

Laparoscopy with augmented reality adaptations

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ABSTRACT

One of the most promising applications of Optical See-Through Augmented Reality is minimally laparoscopic surgery, which currently suffers from problems such as surgeon discomfort and fatigue caused by looking at a display positioned outside the surgeon's visual field, made worse by the length of the procedure. This fatigue is especially felt on the surgeon's neck, as it is strained from adopting unnatural postures in order to visualise the laparoscopic video feed. Throughout this paper, we will present work in Augmented Reality, as well as developments in surgery and Augmented Reality applied to both surgery in general and laparoscopy in particular to address these issues. We applied user and task analysis methods to learn about practices performed in the operating room by observing surgeons in their working environment in order to understand, in detail, how they performed their tasks and achieved their intended goals. Drawing on observations and analysis of video recordings of laparoscopic surgeries, we identified relevant constraints and design requirements. Besides proposals to approach the ergonomic issues, we present a design and implementation of a multimodal interface to enhance the laparoscopic procedure. Our method makes it more comfortable for surgeons by allowing them to keep the laparoscopic video in their viewing area regardless of neck posture. Also, our interface makes it possible to access patient imaging data without interrupting the operation. It also makes it possible to communicate with team members through a pointing reticle. We evaluated how surgeons perceived the implemented prototype, in terms of usefulness and usability, via a think-aloud protocol to conduct qualitative evaluation sessions which we describe in detail in this paper. In addition to checking the advantages of the prototype as compared to traditional laparoscopic settings, we also conducted a System Usability Scale questionnaire for measuring its usability, and a NASA Task Load Index questionnaire to rate perceived workload and to assess the prototype effectiveness. Our results show that surgeons consider that our prototype can improve surgeon-to-surgeon communication using head pose as a means of pointing. Also, surgeons believe that our approach can afford a more comfortable posture throughout the surgery and enhance hand-eye coordination, as physicians no longer need to twist their necks to look at screens placed outside the field of operation.

1. Introduction

Recent developments show great potential in applying optical-see-through Augmented Reality (AR) to laparoscopic surgery. Indeed, wearing modern Head-Mounted Displays will allow surgeons to visualise both the task being performed and patient data simultaneously, while improving both posture and comfort as a result of eliminating the need to stare at a monitor placed at a distance [1]. This is accomplished by enhancing real-world settings with computer-generated information overlaid on a screen, through which both real and virtual objects can be simultaneously observed and interacted with. This approach has a

potentially higher impact on improving laparoscopic procedure quality than even robotic assisted surgery, as the latter only represents a minority of all minimally invasive operations. AR might enhance the capabilities of the operating surgeon, while keeping them in control of the operative field. Potentially, AR-enhanced laparoscopy could be adopted in most minimally invasive procedures at a lower cost.

AR has experienced a surge in popularity thanks to ever more powerful and less expensive hardware. However, its applications to many settings, including surgery, remain a challenging topic. We believe this stems from a lack of effort applied to human-computer interfaces, as there is little work focused on them. Although the

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technology may have matured in terms of implementation, with several commercial products available, such as Microsoft HoloLens, Samsung Gear VR and Magic Leap One to name a few, there is little work done in user interfaces and interaction techniques. In addition, applications of AR require that visualization devices should be ergonomically viable throughout their use and should not limit or increase the movements required to execute the main surgical activity [2].

Indeed, surgery, and in particular laparoscopy, provide many opportunities for AR. Laparoscopy is a minimally invasive procedure performed on the abdomen or pelvis, with the abdominal cavity being expanded with gas to allow the insertion and movement of laparoscopic instruments inside the body. Unlike open surgery, in laparoscopy there is no direct visual contact with the organs, where surgeons use an endoscopic camera, which captures and feeds operating theater images onto a display [1]. This results in a rather limited and restrictive experience as compared to open surgery. This requires extensive training as the surgeon's dexterity and ability to feel feedback from applying pressure on tissues are reduced by the laparoscopic instruments [3,4]. An important issue is hand-eye coordination, as surgeons have to look at screens placed outside the field of operation. This originates discomfort [4], affecting the surgeon's efficiency due to a disconnect between the visual and motor axes, because they cannot look at the instruments or their hands and the video feed simultaneously. To be successful, specific training is required to adapt to this condition, as extra mental effort must be applied [3]. In addition, almost all display screens are limited in the sense that they make visual collaboration more difficult with the rest of the surgical team [5].

In this paper, we contribute by identifying design requirements for laparoscopy surgery through a user and task analysis in close collaboration with surgeons. Based on these requirements, we developed a prototype that proposes novel approaches towards improved surgeon comfort and makes the surgical procedure less laborious. The prototype has been iteratively designed and tested by the target clinicians and our design choices were thus validated. In the remainder of this paper we survey related work, describe our requirements gathering via user and task analysis and explain our approach in detail. Then we describe how our system was evaluated to assess the well foundedness of our design choices. We conclude by describing opportunities for future work.

2. Related work

In the last decade, there has been considerable work on new interaction techniques for AR, and attempts at embedding it in the surgical field, including laparoscopy. With respect to laparoscopy, studies have been performed to better understand how the procedure is conducted, what are its limitations, and how they can be overcome by using AR. These explored different image visualisation modalities, e.g. monitor positioning or head-mounted displays (HMD), as well as different sources of input and ways for people to communicate.

We reviewed research on AR interaction, AR in laparoscopy, as well as other surgical procedures, in an attempt to better understand how to improve procedures via AR. To this end, we reviewed previous work in interaction sources and methods, visualisation techniques, and communication improvements.

As for AR interaction, the hands are the most commonly used body part, with the HoloLens's 'air-tap' gesture being used for control activation [6,7], while hand movement is used for image manipulation [7] and drawing [8]. Voice commands are also popular to control activation [6,7,9]. However, both of these interaction methods are difficult to use in operating rooms. Hands require surgeons to pause the procedure before commencing the interaction, be it an air-tap, gesture or hand movement, which causes interruptions and disrupts the surgical flow. Voice activation may not be effective due to ambient noise in the room. Furthermore, also, its low reliability may also cause disruptions in the procedure flow.

Other sources of input include the head, with head gaze being used

to select targets [6,10]; it provides a simple, yet effective method. Head movement is another approach, especially when content follows head movements [9]. A more elaborate approach is eye-gaze [11,12], which is well-received by users but may not transition well onto the surgical operating field, as its controls would have to be displayed continuously and right in the field of view, unlike in the presented works, which could be distracting to users. Also, more importantly, it would take valuable space from the HMD's already limited field of view. Other interesting techniques use the feet. Two different approaches emerge, using a foot pedal as a means to activate selected controls [10] and using foot movement to select and activate controls [13]. After comparing the two, we conclude using foot movement would be a more flexible choice, as it does not require extra hardware that is situated in a given position in space.

