normal laparoscopic cholecystectomy video, adding further weight to the notion that surgeons have innate patterns of gaze behaviour which directly contribute to how likely they are to detect the risk of a bile duct injury.

Interestingly, blink count was also found to be greater in Group ED across the whole of the BDI video, and specifically in the second half. Blink count is known to be linked to cognitive flexibility,[19] which may suggest surgeons able to detect the risk of BDI early were more able to foresee the inevitable outcome from the initial approach. The blink count was not significantly different in the control video, which may be explained by the lower cognitive demand required to follow the orientation and steps of this procedure compared with the BDI video.

We found no significant difference in age or experience (measured by the number of laparoscopic cholecystectomies performed as the primary surgeon) between the two groups. This is consistent with research that shows bile duct injuries cannot simply be explained as a 'learning curve' problem, occurring with similar frequency regardless of a surgeon's seniority or experience.[20,21] This implies that there are more complex underlying factors involved in avoiding, and presumably by extension, recognising the risk of, a bile duct injury. A preceding study by our group has suggested that surgeons reach a plateau in their orientational skills, in keeping with an innate ability during training.[12] The results of this study are innkeeping with this paradigm and suggest that eye tracking technology could play a greater role in both the training of surgeons and in intraoperative monitoring to ensure a safe surgical approach. For example, if a surgeon's gaze patterns during the crucial steps of the procedure, such as dissecting the windows of Calot's triangle, correlate with that of unsafe surgical technique, the surgeon could be alerted and encouraged to adopt a different approach or seek senior help. Eye tracking technology has already been used to identify distinct visual attention strategies by surgeons during a normal laparoscopic cholecystectomy that are associated with successful orientation.[12]

Using eye tracking technology to study human attention processes has some inherent assumptions. Because attention is composed of higher- and lower-level functions, it is well established that humans can voluntarily disassociate attention from their foveal direction of gaze.[22] Because this experiment involved participants reacting to salient stimuli in a 'bottom-up' process, rather than a more task-specified 'top-down' one, it is possible that visual attention could deviate from the foveal point of gaze. However, we believe that as this affects all participants equally, it does not detract from the findings of this study. Furthermore, capturing the live gaze of a surgeon in theatre who inadvertently causes a bile duct injury during laparoscopic cholecystectomy would be the only true representation of a 'top-down' process, but we are too early in this research line. In the future, surgical simulations could be used to analyse gaze patterns of surgeons actually performing 'surgery' that was associated with the risk of a bile duct injury, representing a more task-directed experimental set-up.

We acknowledge certain limitations of our study. We did not perform a sample size computation, mainly due to the novelty of this work meaning we lack any previous reliable effect size estimation. There is only one video each representing a bile duct injury case and a normal case, which may not present adequate variability. The resolution of the BDI video used for the experiment was relatively poor compared with the control video, due to the scarce availability of such videos. In addition, the scope used in the control video was different, and the equipment less modern. This could introduce possible bias, as participants may have inferred early on that this video was the one more likely to result in a bile duct injury, despite the randomised viewing order. An inherent limitation of the study was having to edit out large parts of the procedure to fit key steps into a short video. Evaluation of risk is a cumulative process, whereas in this experiment participants had to make an assessment in less realistic viewing circumstances. This may have proved particularly challenging for less experienced surgeons, as the edited videos required the participants to reorient themselves several times.

In this study, we have identified quantifiable differences in gaze behaviour between surgeons who are able to identify early the risk of impending bile duct injury versus those who are not, and have made an effort to explain the underlying causes of such differences. Crucially, these differences in gaze patterns of the two groups persist in the procedure in which no injury occurs, demonstrating an underlying behavioural divergence. If this analysis can be automated in real time it could be used as an intraoperative early warning system. For example, if the gaze patterns of a trainee correlate with those associated with an unsafe surgical approach, the surgeon could be advised to reconsider the surgical approach or seek clarification from a senior. In addition to this, behavioural differences could be used in an educational setting away from the operating theatre. 'Gaze training' has been shown to improve the efficacy of laparoscopic tasks, such as by verbally informing trainees which areas of interest they should focus on,[23] or by projecting the supervisor's point-of-gaze onto a trainee's screen.[24] These strategies could complement surgical training in the simulation centre, thus in the future enhancing safety and performance in laparoscopic cholecystectomy.

