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# State-of-the-Art Review

# Observation in Laparoscopic Surgery: Overview of Impeding Effects and Supporting Aids

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## ABSTRACT

**Within a Dutch research program on minimally invasive surgery, a large literature survey has been carried out. This article describes the state of the art in research on observation in laparoscopy. It gives an overview of factors impeding the surgeon and technical developments designed to overcome these problems. A large number of journals, proceedings, patents, and books starting from the year 1991 have been consulted. The survey was completed with a thorough *MEDLINE* search. The survey showed that many authors have an incomplete background in the fundamentals of visual perception. This leads to a lack of understanding and to the design of supporting aids that often are not very useful. The new aspect of this study is that it gives a complete and structured overview of laparoscopic observation problems and current solutions. The observation problems are structured according to visual perception theory. The solutions are critically considered, and their benefits and drawbacks are identified. The study shows that the benefits of stereo-endoscopes and motorized endoscope positioners are questionable. The addition of shadows and movement parallax is still a very important research topic.**

## INTRODUCTION

During the past decade, the number of laparoscopic procedures in abdominal surgery has increased significantly. The use of a laparoscope and long and slender instruments that are inserted through small incisions in the skin reduces tissue trauma and in principle also the risk of infection and recovery time. Despite these significant advantages for the patient, the technique introduces a number of difficulties for the surgeon. The operative protocols of many procedures are still far from optimal, and it is difficult to transpose preoperative information from X-rays, Ultrasound, or MRI images onto the endoscopic camera pictures. Other difficulties concern the indirect way of observing and manipulating. They complicate the surgeon's observation and manipulation activities and disorder the surgeon's eye–hand coordination.

In order to find solutions for these difficulties, a large research program on minimally invasive surgery techniques was initiated at the Delft University of Technol-

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This research is part of the Minimally Invasive Surgery and Interventional Techniques program (MISIT) of the Delft Interfaculty Research Center on Medical Engineering (DIOC-9).

ogy in cooperation with the Academic Medical Center in Amsterdam and several other hospitals in The Netherlands. The program is called MISIT, which is short for Minimally Invasive Surgery and Interventional Techniques.[1] The MISIT program consists of six research projects: task analysis of the surgical process, depth perception and eye–hand coordination, integration of physiological and anatomic information, mechanical design of instruments, mechanical steering of catheters, and miniaturization of sensors in catheters. Within the scope of the MISIT program, a large literature survey has been carried out.[2,3] This review article describes the state of the art in research on *observation* in laparoscopic surgery. It gives an overview of factors impeding surgical observation and technical developments to help overcome them.

## MATERIALS AND METHODS

The literature survey was focused on technical research and developments in laparoscopic surgery. Going back to the year 1991, several volumes of a number of journals, including *Surgical Endoscopy* and *Minimally Invasive Therapy & Allied Technologies*, were scanned for useful information. A number of conference proceedings, patents, and books about laparoscopic surgery and visual perception also were consulted. The survey resulted in about 300 interesting papers and documents that have all been carefully read and checked. In order to be certain no valuable information was overlooked, the survey was completed in the year 1999 with a thorough MEDLINE search relating to all the impeding effects and supporting aids that are mentioned in this article.

## NEW ASPECTS OF THIS STUDY

The literature survey showed that many authors have an incomplete background in the fundamentals of visual perception. This leads to a lack of understanding and to design of supporting aids that often are not very useful. For example, many authors confuse three-dimensional (3D) vision with stereovision and consider stereovision to be the only depth information source. As a result, nearly all the research on depth perception in laparoscopy is focused on stereo-endoscopes. Experiments show, however, that the benefits of stereo-endoscopes are negligible.[4–7] Furthermore, visual perception theory shows that stereovision is only one of the many depth perception cues. This finding indicates that a more thorough background could lead to much better aids to improve the surgeon's depth perception.