Regarding visualisation, most approaches use optical see-through-HMDs [6,13,14,7,9], mainly the HoloLens, but these systems are not applied specifically to laparoscopy, rather to AR and surgery in general. For laparoscopy, non-see-through and video-see-through HMDs are more prevalent [15,4,16,10]. As previously stated, non-see-through, and to some extent, video-see-through HMDs do not allow people to perceive their surroundings, which can impair communication significantly, as there is a loss of perception of the rest of the team. Additionally, very few works regarding laparoscopy aim to improve communication [17,8], with the emphasis being put on visualisation. With respect to using patient data/preoperative data interprocedurally, most works focus on displaying the patient data as 3D imaging overlaid onto the patient's body, instead of imaging such as 2D MRI slices. In conclusion, we find that, as far as we know, there is no work incorporating Augmented Reality in laparoscopy that offers patient data visualization in realtime while supporting collaboration between team members.

3. Materials and methods

In this section we describe the gathering of requirements including user and task analysis in a first step. In subsequent steps we describe our exploration of the design space justifying the options taken on the basis of observed people behavior.

3.1. Design requirements

In the first phase, we applied a user and task analysis to achieve a good understanding of how users achieved their goals and what could be improved. We conducted this procedure according to the methodology used by [18] at the Champalimaud Foundation in Lisbon, Portugal. To this end, we performed a presentational observation of five laparoscopic surgeries. We conducted conversations with surgeons both before and after the procedures. They explained to us what was about to happen or what had just taken place. Furthermore, during the surgery, nurses gave us more insight into the different stages of the surgery, or what was happening at that time. We also had the opportunity to ask questions to surgeons at appropriate moments during the surgery. Besides that, we video recorded crucial steps using smartphones and tablets for further analysis in addition to our field notes, using an inductive bottom-up approach to data analysis in which the authors analyzed their field notes and videos.

Performing user and task analysis allowed us to better understand the existing problems in the procedure of laparoscopy while identifying several constraints, opportunities and design requirements, which a solution has to follow to address those problems.

Briefly, we were able to identify that viewing laparoscopic video over long periods is exerting for the neck. An approach to this problem is to allow people to adopt more comfortable neck postures via a laparoscopic video feed that follows user head movements, instead of forcing non-natural poses. We also identified that surgeons reluctantly release their instruments even if temporarily to interact with the team,

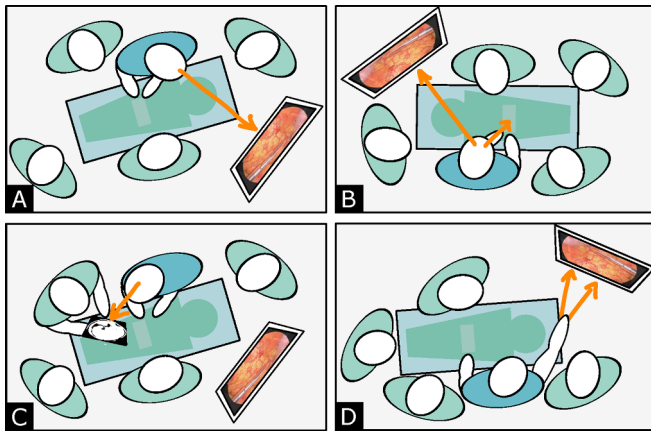


Fig. 1. Illustration of problems identified in performing user and task analysis. (a) Neck exhausting. (b) Lack of hand-eye coordination or requirement them to let go of their tools. (c) Browsing patient data during an operation takes too long. (d) Pointing is unclear and ambiguous.

such as pointing or consulting patient data. To overcome this limitation, surgeons can perform interactions with their feet or head to allow hands-free interactions in order to operate uninterruptedly. Besides, surgeons should be able to look at patient data by themselves, without interrupting the flow of work and adding extra time to the surgery. Last, pointing to perform communication is both unclear and ambiguous. Different people around the table have different interpretations of where a surgeon is pointing at. Surgeons should be able to precisely and unambiguously specify points and understand where other people are pointing at, regardless of their position in the operating room. Fig. 1 illustrates the problems identified in performing user and task analysis.

3.2. Prototype overview

Based on these insights, we developed a prototype tackles the problems we observed in Section 3.1 that surgeons currently experience during laparoscopic surgery. Furthermore, we wanted the prototype to be as unobtrusive as possible in order to interfere as lightly as possible with the flow of the operations. Towards this goal, achieve this, we adopted a fully hands-free approach so that surgeons would not have to put down their tools to interact, allowing for a continuous surgical experience.

3.2.1. Laparoscopic video

Laparoscopy currently faces the glaring problem of monitor positioning. During surgery, screens are usually placed far away and at an uncomfortable angle, causing neck and eye strain throughout the procedure, especially if it lasts for too long. Thus, it was important to allow the surgeons freedom in how they visualize the video feed, which led to a conclusion: The video, while visible, should follow user head movements, so users do not have to reposition it in the augmented space, should they feel the need to assume a different posture. We, therefore, implemented this approach in our prototype, as illustrated in Fig. 2, centering the video feed in the HMD field of view (FOV) and making it as large as possible without exceeding the FOV borders.

3.2.2. Patient imaging

Regarding patient imaging data during the operation, to mimic the software surgeons commonly use in preoperative planning, as well as to evoke a feeling of familiarity, the data are presented in 2D. Two planes would be displayed, while the third would be accessible via controls underneath the images. The patient imaging was initially meant to follow user head movements as well, but the idea was scrapped in favor of having them placed in the augmented world, as surgeons usually consult two images at once, and presenting both images at the same

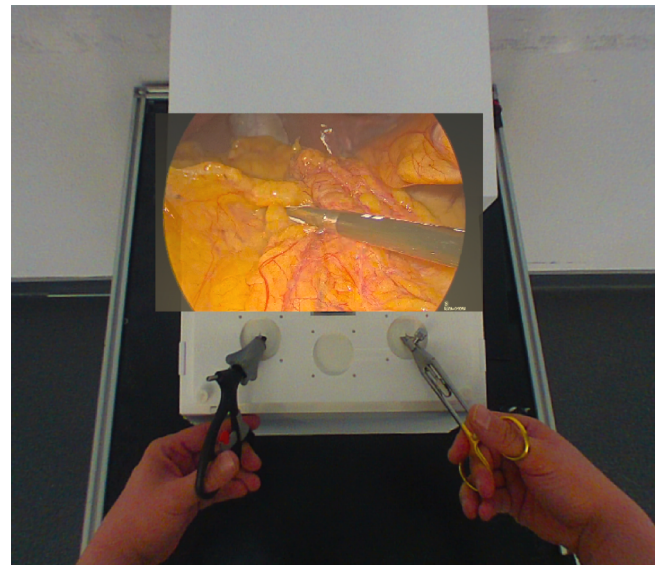


Fig. 2. The user can change head positioning and still be able to see the video.

time meant these had to be viewed at a smaller scale in order to fit the Metavision Meta 2's HMD¹ narrow field of view.² By fixing these data on the world, they can assume a larger scale, which means they can be viewed in greater detail, but still remain accessible at the distance of a gesture by placing them close together and allowing the user to look around.