AUTHOR CONTRIBUTIONS

(I) Conception and design: MS, CS

(II) Administrative support: CS, MS

(III) Provision of study materials or patients: MS, AD

(IV) Collection and assembly of data: CS

(V) Data analysis and interpretation: CS, MS, HS, FOE

(VI) Manuscript writing: All authors

(VII) Final approval of manuscript: All authors

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DISCLOSURES

Drs Chetanya Sharma, Harsmirat Singh, Felipe Orihuela-Espina, Ara Darzi and Mikael H Sodergren have no conflicts of interest or financial ties to disclose. This research was funded by a lectureship grant to Mikael Sodergren from the Academy of Medical Sciences. The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

REFERENCES

1. Maddah G, Rajabi Mashhadi MT, Parvizi Mashhadi M, et al. Iatrogenic injuries of the extrahepatic biliary system. J Surg Res.2017;213:215-221.

2. Alkhaffaf B, Decadt B. 15 years of litigation following laparoscopic cholecystectomy in England. Ann Surg. 2010;251(4):682-685.

3. Coccolini F, Catena F, Pisano M, et al. Open versus laparoscopic cholecystectomy in acute cholecystitis. Systematic review and meta-analysis. Int J Surg. 2015;18:196-204.

4. Connor S, Garden OJ: Bile duct injury in the era of laparoscopic cholecystectomy. Br J Surg. 2006;93:158-168.

5. Ahmad F, Saunders RN, Lloyd GM, et al. An algorithm for management of bile leak following laparoscopic cholecystectomy. Ann R Coll Surg Engl. 2007;89:51–56.

6. Strasberg SM, Hertl M, Soper NJ. An analysis of the problem of biliary injury during laparoscopic cholecystectomy. J Am Coll Surg. 1995;180:101–125.

7. Connor SJ, Perry W, Nathanson L, et al. Using a standardized method for laparoscopic cholecystectomy to create a concept operation-specific checklist. HPB (Oxford). 2014;16(5):422–429.

8. Way LW, Stewart L, Gantert W, et al. Causes and prevention of laparoscopic bile duct injuries: analysis of 252 cases from a human factors and cognitive psychology perspective. Ann Surg. 2003;237:460–469.

9. Hugh TB. New strategies to prevent laparoscopic bile duct injury – surgeons can learn from pilots. Surgery. 2002;132:826–835.

10. Abdel Wahab M, el-Ebiedy G, Sultan A, et al. Postcholecystectomy bile duct injuries: experience with 49 cases managed by different therapeutic modalities. Hepatogastroenterology. 1996;43:1141–1147.

11. Francoeur JR, Wiseman K, Buczkowski AK, et al. Surgeons' anonymous response after bile duct injury during cholecystectomy. Am J Surg. 2003;185:468–475.

12. Sodergren MH, Orihuela-Espina F, Clark J, et al. Evaluation of orientation strategies in laparoscopic cholecystectomy. Ann Surg. 2010;252(6):1027-1036.

13. Sodergren MH, Orihuela-Espina F, Froghi F, et al. Value of orientation training in laparoscopic cholecystectomy. Br J Surg. 2011;98:1437-1445

14. Lami M, Singh H, Dilley JH, et al. Gaze patterns hold key to unlocking successful search strategies and increasing polyp detection rate in colonoscopy. Endoscopy. 2018;50(7):701-707.

15. Edmondson MJ, Pucher PH, Sriskandarajah K, et al. Looking towards objective quality evaluation in colonoscopy: Analysis of visual gaze patterns. J Gastroenterol Hepatol. 2016;31(3):604-609.

16. Sodergren MH, Orihuela-Espina F, Mountney P, et al. Orientation strategies in natural orifice translumenal endoscopic surgery. Ann Surg. 2011;254(2):257-266.

17. Sodergren MH, Orihuela-Espina F, Clark J, et al. A hidden Markov model-based analysis framework using eye-tracking data to characterise re-orientation strategies in minimally invasive surgery. Cogn Process. 2010;11(3):275-283.

18. Dekker SW, Hugh TB. Laparoscopic bile duct injury: understanding the psy- chology and heuristics of the error. ANZ J Surg. 2008;78:1109–1114.

19. Jongkees BJ, Colzato LS. Spontaneous eye blink rate as predictor of dopamine-related cognitive function—A review. Neuroscience & Biobehavioral Reviews 2016;71:58-82.

20. Windsor JA, Pong J. Laparoscopic biliary injury: more than a learning curve problem. Aust. N. Z. J. Surg. 1998; 68:186–189.

21. Francoeur JR, Wiseman K, Buczkowski AK, et al. Surgeons' anonymous response after bile duct injury during cholecystectomy. Am. J. Surg. 2003;185:468–475.

22. Posner MI, Snyder CR, Davidson BJ. Attention and the detection of signals. J Exp Psychol. 1980;109:160–174.

23. Vine SJ, Masters RSW, McGrath JS, et al. Cheating experience: guiding novices to adopt the gaze strategies of experts expedites the learning of technical laparoscopic skills. Surgery 2012;152:32–40.