The unique aspect of this study is that it gives a structured overview of all of the observation problems and solutions that are currently available. The observation problems are structured according to visual perception theory. The solutions are critically considered, and their benefits and drawbacks are identified. The study ends with a list of problems that are still unsolved and a discussion of the direction in which we believe research should go. It is the authors' wish that the study will give a more fundamental insight into laparoscopic observation and that it will lead to better supporting aids.

## RESULTS

In order to structure the information from the literature, it was decided to subdivide the impeding effects on the surgeon's observation activities into three main groups: *acquisition, nature*, and *perception* of the visual information (Table 1). These groups are discussed in detail in the various sections of this article. Each section starts with an overview of impeding effects, followed by a survey of supporting aids that have been found in the literature. The article ends with a discussion in which the advantages and disadvantages of the aids are critically considered and a number of important research topics are identified.

The article focuses on the effects of the endoscopic camera and the monitor on surgical observation. The fundamentals of observation are only briefly described. A thorough treatment of visual perception is given by Gibson,[8] Regan and associates,[9] and Rock.[10] More specific information about visual perception in minimally invasive surgery is described by Cuschieri,[11] Sheridan,[12] and Wade.[13]

## ACQUISITION OF THE VISIBLE INFORMATION

### *Impeding effects*

Indirect viewpoint adjustment by camera assistant. It is common in laparoscopic operations that the surgeon is not directly in control of the endoscope. The visual information is collected by a camera assistant, who controls the endoscope by listening to the surgeon's instruc-

TABLE 1. OVERVIEW OF IMPEDING EFFECTS ON SURGEON'S OBSERVATION IN CONVENTIONAL LAPAROSCOPIC SURGERY

| |
|---|
| Acquisition of the visual information |
| Indirect viewpoint adjustment by camera assistant |
| Nature of the visual information |
| Finding and identifying anatomic structures |
| Perception of the visual information |
| General effects on visual perception |
| Dirt and vapor on endoscope lens |
| Reduced resolution, contrast, and illumination |
| Specific effects on depth perception |
| No shadows in endoscopic camera picture |
| No stereovision |
| No movement parallax |
| Misfits of accommodation and convergence |

tions and using a set of empirical rules.[14] Examples of such rules are "the top of the moving instrument should stay in the middle of the picture" and "the abdominal wall should stay at the top of the picture." This indirect way of adjusting the viewpoint is not very intuitive. It can lead to communication problems between the surgeon and the assistant and to an unsteady camera picture when the assistant has to stand still for a long time.[15] Mohrmann-Lendla and Fleischer[16] showed in an experiment that an unsteady camera picture decreases the performance of aimed hand movements.

### Supporting aids

*Passive endoscope positioners.* Direct viewpoint adjustment can be realized by replacing the assistant by a passive or an active endoscope positioner that is directly under the surgeon's control. A passive endoscope positioner is an endoscope holder with passive joints. Its base can be attached to the operating table, and its tip contains a clamp that holds the endoscope. The surgeon can grasp the holder and move it to the desired location. The friction in the joints prevents the holder from moving when it is released, so that the endoscope is locked in the desired position. Passive endoscope positioners are mentioned in a number of references.[17–21] Their advantages are that they are directly under the surgeon's control and that they result in a steady picture. Their disadvantage is that the surgeon has to release a laparoscopic instrument to move the endoscope into another position. This is inconvenient.

*Active endoscope positioners.* An active endoscope positioner has joints that are driven by electric motors. Active endoscope positioners are described in a large number of references. Most are controlled by using a hand controller,[22–26] but some can be also controlled by grasping and moving like a passive endoscope positioner.[24,25,27,28] The drawback of these ways of controlling is that the surgeon still has to release an instrument to move the endoscope. This problem can be solved by using an instrument-mounted hand controller,[27–30] a foot controller,[24–26,31,32] voice control,[33] or head movements to control the robot.[3,34–38] The disadvantages of foot controllers are that foot switches are already used for other tasks in the operating room. Adding one more can be confusing. Voice control can be accurate but is subject to operator–interface failures.[33] Head control is probably most intuitive but is still in an early stage of research.