We thought about where to best place the images since we had both the left and the right sides of the FOV available. Eventually, we settled on showing the images on both sides, letting users access medical imaging by slightly pivoting their head to whichever side they found most comfortable. Following in the footsteps of Jayender et al. [10] and Walczak et al. [19], we positioned the images at an angle of 30 degrees below eye level, which also lets users comfortably look at the rest of the surgical team, as well as their surroundings.

With the placement decided, we decided that the image data sets could be navigated using arrows. The Meta2 glasses make it possible to detect where the user's head is facing thanks to their accelerometer and gyroscope, which we use to activate these arrow controls. They were placed above and below each image, with the upwards arrow used to navigate to the next image and the downwards arrow used to navigate to previous image. These arrows react differently according to the area looked at, as they were divided into four equally-sized sections, representing four different levels of speed. If the user stares more to the bottom of the arrow, the corresponding section is highlighted in a cyan contour, and the image changes very slowly, at one new frame per second, but if they gaze to the last section at the pointy end, the images change far quicker, at 16 frames per second, which allows for swifter traversal of the data set, while the second and third sections change images at four and eight frames per second, respectively.

To aid in navigation, we considered using the users' feet as a source of input. We could not rely on USB pedals, as we observed that not only surgeons move around the patient, which meant the pedal had to be moved around as well, but they also already have other pedals underneath the patient's bed, which could induce errors. Given this, we drew inspiration from the work of Müller et al. [13]. They used tapping with the foot to activate controls, which we deemed not viable due to the risk of activating a pedal inadvertently, but gave us the idea to implement image scrolling simply via foot gestures. Several ideas were initially

¹ <https://wonder.store/metavision/meta-2/> (Accessed 25 May 2020).

² However, the Metavision HMD see-through glasses have an impressive 90 degree FOV, which led us to adopt them.

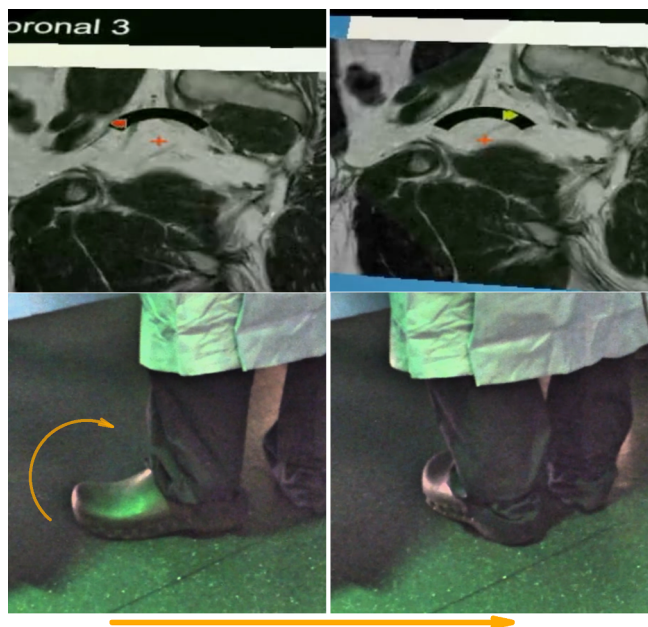


Fig. 3. The curved bar helps users perceive the rotation their foot is assuming. Sensitivity was adjusted so users could reach both red icons without lifting the foot.

explored, involving vertical and horizontal movements akin to swipe gestures, but these were dismissed as they could interfere with user balance since they required lifting a foot off the ground to perform the gesture. We eventually settled on heel rotation, as it enables users to keep their balance. Using heel rotation, turning their foot like a dial, people can rotate the foot to the left to access previous images and to the right to access the next ones, as shown in Fig. 3.

The more the foot was rotated from the starting point, the faster the images would change. However, this would only happen when the user was looking at the image, to prevent errors or accidentally triggering the action, as well as letting users move their feet freely when not using the mechanism and also not constraining their movements. Furthermore, to avoid inadvertent activation when looking at an image without the intent to change it, we implemented a dead zone, allowing for small foot movements without affecting the display. After that dead zone is crossed, images can be changed at three different speeds, represented by three differently-coloured icons in the interface: a green icon changes frames at two per second; a yellow icon enables four frames per second (FPS); a red icon changes images at ten FPS. It should be noted that these changes happen continuously, meaning that the images change one by one instead of jumping after a full second, giving surgeons a sense of movement and fluidity. This is also enhanced by having the displayed icon fade in and out. The icons are positioned in a curved bar in accordance with the detected foot position, and the bar, in turn, is positioned around the reticle for accessibility, following the concept of indirect interaction presented by Müller et al. [13] (Fig. 4).

To implement foot movement detection, we embedded a wireless optical mouse in the rubber clogs used by the surgeons, as shown in Fig. 6.

We decided to complement this interaction method and made the progress bar interactive, allowing it to change images when intersected by the user's gaze, akin to an application window's scroll bar. This would let a person to go through the whole image data set quickly, roughly obtaining the desired position and then fine-tuning it with their foot. We also took into consideration that the user might accidentally hit the bar with the gaze, especially when looking up to activate pointing an interaction technique described ahead in Section 3.2.3. In order to prevent undesired image changes, we developed a script, which we present in Section 3.3, that lets the prototype understand



Fig. 4. Mouse clog. We can observe the wireless mouse does not interfere with the clog form factor.

whether the user has hit the bar by accident or intentionally. Finally, we considered that surgeons should all be on the same page when it comes to patient MR images, and so we implemented a synchronisation feature that, when a user changes images or planes, these changes are also reflected on other HMDs around the operating table as well, to improve communication.

We also attempted to replace the plane-switching buttons with foot gestures. For this, we thought of the works of Esteves [11] and Velloso [12] and tried using circular foot gestures to activate these controls, as illustrated in Fig. 5.