24. Chetwood AS, Kwok KW, Sun LW, et al. Collaborative eye tracking: a potential training tool in laparoscopic surgery. Surg Endosc. 2012;26:2003–2009.

List of supplemental digital content

Video 1. "BDI video" - Laparoscopic cholecystectomy showing a bile duct injury (mp4)

Video 2. "Control video" - Laparoscopic cholecystectomy showing a normal procedure (mp4)

Table 1: Key eye tracking metrics for bile duct injury and control videos

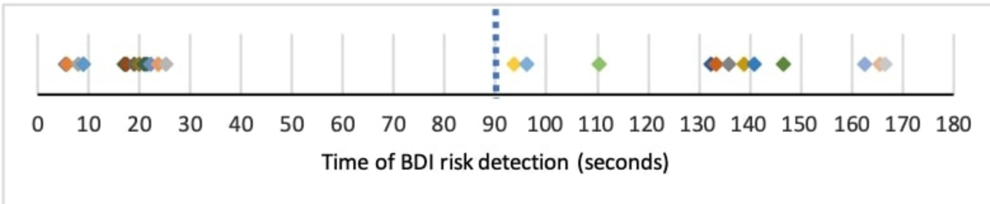
Time period	Eye tracking metric	Group ED median	Group ED IQR	Group LD	Group LD IQR	U-value	η²	P-value
First half of BDI video	CBD dwell time [ms]	6632.500	3600.3	9249.300	3924.8	152.0	0.150	0.041
	CBD normalised dwell time [ms/coverage]	112415.254	61022.0339	156767.797	66522.4576	152.0	0.150	0.041
	CBD dwell time %	7.200	3.9	10.050	4.3	152.0	0.150	0.041
	CBD fixation time [ms]	6465.800	3633.5	8899.800	3758.1	153.0	0.156	0.037
	CBD fixation time %	7.000	3.9	9.650	4.1	152.5	0.154	0.037
Final quarter of BDI video	Liver glances count	2.00	2	1.00	2	53.0	0.195	0.023
	Liver revisits	1.00	2	0.00	1	51.0	0.231	0.018
Whole BDI video	CBD fixation time [ms]	7066.000	233.8	9466.350	3583.0	150.5	0.141	0.046
	CBD fixation time %	3.800	1.3	5.150	2.0	150.5	0.141	0.046
Third quarter of control video	Cystic duct dwell time [ms]	15665.300	7999.5	12715.650	8348.7	54.0	0.177	0.026
	Cystic duct normalized dwell time [ms/coverage]	870294.444	444416.667	706425.000	463813.889	54.0	0.177	0.026
	Cystic duct dwell time %	35.900	18.4	29.150	19.2	54.0	0.177	0.026
	Cystic duct fixation time [ms]	15565.200	8166.5	12348.900	8140.4	55.0	0.170	0.029
	Cystic duct fixation time %	35.700	18.7	28.300	18.7	55.0	0.170	0.029
	Calot's triangle glances count	3.00	2	1.50	1	51.5	0.211	0.018
	Calot's triangle revisits	2.00	2	0.50	1	53.5	0.199	0.023
	Calot's triangle fixation count	5.00	4	3.00	3	58.5	0.150	0.041

AOI = Area of interest; Group ED = 'Early Detectors'; Group LD = 'Late Detectors'; IQR = Interquartile range; CBD = common bile duct