Taylor and associates[27,28] described a robot with an option to save a number of camera positions in a computer memory. The surgeon selects a viewpoint by using an instrument-mounted hand controller, and the robot determines the spatial position of the viewpoint by means of image manipulation techniques. The selected viewpoints are saved in the computer memory and shown in small snapshot images on the monitor. The robot moves the endoscope automatically to the saved viewpoint when the surgeon selects one of the snapshots. A similar option, in which previously selected robot positions can be restored by pressing memory buttons, is offered by the Automatic Endoscope System for Optimal Positioning (AESOP), which is mentioned in a large number of references.[23–26,31–33,39]

*Comparison between human and automatic endoscope control.* Commercially available active endoscope positioners are the FIPS,[29,30,40] which is controlled by an instrument-mounted hand controller; the EndoSista,[36,37] which is controlled by head movements; and the AESOP, which can be controlled by using a hand or foot controller, by grasping and moving, by voice commands, and by memory buttons.

Kavoussi and associates[32] compared the AESOP with a human camera assistant in 11 pelvic laparoscopic procedures that required bilateral surgical manipulations. Eight men underwent diagnostic laparoscopic pelvic lymphadenectomy, and three women underwent laparoscopic Burch bladder suspension. Surgery was performed similarly on the left and right sides of the pelvis except that on one side, the endoscope was controlled by the camera assistant, and on the other side, the endoscope was controlled by the AESOP. The robot was controlled via a foot controller. The side (left *v* right) on which the AESOP was used was alternated with each case. The AESOP gave a more stable camera picture, but the difference in operation time was negligible.

Jacobs and coworkers[31] performed an experiment with 31 medical students having negligible laparoscopic experience. They performed a standardized task in a pelvitrainer during 10 minutes of practice, either with hand control over the endoscope or with AESOP control by means of a foot pedal. The subjects were randomized by alternating hand control and AESOP control first. The use of AESOP resulted in much longer task completion times than hand control.

These studies show that, apart from stabilizing the picture, the advantages of the AESOP are questionable. Passive endoscope positioners, controlled either by the surgeon or by a camera assistant, can be used as well to stabilize the picture and are usually smaller, much cheaper, and simpler in construction. New developments are needed to prove that a robot can be really more convenient than a passive endoscope positioner or a human camera assistant.

## NATURE OF THE VISIBLE INFORMATION

### Impeding effects

*Finding and identifying anatomic structures.* In an open abdominal operation, the surgeon looks down at the patient's abdomen, observing a top view of a large part of the operative area. In a laparoscopic operation, the surgeon looks forward at the monitor, observing an enlarged side view of a small part of the operative area. The nature of the visible information thus differs from what the surgeon is used to. The endoscope shows a *magnified view* of the operative area, with a *different line of sight* and with a *small field of view*.

An advantage of the magnified view is that the picture of the operative field is larger and more detailed so that small anatomic structures are easier to discern.[41,42] An advantage of the different line of sight is that it can be more convenient for some operations. Disadvantages of the magnification, the different line of sight, and the small field of view are that it becomes more difficult to find and to identify anatomic structures.[15,41] The small field of view of conventional endoscopes leads to frequent endoscope maneuvers; e.g., to move the endoscope lens to the abdominal entry point of a newly inserted instrument. Such maneuvers are not only inconvenient and time consuming, but they can also lead to potentially dangerous situations; e.g., when instruments not in sight injure structures in the operative area.[15,29,43,44]

### *Supporting aids*

*Graphical overlays, additional endoscopes, and panoramic endoscopes.* In order to assist the surgeon in finding and identifying anatomic structures, Satava and Robb[45] developed a graphical overlay that visualizes the position and orientation of the endoscope relative to the patient. The overlay, which is superimposed on the endoscopic camera picture, consists of two icons: a transversal cross-section of a human body and a spatial picture of a human being in recumbent posture. The cross-section informs the surgeon about the position of the endoscope, and the human image informs the surgeon about the orientation of the endoscope. The image of the human being rotates when the endoscope is rotated. The cross-section remains stationary.