A clockwise rotation would change the plane on the right, and a counter-clockwise one would change the plane on the left. While the prototype recognised these movements well enough on their own, this interfered with heel rotation gesture, as it would most times recognise a foot rotation in place of a heel turn and vice versa. Thus, the gesture ended up not being implemented and we retained the buttons.

3.2.3. Pointing reticle

Because the physical screen is removed when wearing an HMD, surgeons lose the ability to point at it. Therefore, a new mechanism for pointing was necessary as well. We opted to use the head gaze as means of pointing, as a similar interaction had already been experimented when development the patient data browsing functionalities, with the reticle used for interface navigation being stable enough to be used as a pointing reticle as well. We chose not to use voice activation because we consider it to be an unreliable method, which is avoided in critical situations during surgery. Works such as Kim et al. [6], Feng et al. [8], Pratt et al. [7] and Grinshpoon et al. [9] used voice commands, but their authors did not evaluate how effective the use of voice commands was. Furthermore, we do not consider this type of interaction to be as fast or as dependable as simply pointing at controls with head movements.

When using the pointing reticle on the video feed, the video would be fixed in the augmented space so it could be properly pointed at, being immobilized at a centered position, instead of following the user's head movement, and while pointing at patient images, the pointing reticle would replace the red navigation reticle.

For consistency, the pointing reticle is cyan-coloured and, in addition to the cross already present in the red reticle, it features a coloured circumference. These differences let the user immediately know whether they are pointing or not and provide greater contrast with the laparoscopic video, whose frames are comprised of mostly red and orange colours. On the other user's HMD, the reticle appears in a bright neon green, which also highly contrasts with the video, and helps distinguish which reticle belongs to which user, in the case two are simultaneously pointing at the video.

To activate the reticle we decided to explore the only direction that



Fig. 5. A conceptual sketch of how the video and the data are displayed. Because the video follows head movements, looking to the side to visualise patient data would hide it. To implement foot movement detection, a mouse was introduced inside the rubber clogs used by the surgeons.

was not yet in use: the space above both the video and the patient data. Looking up past a threshold and holding the gaze there for a brief moment would activate the pointing reticle, regardless of where the surgeon was looking at, video or MR images, and looking up again would disable it. After experimentation, we considered the amplitude of 20 degrees above eye level to be an adequate value for the threshold, as it was reachable without either activating the mode by accident or requiring too much effort.

Despite the flexibility of this interaction method, however, we considered the possibility that the activation movement could be too uncomfortable or just not practical for users to perform. Therefore we also implemented a small virtual button. This virtual button sits between the video and the patient data on both sides, so it would be easy to access, whether the user is looking at the video or the images.

3.2.4. Colour of interface theme and reticles

When developing the prototype, the buttons for switching planes were found to be easily mistaken for simple labels, as it was not clear they afforded interaction. Furthermore, users were also not clear that the navigation bar actually reacted when they gazed upon it. This was attributed to a lack of colour in the prototype, as all interface elements were black and white. To solve this issue, and to let users easily understand what is interactive and what is not, interactive objects were coloured in blue, while informational text was depicted with black labels. Blue is commonly associated with calmness and trust, which are good to have in an operating environment.

We observe that, during the surgery, the room is lit in a green tint, and therefore it was important to choose colours that would contrast with it. For the navigation reticle, which is always visible whenever the surgeon is not looking at the video, we chose to use red, as it directly contrasts with green. For the pointing reticle, however, the problem is more complex. Not only does it need to contrast with the room, but it

also needs to contrast with the video, which assumes tones of red and orange. We deferred to the video and chose two colours which would contrast with it: green and cyan. More specifically, green for the other user's reticle and cyan for the user's own reticle, which matches the blue chosen for the rest of the interface. We also added a black outline to these reticles to assure better contrast when viewing them against greyscale patient images.

3.3. Architecture

In this section, we present the prototype's architecture and describe its components in greater detail. The prototype is a Microsoft Windows 10 application developed in Unity 2017.4 using two hardware components: a Meta2 HMD and a HP Z3700 wireless mouse embedded inside a rubber clog. The Meta2 is a see-through Augmented Reality HMD which, due to its tethered nature, can be used during extended amounts of time, therefore lasting throughout an entire surgical procedure, regardless of its duration.

The architecture depicted in Fig. 7. Red depicts hardware components, blue stands for image visualisation, green pertains to patient image viewing, yellow is for the pointing mechanism and brown colors the networking part of the prototype.

3.3.1. Hardware: Mouse clog

For the Mouse clog, we used an HP Z3700 wireless mouse that fits underneath the sole of a rubber clog ceded by the Champalimaud Foundation. This clog is just like the ones used by surgeons during surgeries, and its sole was ground with a Dremel rotary tool to fit the mouse. Before its embedding, the mouse was partially disassembled and its buttons were removed: the choice of removing the buttons was a result of initial testing, where mouse buttons would accidentally be pressed when the clogs were simply being worn. Additionally, we



Fig. 6. While pointing, the video is fixed on the augmented space. Additionally, it is possible to interact with the images while pointing.

removed some plastic parts from the mouse to save space and fit more easily into the clog.

3.3.2. Image visualization

The Meta rig Game Object is a prefab made available by the Meta SDK³ and establishes the connection between the Unity⁴ application and the Meta 2 HMD. On one hand, it receives data such as position and rotation, which is then made available to the application through the prefab's transform, while on the other, it handles the scene cameras, being responsible for what is shown to the user via the display.

The Gaze controller is a simple script, yet central part of the prototype. It reads the rotation values of the Meta2 HMD in order to determine whether the laparoscopic video should be displayed or hidden to show the patient MR images instead. The threshold value after which the video is hidden is 50 horizontal degrees for either side, granting the user the possibility to move their head with the video following the head motion in a range of 100 degrees. There is another threshold of 20 vertical degrees when looking up which, after crossing it for a short period of time, toggles the pointing mechanism. We determined these threshold values by trial and user testing.

Finally, the Video screen Game Object displays either video from a USB camera or an existing file, if needed for demonstration purposes. The prototype displays the video from the laparoscopic camera on the HMD's transparent visor in an aspect ratio of 16:9, while making as much use of the Meta2's screen real estate as possible.

3.3.3. Patient image viewing

There are two sets of Patient Data objects, one for each side, and they hold Game Objects and Canvas elements related to displaying information pertaining to patient imaging, such as labels with the current plane and image index, navigation bars, change plane buttons, as well as the patient MR images themselves.