Table 2: Normalised dwell times for BDI and control videos

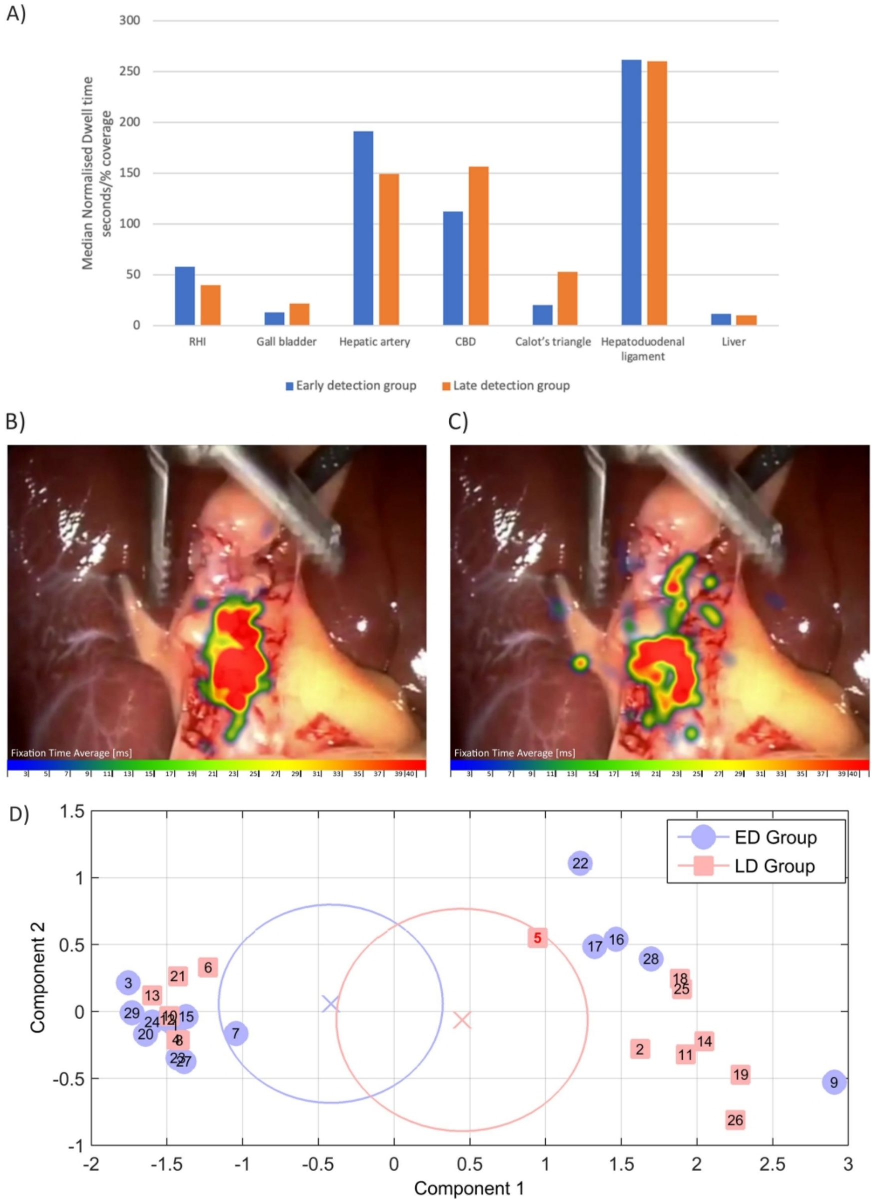
	AOI	Group ED median [ms/coverage]	Group ED IQR [ms/coverage]	Group LD median [ms/coverage]	Group LD IQR [ms/coverage]	U-value	η^2	P-value
First half of bile duct injury video	Right hand instrument	58226.5060	25603.6145	39752.4096	18772.5904	62.0	0.126	0.063
	Hepatic duct	-	-	-	-	-	-	-
	Gall bladder	13157.8947	29826.3158	21926.3158	38812.5000	114.5	0.006	0.683
	Duodenum	0	0	0	0	112.0	0.012	0.780
	Rouviere's sulcus	0	0	0	0	107.0	0.001	0.949
	Hepatic artery	191408.571	113311.429	149304.286	103325.714	94.0	0.008	0.652
	Common bile duct	112415.254	61022.0339	156767.797	66522.4576	152.0	0.150	0.041
	Calot's triangle	20588.2353	49023.5294	52938.2353	79404.4118	129.5	0.041	0.290
	Hepatoduodenal ligament	261430.806	39968.2464	259850.711	12910.3081	94.0	0.008	0.652
	Liver	11413.8958	3474.93797	10420.8437	8848.13896	99.0	0.002	0.813
Third quarter of the control video	Hepatoduodenal ligament	0	0	0	0	105.0	0.000	1.000
	Rouviere's sulcus	0	0	0	16668.7500	113.5	0.011	0.715
	Right hand instrument	32625.5319	26946.8085	59218.0851	76942.0213	142.5	0.096	0.102
	Cystic artery	899955.556	474033.333	714750.000	674922.222	78.0	0.050	0.252
	Cystic duct	870294.444	444416.667	706425.000	463813.889	54.0	0.177	0.026
	Common bile duct	0	0	0	19050.0000	113.0	0.008	0.747
	Calot's triangle	159077.273	113631.818	99234.0909	162485.227	63.0	0.120	0.070
	Gall bladder	12771.0280	15263.5514	30682.7103	29435.2804	145.0	0.109	0.085
	Duodenum	0	0	0	0	105.0	0.000	1.000
	Liver	9722.94618	11707.6487	12039.3768	8096.10482	125.0	0.027	0.400