Schippers and Schumpelick[44] suggested enlarging the field of view by using an additional endoscopic camera that gives a total view of the peritoneal cavity. The additional view makes it easier to find anatomic structures, thus reducing the required number of endoscope movements. Schurr and coworkers[29] performed an animal test with a 135° panoramic endoscope that showed a large part of the peritoneal cavity. The center of the panoramic picture, which contained the actual operative area, was enlarged and displayed on a separate monitor. The endoscope had the drawback that sufficient illumination of the whole abdomen was hardly achievable with conventional light sources. In order to solve this problem, Schurr and coworkers[29] tested a more sensitive infrared panoramic camera as well. However, this camera produced a monochromatic picture. The colors of the different anatomic structures thus were not visible.

The disadvantage of using two monitors to display the panoramic and the enlarged central view is that the surgeon has to divide attention between two pictures, which increases the risk of overlooking something. Greguss[46] described a novel optical system that combines the two pictures in one. The picture formed by the system consists of a circular center surrounded by a ring. The center shows an enlarged view of the area of interest, and the ring shows a panoramic view of the environment. The panoramic view is created by a patented donut-shaped lens consisting of only one part, making it suitable for miniaturization and for application in an endoscope.

Besides observers of endoscopic camera pictures, observers of ultrasound images also have problems in finding and identifying anatomic structures. Bajura and collaborators[47] developed a supporting aid that projects an ultrasound image on the patient's abdomen. The scan is recorded with a 3D ultrasound scanner, filtered, and transformed into a 3D graphical image. The image is animated online as a stereo overlay on two television screens before the observer's eyes. The observer's head position is measured, and the image is rotated such that its orientation matches the observer's line of sight when looking at the patient's abdomen. The observer is thus able to see both the patient and the organs, having the experience of looking through the patient.

## PERCEPTION OF THE VISIBLE INFORMATION

### *General effects on visual perception*

*Dirt and vapor on the endoscope lens.* The surgeon's visual cortex uses the endoscopic camera picture to determine the spatial position of the instruments with respect to the anatomic structures. A potential cause for general visual perception problems is the quality of the picture on the monitor. Dirt and vapor on the endoscope lens is a frequent and irritating event that requires the surgeon to interrupt the operation to clean the lens.

*Reduced resolution, contrast, and illumination.* Besides dirt, and vapor, the camera and monitor properties have a large effect on the quality of the picture.[11,29,44] Comparisons in resolution, contrast, and illumination between different endoscopic systems have been found in a number of references.[48–50] Psychological experiments on the effects of resolution are reported by Motoki and associates,[42] Pasman et al,[51] Pichler and coworkers,[52] and Sheridan.[12] Sheridan noticed that in simple manipulation tasks, an increase in resolution improved the task performance. However, there was a saturation effect in which the performance leveled off with further increases in resolution.

## *Supporting aids for visual perception*

*Automatic lens-cleaning systems.* Schurr and colleagues[29] described a commercially available lens-cleaning system consisting of a tube into which the endoscope can be inserted. The tube contains channels that irrigate the lens with saline, similar to the irrigation system of a human eye. Blood or vapor can thus be washed away easily. A number of surgeons who are cooperating with the MISIT project mentioned that warming up the endoscope to body temperature before putting it into the abdomen can reduce vapor problems. Some surgeons mentioned also that the problem can be reduced by using another detergent in the endoscope cleaning procedure. No information about these solutions has been found in the literature.

*Improved resolution, contrast, and illumination.* The quality of endoscopic systems has advanced strongly in the past 10 years. The picture quality of modern rigid endoscopes is usually very good. The picture quality of flexible endoscopes and stereo-endoscopes, however, is usually less good because of the use of glass fibers or a double lens system within the same endoscope diameter. A luggage inspection experiment conducted by Pasman and associates[51] showed that the negative effects of a low resolution on the subject's depth perception can be strongly reduced by using a moving camera that enables the subject to look around the object. Similar results are reported by Smets and Overbeeke.[53] This pleads for endoscopic systems that enable the surgeon to observe the anatomic structure from different sides.