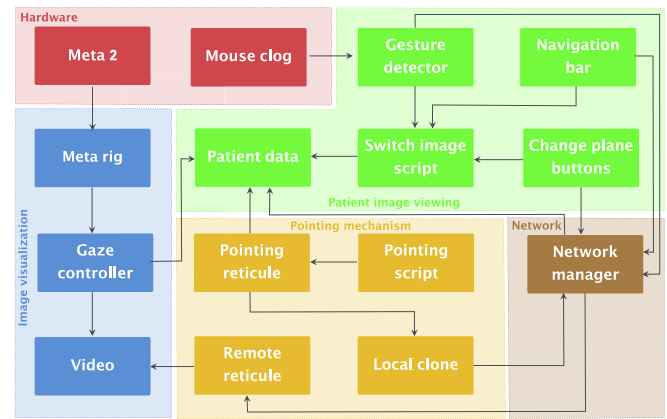


Fig. 7. Conceptual overview of the prototype. Arrows indicate information flow.

The Switch image script is responsible for loading patient images from disk and displaying them on screen. It also holds all state pertaining to displaying the MR images, this includes the current plane and index for both left and right image, number of total images per plane and path to the images. Finally, it also manages the navigation bar appearance. The navigation bar sits between the image and its label in the UI. Its functions are twofold:

1. Show the user how far in the plane he or she has navigated, using the ProgressBar script. This script dynamically updates the Navigation Bar's size according to the current image being displayed. The need to perform this resizing programmatically stems from the fact that Unity is unable to simply scale objects on one side only. Thus, a rescale and reposition is required every time the next or previous image is loaded.
2. Allow for image navigation using the head gaze, with the BarNavigation script. The Navigation Bar is divided into ten equally-sized, but invisible segments. The choice to go with segments in lieu of casting a ray from the camera to the object, calculating the hit's local position and obtaining the corresponding percentage resulted from verifying in earlier experiments with the arrows that, although the HMD works reliably well with objects tightly stacked vertically, such was not the case horizontally, as the gaze could not be held on one object consistently, which would translate to images quickly jumping back and forth, especially in larger data sets. Thus, using ten horizontal but large segments was a preferable alternative. These segments correspond to a given percentage, ranging from five to ninety-five. Activating these segments loads the image on the index equivalent to the percentage attributed to a said segment. Additionally, there is a safety feature concerning the activation of these targets, to prevent unintended activations, and to distinguish accidental gazes from intentional attempts at interacting with the bar, a small timer was implemented, waiting for the user to initially hold the gaze on the bar for 0.2 s before it becomes responsive. After this, they may drag the gaze left and right and the bar responds immediately, loading the image associated with the activated control. The user may also accidentally break gaze contact with the bar, and to prevent him or her from having to suffer that 0.2 s delay, which may lead to feeling that the prototype is unresponsive, or responds unreliably, a second timer was implemented, distinguishing whether users stopped gazing at the bar accidentally or intentionally, allowing users a half-second to reestablish gaze contact so they can resume manipulating the bar without any delays.

The Gesture detector script for this Game Object reads horizontal input data from the mouse, calculating how far the mouse has moved from a starting position on each update cycle. This calculation starts when the

³ <https://www.schenker-tech.de/en/meta-2/> (Accessed 25 May 2020).

⁴ <https://unity.com/> (Accessed 25 May 2020).

user places the head gaze on either patient image and stops when the gaze is no longer upon the image. This value is then compared against a maximum value to obtain a percentage of movement. For the first ten percent, a dead zone is present in order to prevent accidental triggers, so nothing happens. Between ten and forty percent, images start progressing at a rate of two per second. Between forty and seventy percent, images progress at a rate of four per second. In the last thirty percent, the rate at which images change is of ten per second.

A colour bar represents a state pertaining to the gesture detector mentioned above. The bar is curved to better convey the user how much the foot has been rotated, with an icon being placed depending on the position. The icon can be coloured green, yellow or red, depending on speed. Also depending on speed is the shape of the icon. While green, the icon is a play icon; on the yellow colour it is a fast-forward icon, representing greater speed. For the red colour, the fast-forward icon was adapted to feature a third play icon to represent an even faster speed. While visible, the icons fade in and out to confer a feeling of dynamism in the prototype.

Lastly, Change plane buttons sit below the image and change the plane from either side to the third, unselected one. For example, if the Axial and Coronal planes are shown, the button will switch the image from either to the Sagittal. When changing plane, the image index is kept to prevent the user from having to browse the entire plane again up to that point.

3.3.4. Pointing mechanism

The interface provides three pointing enable buttons, one on each side and another one on top. The top one is disc-shaped, positioned such that it allows a person to look up to 20 degrees before it activates.

The Pointing script is responsible for handling prototype behaviour when the pointing feature is active, as well as the process of enabling or disabling it. When enabling pointing, the script fixes the laparoscopic video in the world in a centred position, hides the Navigation reticle and enables the Pointing reticle.

The navigation reticle is a red cross-hair that appears whenever the laparoscopic video is not in view and pointing is not enabled. It is used to help users target button controls via head movements.

When disabling pointing, the opposite is done. The Navigation reticle is again shown when appropriate, the Pointing reticle disappears and the video resumes following head movements. While pointing is active, the script acquires the Meta Camera Rig Game Object's rotation values and places the reticle 0.7 units away from it, so it is always facing the user at the same distance, while not colliding with the remaining objects in the world, which are 0.8 units away from the camera. After positioning the reticle, it calls a Network Manager function to broadcast its transform to other users.

Unlike the Navigation reticle, the Pointing reticle is always visible regardless of whether the user is looking at the video or not. For better visibility, it features an additional circumference around the cross-hair, it is coloured in cyan so it better contrasts with the laparoscopic video, and the black outline help visibility when pointing to patient images.

The Remote reticle represents what the other user is pointing to. It is similar in form to the Pointing reticle, but is coloured in green instead of cyan.

Finally, when the user points at the screen, the Local Clone Game Object is used to copy the reticle's transform in order to send the local position in lieu of the global position. Because the Local Clone is a child object of the Video Screen, a user that is not pointing can look around, have the video follow his or her head movements and still see the other user's reticle pointing in the correct position. If the user points at patient data, the Local Clone's local position is not used and the Pointing reticle's global position is sent instead.

3.3.5. Network

This custom object uses Unity Networking classes `NetworkServer` and `NetworkClient` to streamline communications. Due to the

architecture of these classes, a user is required to act as the Server for the session, while the other joins as a Client. However, the messages that each exchange are identical and are processed identically as well. These messages include loading images and switching planes, as well as positioning the Remote reticle, hiding the Remote reticle when the other user disables turns off Pointing. To connect a new pair of glasses, all that is necessary is the IP address of the computer acting as Server and that all clients are connected to the same network.