'–' indicates AOI did not appear in this time period.
'0' indicates no dwell time on the AOI
AOI = Area of interest; Group ED = 'Early Detectors'; Group LD = 'Late Detectors'; IQR = Interquartile range



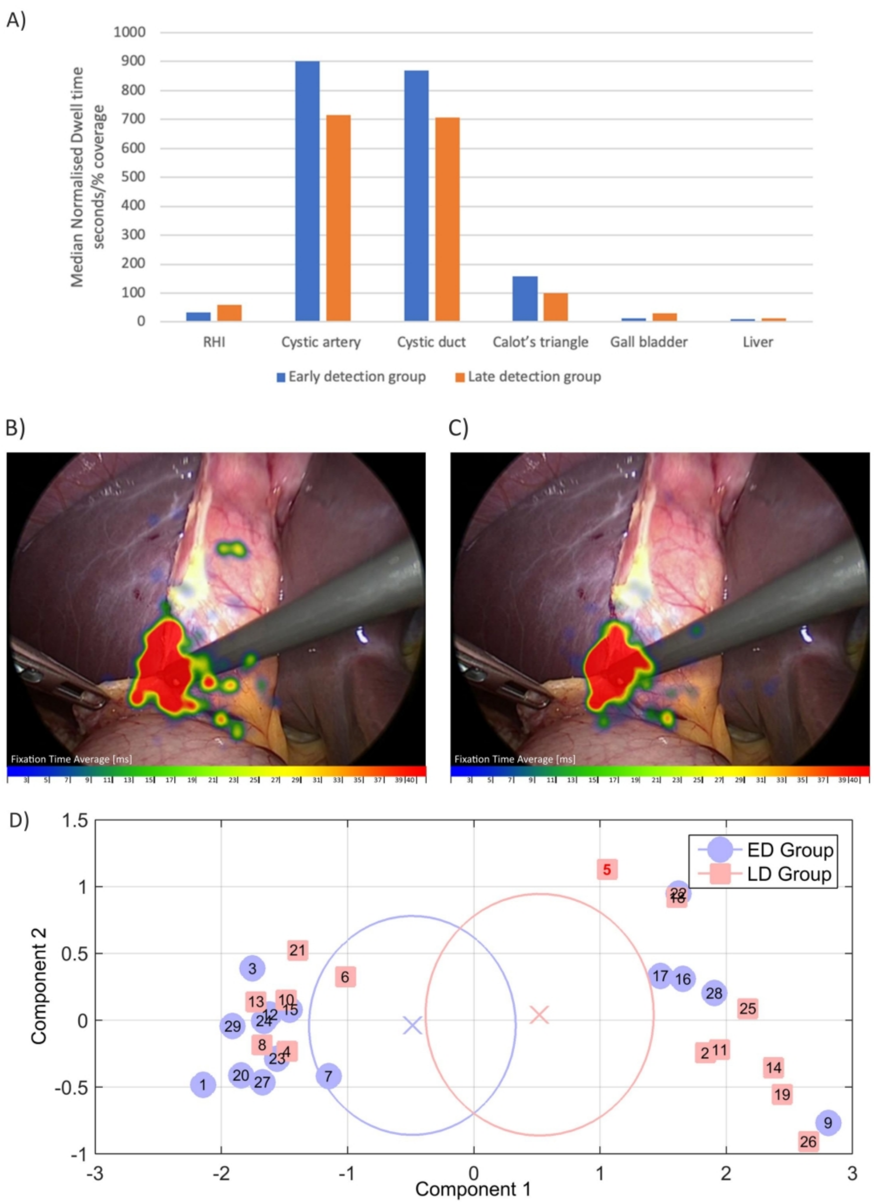
Time at which each participant detected the risk of bile duct injury while watching the bile duct injury video. Each horizontal point represents a participant. The dotted line at 90 seconds represents the separation of the early and late detector groups.

277x57mm (72 x 72 DPI)



A: Median normalized dwell times for different areas of interest in the BDI video, comparing Group ED and Group LD. B & C: heat maps during the dissection of Calot's triangle in the BDI video for Group ED and Group LD respectively (red areas correspond with increased average dwell time). D: Hidden Markov model similarity-based profiling for the BDI video (each numbered point represents a participant, from either Group ED or Group LD as shown by the key).

187x257mm (300 x 300 DPI)



A: Median normalized dwell times for different areas of interest in the control video, comparing Group ED and Group LD. B & C: heat maps during the dissection of Calot's triangle in the control video for Group ED and Group LD respectively (red areas correspond with increased average dwell time). D: Hidden Markov model similarity-based profiling for the control video (each numbered point represents a participant, from either Group ED or Group LD as shown by the key).

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