## *Specific effects on depth perception*

One of the largest problems in the determination of spatial information concerns the perception of distances and movements perpendicular to the image on the retina. A human can use three depth information sources to determine such distances and movements: *pictorial information, parallax*, and *visuomotor cues*.[8–11]

Pictorial information concerns the cues in the retinal image that give information about distances and movements perpendicular to that image. Examples of such cues are "an object that overlaps another object is closer to the observer" and "an object touches a surface when it touches its shadow on the surface."[11,12] The last cue is very helpful for accurate spatial positioning tasks.

Parallax concerns the changes in the mutual positions of objects in the retinal image when the viewpoint of the eye changes. Two kinds of parallax can be distinguished: *stereovision* and *movement parallax*. Stereovision concerns the disparity between the two pictures seen by the left eye and the right eye as a result of the distance between the two eyes. Objects with a different distance from the observer are shifted with respect to each other in the two pictures. The size of the shift gives information about their spatial position. The disparity between the two retinal images is reduced when the distance to the objects increases, and at distances >9 m, the two images are almost equal. The retinal cortex is then no longer able to detect a difference between them.[11] Movement parallax concerns shifts in the picture seen by one eye when the observer moves his or her head. The head movement causes the visible objects to shift with respect to each other, and this shift gives information about their spatial position. *Motion parallax* is a shift in the retinal image not caused by the observer's head movement but by an external influence; for example, the movement of a camera when the observer watches a camera picture.

Visuomotor cues concern the movements of the eyeballs and the eyelenses to focus on an object. *Accommodation* is the adjustment of the eyelens to focus on an object, and *convergence* is the horizontal and inward rotation of the two eyes to point them to the object.

In normal life, a human can use all these depth information sources to perform a spatial manipulation task. In conventional laparoscopic surgery, however, many of these sources are not available.

*1. No shadows in the endoscopic camera picture.* In all standard endoscopes, the light source is located at the tip, creating a ring of light around the lens. This is advantageous for the brightness of the picture but disadvantageous for the surgeon's depth perception, because the endoscopic camera picture contains in principle no shadows.[29]

*2. No stereovision or movement parallax.* Conventional endoscopes are monocular and controlled by a camera assistant. The surgeon is thus not able to use stereovision and movement parallax as depth information sources. When the assistant moves the endoscope, motion parallax is present to some extent, but the amount of information is limited, because the endoscope movements are limited. The endoscope incision point acts like a spherical joint that limits the degrees of freedom (DOFs) of the endoscope from six to four (Fig. 1). This makes it impossible to observe the anatomic structure from different sides while keeping the viewpoint in focus. Many laparoscopic surgeons experience this as a handicap.[54]

*3. Misfits of accommodation and convergence.* When the surgeon looks at the monitor, the eyelenses focus on the surface of the television screen, not on the visible objects behind the screen. This makes the information coming from visuomotor cues useless for depth perception.

Especially the absence of shadows, stereovision, and movement parallax makes it difficult for a surgeon to determine spatial distances and movements accurately. The

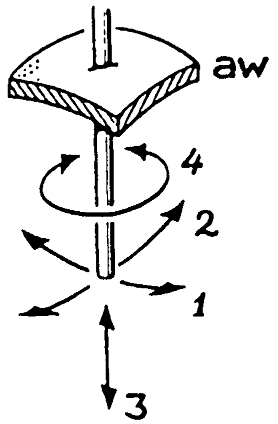


**FIG. 1.** Four degrees of freedom of standard endoscope. aw = abdominal wall.

next section describes a number of aids that have been found in the literature to support the surgeon in estimating depth.