4. Evaluation

In order to evaluate how the users perceived the implemented features in the prototype, in terms of both usefulness and usability, we used a think-aloud protocol to conduct qualitative evaluation sessions with users. Also, we check the advantages of the prototype compared to traditional laparoscopic procedures, we also chose to include a System Usability Scale (SUS) [20] questionnaire for measuring the usability, and a NASA Task Load Index (NASA-TLX) [21] questionnaire for rates perceived workload to assess prototype effectiveness.

4.1. Setup and apparatus

The qualitative evaluation sessions were conducted in an office inside the Champalimaud Foundation's building, under slightly reduced lighting conditions. The prototype, running on Unity Editor version 2017.4, hosted on an ASUS Strix laptop, with an Intel Core i7-6700 HQ CPU, 16 GB of RAM, a Nvidia GeForce GTX 1070 graphics card with 8 GB of VRAM and Windows 10 installed. To better emulate usage in the context of a real operation, the prototype played a 720p video footage of a laparoscope feed, recorded in a previous surgery, while the displayed MR images are PNG files, converted from a set of anonymised DICOM images, pertaining to a rectum magnetic resonance, using IrfanView. While experimenting with the prototype, users were asked to hold two laparoscopic instruments, which were partially inserted into a custom-made laparoscopic exercise training box. Having the users hold the tools not only helped mimic the context of an operation, but it also prevented them from accessing the patient's MR images by rotating their torso, which would have made the task much easier and unrealistic.

4.2. Participants

The participants were laparoscopic surgeons working for the Champalimaud Foundation who came in either at random occasions or at an agreed time. The user population included eight participants, one of them female, with ages ranging from 33 to 52. All of them had at least seven years of experience performing traditional laparoscopy, averaging eleven. In terms of robot-assisted laparoscopy, none of them had over five years of experience. However, on the topic of HMDs, almost all reported having very limited experience, with only one having used them more than once. Fig. 8 shows the alluvial diagram that highlights important user characteristics emphasized by color and node clustering.

4.3. Tasks and procedure

Initially, the participants were explained the context and purpose of the session, which was to evaluate the prototype itself and not their performance as users. Subjects were then asked permission to record the session, for later analysis to get a better understanding of the given feedback. Each participant was also asked to fill a profile questionnaire before the experiment.

The prototype's features were briefly explained and demonstrated. In the end, subjects were asked if there was something they would like to be explained again. Then, each participant was asked to put on the prototype and was given ten minutes to explore it freely and informally,

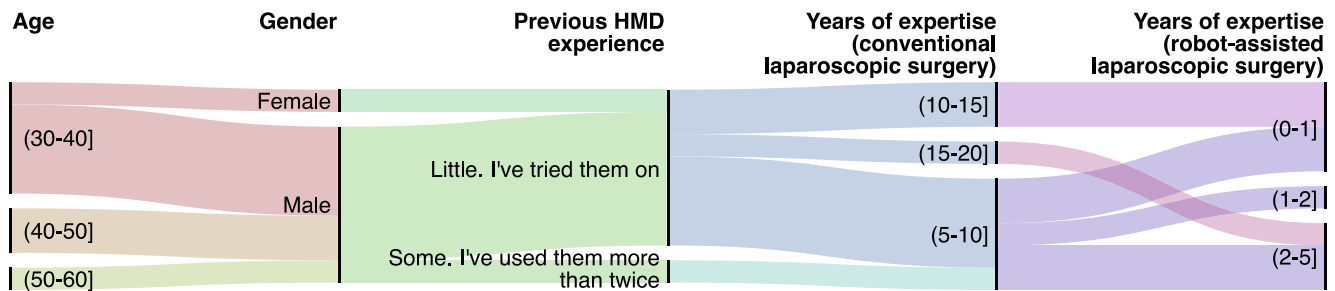


Fig. 8. Alluvial diagram of general participants' profiles of the usability testing. The sizes of edges and flows are therefore linked to the values containing the same couple of nodes. Flows coming from and going to the same couple of nodes are grouped.

with the session moderator giving suggestions to try certain features they had not exercised before. Subjects were also advised to talk out loud what they were trying to do in case they ran into problems.

After the ten minute mark, subjects were told to halt the experimentation and take off the headset, before being instructed to fill out a user preference questionnaires. This questionnaire was then followed by a semi-structured interview, in order to better appraise the participant's experience and opinions regarding the prototype.

Also, to check the advantages of the prototype as compared to traditional laparoscopic procedures, we also conducted a System Usability Scale questionnaire for measuring the usability, and a NASA Task Load Index questionnaire to rate perceived workload in order to assess the prototype effectiveness. These additional data were not collected in-person. Since there were several weeks elapsed since the original test, the data collected could be affected by recall bias.

5. Results and discussion

In this section we discuss the results of the qualitative evaluation, focusing first on each component of the prototype and presenting general opinions and impressions afterwards. We take into consideration not only the results of the user preference questionnaires, but also responses given during the semi-structured interview and impressions shared during the prototype exploration phase.

We assessed user preferences and experience through a questionnaire with a list of statements for participants to score on a 6-point Likert Scale (6 indicates full agreement). Table 1 shows the participants' reception to the proposed features of the prototype, showing that all were well received.

Furthermore, We evaluated prototype using SUS, and the results

depict good usability and high learnability (usability score: 72.92), as shown in Table 2. The scores of the 10 items were transformed into a summary score ranging from 0 to 100, the higher the value, the more friendly. We also studied the subjective workload experienced by users during the prototype evaluation. For this purpose, we conducted a workload analysis study using NASA-TLX. We asked users to rate their levels of mental, physical, and time demands associated with a task on a scale of 20 points, as well as their effort, performance, and frustration during that task. The 1–21 scoring system that was used was taken directly from the downloadable form from the NASA website. Fig. 9 shows the sub-scale summary of workload analysis.

5.1. Laparoscopic video

Initial impressions regarding the laparoscopic video were positive. Surgeons found the video following the user's head movements to be both useful and easy to visualise, with some participants remarking how ergonomic it was, as compared to the current way of looking at the video. Other participants found it to be the core benefit of the entire prototype.

However, the main argument against the video is its display size. Participant 1 complained that the video looked unfocused. P6 also wished the video would take a larger amount of the user's FOV, and P3 felt that the video looked small when compared to the screens used in the surgical room. P4 also felt that the video was better on a larger screen, but also considered that the number of people passing by in the background could work against it, which is something that may not happen with the HMD if the user is looking down.