### *Supporting aids for depth perception*

*Creating shadows in the endoscopic camera picture.* Research on pictorial information has been found in two references.[29,38] Schurr and associates[29] described two methods to introduce shadows to the endoscopic camera picture. In the first method, shadows are introduced by using illumination cannulas. These are trocars with light bundles integrated into their shafts that can be used as additional light sources. In the second method, the ring of light around the lens of a standard endoscope is replaced by a half moon of light beside the lens that illuminates the scene from one side. Both aids are already commercially available. Voorhorst[38] developed a shadow endoscope with two separate light bundles instead of one. The ring of light is divided into two half rings with variable intensity. An animal test showed that a variation in the balance of intensity was hardly visible in the endoscopic camera picture. This was caused by the fact that the distance between the light sources and the endoscope lens was very small.

*Stereo-endoscopes and shutter-glass systems.* Stereovision can be introduced by using a stereo-endoscope instead of a standard monocular one. In the literature, many applications of stereo-endoscopes have been found. Detailed information about their construction is given by Frank and associates,[55] Jones and colleagues,[56] Melzer and coworkers,[20] and Zobel.[57]

The two images of a stereo-endoscope must be displayed such that the left eye sees only the picture from the left lens and the right eye sees only the picture from the right lens. Griffin[58] and Motoki and associates[42] give a detailed overview of stereo television systems that can be used for this purpose. A frequently used stereo television system is the shutter-glass system, which displays the two pictures from a stereo-endoscope alternately on one monitor at a switching rate of 120 Hz. The observer uses a special kind of eyewear that separates the two pictures into one for each eye.

Shutter-glass systems can be subdivided in two groups: *active eyewear* and *passive eyewear systems*.[58,59] In an active eyewear system, the observer wears a pair of liquid crystal shutter-glasses that are fixed in front of the eyes. The two shutter-glasses are synchronized with the monitor. They switch alternately from transparent to dark at the switching rate of 120 Hz, so that each eye sees only the matching picture. In a passive eyewear system, the two small shutter-glasses are replaced by one large shutter-glass that is fixed to the television screen. The shutter-glass polarizes the two pictures on the screen into a left-polarized picture for the left eye and a right-polarized picture for the right eye. The observer wears a pair of passive glasses with opposite polarization that allows each eye to see only the matching picture. Shutter-glass systems have been applied in robotic systems for eye surgery[60] and for telepresence surgery,[61,62] in advanced simulators for open surgery,[63] and in many other applications.[56,59,64,65]

*Comparisons between monocular and stereo-endoscopic systems.* Monocular and stereo-endoscopic systems are compared in a number of references, most concerning pick-and-place, knotting, sewing, or threading experiments in a pelvitrainer. The results are ambiguous. Some experiments show significant improvements in execution time, error rate, or accuracy with stereo-endoscopes over conventional monocular systems,[52,66–69] whereas other experiments show no significant benefits.[4,5,7]

Hanna and colleagues[6] performed a randomized study to investigate the effect of stereovision on the performance of a laparoscopic surgeon in clinical practice. Four specialist registrars performed 60 laparoscopic cholecystectomies using either a conventional mono-endoscope or a stereo-endoscope with shutter-glasses (30 operations by each method). The operation time and the errors made during the procedure were measured, as well as the surgeon's subjective response. There was no difference between the mono-endoscopic and stereo-endoscopic systems in median operation time or error rate. The scores for visual strain, headache, and facial discomfort were higher with the stereo-endoscopic system.

These studies show that with the current technology, the advantages of stereo-endoscopes are questionable. Disadvantages of shutter-glasses are that the eyewear is annoying for the surgeon, there is poor lighting because of the use of a stereo-endoscope and polarized glasses, and there are imperfections of the shutter-glass system, resulting in flicker, interocular cross-talk, and conflicts between accommodation and convergence that can produce eyestrain. A general disadvantage of using stereovision as the *only* depth information source is that many human observers have problems in the perception of stereoscopic depth.[68] It is questionable whether stereo-vision is really so important for the surgeon's depth perception.

*Independent and head-coupled movement parallax systems.* In the literature, different movement parallax systems have been found. They can be subdivided into two groups: *independent* and *head-coupled movement parallax systems.*

In an independent movement parallax system, the observer's head movements are not measured. The image is displayed on a special kind of screen that shows a 3D image of the picture. Stereovision is automatically included, and the system can be used by different observers who all experience movement parallax. Detailed information about independent movement parallax systems has been found in a number of references.[42,70–72] Independent movement parallax systems are complex and expensive and are therefore hardly used in practice. One of the very few commercially available systems is the varifocal mirror display.[70,71] This system presents an image as a 3D dataset of points. The dataset is divided into a set of 2D slices that are projected one by one on a mirror. The mirror is mounted on a loudspeaker, which moves forward/backward with a frequency of approximately 30 Hz. The projection of the slices is synchronized with the mirror movement such that the slices appear to be floating in 3D space. The resulting image thus appears to be three-dimensional.

In a head-coupled movement parallax system, the observer's head movements are measured and transformed into movements of a camera or a graphical image. This is done such that the picture on the monitor moves opposite to the observer's head movement, thus giving the observer the experience of looking through the monitor. Stereovision is not automatically included. Only the observer in control experiences movement parallax; others experience motion parallax. Head-coupled movement parallax systems are relatively simple and cheap and are therefore used in many applications.

*Head-coupled movement parallax systems without stereovision.* Dowler and Holland[36] and Finlay and Ornstein[37] developed a commercially available head-coupled movement parallax system for laparoscopic surgery. The system, called EndoSista, measures the surgeon's head movements and transforms them into movements of an active endoscope positioner that holds the endoscope. The endoscopic camera picture is displayed on a monitor. Stereovision is not present. A similar system was developed by Voorhorst.[38] These systems enable the surgeon to position the endoscope directly without having to release an instrument or to use a foot controller. Their main disadvantage is that they do not compensate for the endoscope's limited freedom of movement. Movement parallax is realized only to some extent, because it is impossible to observe the anatomic structure from different sides while keeping the viewpoint in focus.

This problem can be solved by replacing the standard endoscope by a flexible endoscope[38] or by a 90° endoscope that looks around a corner[3,34] (Fig. 2). Advantages of the 90° endoscope are that its construction is more simple and that it can be used to improve the surgeon's eye–hand coordination.[3] Another advantage is that it offers the ability to look around the abdomen by rotating the endoscope around its shaft. Both endoscopes can be controlled by an active endoscope positioner, which is controlled by the surgeon's head movements.

*Head-coupled movement parallax systems with stereovision.* An example of a system that combines head-coupled movement parallax with stereovision is a Cave Automated Virtual Environment or briefly CAVE. A CAVE is a room with walls and a floor on which a stereoscopic animation is projected. The observers in the room wear active shutter-glasses that separate the two stereoscopic pictures into one for each eye. The head movements of the observer in control are measured and transformed into movements of the graphical image to simulate movement parallax. This gives the observer the experience of being within the displayed world. Only the observer in control experiences movement parallax; the others experience motion parallax. About 100 CAVEs have been built worldwide, among them the CAVEs in Amsterdam and at the University of Tokyo. A table model of a CAVE was developed by Djajadiningrat.[73] No medical applications of CAVEs have been found in the literature.

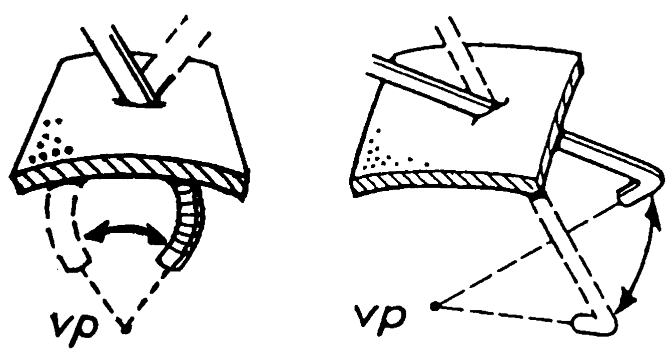


**FIG. 2.** Use of flexible endoscope (left) and 90° endoscope (right) to observe anatomic structure from side such that viewpoint remains centered in picture. vp = viewpoint.