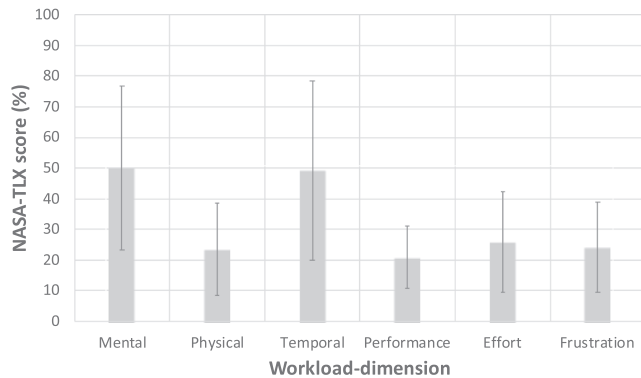
Table 1
Results for the user preference questionnaires: median (interquartile range - IQR).

Features	Statement	Median (IQR)
Laparoscopic video	It was easy to visualise the video	6 (0)
	I liked having the video follow my head movements	5 (1)
Patient data	It was easy to examine the patient images	6 (1)
	I liked where the images were positioned	5 (2)
	It was easy to browse the images along the axis using the bar	6 (2)
	It was easy to browse the images along the axis by rotating the foot	6 (0)
	It was easy to switch between axial, coronal and sagittal planes with the button	6 (0)
	It was easy to understand how fast the images were changing	6 (1)
	I liked having different speeds to navigate the images	6 (1)
Pointing	It was easy to activate the pointing reticle by looking up	5 (1)
	It was easy to activate the pointing reticle by using the button	6 (0)
	I could easily understand whether I was pointing or not	6 (0)
	I could easily understand where/what I was pointing at	6 (0)
General impressions	Overall, I liked using the system	5 (0)
	I think the system would help making laparoscopic surgery less fatiguing	5 (1)
In comparison with conventional laparoscopic procedures	Improves communication as it is possible to let others know what part of the video I'm pointing at talking about	5 (0.75)
	Improves perceptions of what part of the video others are talking about	5 (0.75)
	Improves hand-eye coordination, as surgeons no longer need to look at screens placed outside the field of operation	4 (0.75)
	Enables a comfortable posture throughout the surgery	4 (0.75)

Table 2

Descriptive statistics of SUS items: average, median, minimum value - Min, largest value - Max, standard deviation - SD, interquartile range - IQR.

SUS item	Average	Median	Min	Max	SD	IQR
I think that I would like to use this system	4	4	3	5	0.63	0
I found the system unnecessarily complex.	1.5	1.5	1	2	0.55	1
I thought the system was easy to use.	4	4	3	5	0.63	0
I think that I would need the support of a technical person to be able to use this system.	2.67	3	2	3	0.52	0.75
I found the various functions in the system were well integrated.	4	4	3	5	0.63	0
I thought there was too much inconsistency in this system.	1.83	2	1	3	0.75	0.75
I would imagine that most surgeons would learn rightarrow use this system very quickly.	3.67	4	2	5	1.03	0.75
I found the system very cumbersome to use.	2.33	2	2	3	0.52	0.83
I felt very confident using the system.	3.67	4	3	4	0.52	0.75
I needed to learn a lot of things before I could get going with this system.	1.83	2	1	2	0.41	0
Total SUS score	72.92	75	60	85	9.80	13.13

**Fig. 9.** NASA-TLX workload analysis results. The six ratings can be converted the 0–100 scale by subtracting 1 and multiplying the result by 5 (average, standard deviation - SD).

5.2. Patient data

With respect to the patient data images and their navigation through the navigation bar, the foot and the button, users liked the interaction mechanisms. Users were all able to perform all types of image interaction autonomously, although one of the users did not understand how to stop the images.

In terms of image navigation, users found the navigation bar and the foot to be complementary mechanisms, as they could make an approximation of what they wanted with the bar and make a fine adjustment with the foot. The foot itself was found to be comfortable, as surgeons were already used to using the pedals in the surgical room. In addition, participant 8 felt that the prototype could be improved if, when navigating on one plane, the other plane kept up. This participant also criticised the navigation bar, saying that when controlling it, the focus is on the bar and not the image, thus preferring the foot and complimenting how the foot rotation and scroll speed were being represented.

Displaying two images as a means to mimic the imaging software used in the preoperative meeting was a generally accepted idea, although one recurring piece of feedback was a desire to have the option to hide one of the images and enlarge the other.

Due to a good image definition, users found that it would be viable to use the prototype in real surgical environments. They remarked that it is not always necessary to consult images, but when it is, the prototype would prove useful.

In the end, users liked how easy it was to consult the images and how it is not necessary to call an assistant, which gives the surgeon a feeling of control, as an assistant might not know exactly what to look for. In particular, participant 4 said "It's better to see it by yourself instead of asking an assistant to scroll, or to focus", calling the foot mechanism "quite nice".

5.3. Pointing

Feelings regarding the pointing mechanism were positive as well. Users had no problem telling the red reticle, used to aid the person in activating interface elements, from the blue reticle, which is also used in pointing.

Regarding the two activation methods, using the button preferred by the majority, with only two participants leaning towards looking up instead. The most common complaint regarding looking up required a more extreme movement, whereas a button would be easier to reach. As such, participant 5 felt that the button was easier to activate because it is closer, but remarked that by looking up it is not necessary to think about where to look. Participant 4 felt that looking up requires too much effort, preferring the button as well, saying "you look at the button and you immediately know when it works, it's blue and then you can point", while complimenting the prototype for allowing one surgeon to point and still allowing the other to look around.

With respect to the reticle itself, subjects felt that it was easy to notice and to control and that unlike the current procedure of pointing at the screen, it was unambiguous. In particular, participant 1 felt that the pointing reticle is simple and easy to learn and use, and useful to communicate with colleagues and to explain certain things to them. Participant 7 noted that there is not much of a difference compared to pointing with the robot, and participant 1 felt the pointing reticle was clear and praised the choice of the colour cyan, not only because it is similar to the reticle present in the Da Vinci robot, but also because there are no human structures in this colour and therefore it clearly contrasts with them, while also saying it contrasts well with the MR images. Participant 6 felt the pointing mechanism was more beneficial to users who are not holding surgical tools, such as surgeons wielding the laparoscope, while on the other hand participant 8 commented that the reticle is useful even when holding tools, as it sometimes is necessary to release a noble structure, or ask someone else to hold it, in order to use the tool to point, calling the reticle "extremely useful".

5.4. General impressions

Impressions regarding the prototype, in general, were positive. Overall, participants were receptive to the idea of using the prototype in a surgical environment. One subject noted that it was perfectly possible to observe the video and look at the tools, while another said "everything was quite easy to get, intuitive and natural", praising the control activation times. Participant 5 also felt that the interaction was almost natural, that it could be learned in two or three minutes and that no interface elements seemingly activated by accident. Participant 1 stated that unlike some other devices the Champalimaud Foundation has, the prototype is easily usable by everyone.

5.5. In comparison with conventional laparoscopic procedure

Overall, the results of the comparative evaluation between the

prototype and conventional laparoscopic procedures were positive. Users consider that the prototype can improve communication and perceptions of what part of the video others are talking about. Also, users believe that the prototype can enhance hand-eye coordination, as surgeons no longer need to look at screens placed outside the field of operation. Besides, in comparison with conventional laparoscopic procedures, users consider that the prototype can enable a comfortable posture throughout the surgery.

Considering the limitations of laparoscopy and the hurdles it places on surgeons, be it physically or mentally, our work offers approaches to some of these problems. Notably, our prototype offers a way to visualise the laparoscopic video while not forcing the surgeon to assume unnecessarily uncomfortable positions, presenting a solution for the neck tension problem. Results have been extremely positive in this regard, with some physicians remarking this constitutes the most important aspect of the prototype. Also, from our field observations, we noticed that surgeons place down their tools to perform some secondary tasks, which interrupts the procedure. We designed our prototype to avoid this type of situations, with a completely hands-free approach, using both head gaze and foot movement as sources of input. Despite the novelty of the idea, participants found it easy to get used to. Finally, our approach improvements to surgeon-to-surgeon communication. Currently, communication between surgeons is ambiguous at best, with surgeons being barred from touching the screen due to sterilisation. Our prototype takes a very effective mechanism, the cursor, which is already found in robot-assisted laparoscopy, and introduces it to the more sustainable method that is traditional laparoscopy through the HMD. Leveraging this familiarity proved useful, with surgeons commenting on how well it works, both in terms of activation as well as usage.

5.6. Limitations

Some drawbacks about the prototype were noticed. There were grievances about the weight of the Met2a, with participants 1, 4, 6 and 8 complaining about it. Participant 8 further specified that the problem lied not so much in the headset weighing too much, but rather how the weight was distributed, very unevenly and completely at the front, which corroborates Knight et al.'s findings [22]. In addition, participant 4 likened the prototype's weight effect to using a surgeon's lamp. However, participant 2 commented that the HMD is actually comfortable and that over time the wearer forgets that they're wearing a HMD, comparing it to a PlayStation VR. Participant 3 also remarked that in terms of comfort, it is not much more uncomfortable than the current procedure.

Some people also complained that the laparoscopic video itself looked unfocused, while others thought it looked too small. In terms of image quality, we can attribute this to the footage being presented in 720p, rather than the 1920x1080 resolution that the surgeons claim the operating room screens use, as well as the video itself not being in the highest quality, with the visibility of block artefacts throughout the footage. The quality of the MR images however, was widely praised as being very clear and sharp.

Last, there were also problems in terms of calibration. The Meta2 places the objects in the game world according to its initial calibration values, meaning a poor positioning of the headset while launching the application would result in the user observing the objects as if they were tilted. This also sometimes resulted in physicians seeing the patient data presented in one side much closer than the other and later complaining that the data were very hard to reach. When facing this situation, people were then asked to visualise the data on the other side, which they in turn reported was very easy to access.

6. Conclusions and future work

We have made a study of the conditions in which the laparoscopic surgeons perform their tasks, analysed areas of improvement, and designed our prototype in an attempt to improve upon those aspects. First,

our prototype allows surgeons to visualise the laparoscopic video feed while looking at the tools by following user head movements. Second, it will enable patient data to be consulted during the operation, without needing to interrupt the procedure and call in an assistant, by merely requiring the surgeon to look to either side. Last, it allows surgeons to point at the screen precisely in a non-ambiguous and more effective fashion than using the finger or the laparoscopic tools.

In our evaluation, we found that users were receptive to the innovations brought forth by our work, showing excitement about the fact that their issues are being approached. The ability to observe the laparoscopic video feed in one's FOV has the potential to reduce the physical effort required of surgeons. The displaying of MR images cuts time losses whenever the need to consult an image arises, and the ability to accurately target anatomic structures on the screen improves understanding between team members.

Finally, we believe that, by streamlining the visualisation of important data, as well as team communication, our work has the potential to change the laparoscopic procedure so that it does not require as much mental and physical effort as it does today.

While the work presented in this paper represents a new way to perform laparoscopic surgery that mitigates some shortcomings that currently affect the procedure. We believe our work provides a solid foundation upon which laparoscopy can eventually benefit from the application of AR. As such, there are several ways in which the current work can be expanded.

There are also ways in which the current prototype can be improved. While the scope of this work focused on the visualisation of laparoscopic video with the liberty to look around and assume different neck postures, it would be interesting if users could better observe the inside of the patient as if they were in an immersive environment.

The 2D visualisation removes the perception of depth from the user, which increases their mental effort in understanding how the tool is moving. Stereoscopic 3D mitigates this problem and improves task performance [23]. Therefore it would be useful if the technical constraints could be solved in order to bring stereo visualisation to the prototype.

Akin to the preparation procedures employed by nurses, the prototype would benefit from storing user preferences specific to each surgeon, which would in turn be loaded during said procedure. These preferences could specify parameters such as screen and image distance and size.

In our observations, we found that sometimes senior surgeons would come in and give counsel on the operation at hand. This type of help consisted of the surgeon pointing at the monitor embedded in the wall. Currently, there is no way to convey what that surgeon is pointing to. We can suggest adapting the work of Sousa et al. [24] to implement this type of functionality.

Lastly, there are some issues and limitations with the Meta 2 glasses, and since the Meta company has shut down and left the product unfinished in its development stage, we question whether these issues will eventually be sorted out or not. Because of this, we believe the work could continue to evolve in a more stable manner if a change in hardware occurred. We thus propose the migration to Microsoft HoloLens2, as it is untethered, which should help reducing clutter in the operating room. Furthermore, it improves the previous product by investing heavily in ergonomics, benefiting from a weight reduction and adjustment of the center of gravity more to the center of the head.

In conclusion, our work has unveiled some of the vast potential that AR can bring to conventional minimally-invasive surgical settings. While this is a first prototype, there is seemingly a bright future to applying Extended Reality tools and interfaces in modern surgical procedures and we are excited to trailblaze it.

Declaration of Competing Interest

None.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.jbi.2020.103463>.

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