Another, more frequently used, system that combines head-coupled movement parallax with stereovision, is a head-mounted display (HMD).[47,74–77] A HMD displays the two pictures from a stereo-endoscope or a graphical animation on two small liquid crystal displays (LCDs) that are mounted in a helmet in front of the observer's eyes. The observer's head movements are measured and transformed into opposite movements of the pictures to simulate movement parallax. Drawbacks of HMDs are the computing time delays between the observer's head movements and the movements of the pictures and conflicts between the simulated depth information sources, which can result in eyestrain and dizziness.[35,74,78] A disadvantage of displaying endoscopic camera pictures in a HMD is that it provides an immersive environment that gives the surgeon the experience of being within the peritoneal cavity. This is unnatural to human beings, who are onlookers by nature and interact with the environment in a nonimmersive external way. Furthermore, it isolates the surgeon from the medical team and the patient.[35,78]

The isolation problem can be solved by not only showing the surgeon the endoscopic camera picture but by projecting the picture on the patient so that the surgeon can see them both. Bajura and colleagues[47] developed an advanced HMD system that projects an ultrasound image on the patient's abdomen. The image is recorded with a 3D scanner, filtered, and transformed into a 3D graphical image. The image is animated online as a stereo overlay in a see-through HMD with transparent LCDs. This enables the observer to see both the animated organs and the patient, having the experience of looking through the patient. Movement parallax is simulated by measuring the observer's head movements and transforming them into opposite movements of the animated organs. This enables the observer to inspect the organs from different sides by moving the head.

*Restoration of accommodation and convergence.* Unlike the research on parallax, not much research on visuomotor cues has been found in the literature. Shutter-glass systems and HMDs usually suffer from conflicts between accommodation and convergence. In both cases, the eyeballs are pointed at objects *behind* the television screen. In a shutter-glass system, however, the eyelenses usually focus on the *surface* of the television screen, whereas the optics in an HMD are usually constructed such that the eyelenses focus on *infinity*. Motoki and associates[42] performed a psychological experiment with shutter-glasses to investigate the effects of such misfits. The results showed that a misfit between accommodation and convergence causes eyestrain.

The only system that causes no conflicts between the depth perception cues is the commercially available varifocal mirror display described earlier in this section.[70,71] Movement parallax, stereovision, accommodation, and convergence are in harmony, and the observer has the experience of observing a real 3D object. The disadvantage of the system is that it was developed for spatial animation: it cannot be used to visualize camera pictures.

## DISCUSSION

The objective of this article was to give an overview of factors impeding surgical observation and technical developments to help overcome them. The impeding effects are largest for a resident surgeon who is not used to the laparoscopic technique. The absence of many depth information sources necessitates an intensive and time-consuming training period in which the resident learns to compensate for the absent sources by increasing sensitivity to the sources that are still present. For example, the resident learns to compensate for the absence of shadows by replacing the pictorial cue "the instrument touches the tissue when it touches its shadow on the tissue" by the cue "the instrument touches the tissue when the tissue starts to deform." Because of the intensive training period and the large adaptability of the human perception system, relatively simple laparoscopic procedures such as cholecystectomies and hernia repairs can be carried out successfully despite the reduced depth information. It is likely, however, that the development of useful supporting aids can greatly reduce the training period and extend the applicability of laparoscopic surgery techniques to procedures that are as yet too difficult to carry out in a minimally invasive way.

The article describes a large number of supporting aids, such as passive and active endoscope positioners like the AESOP and the EndoSista, shadow, half-moon, and stereo-endoscopes, and movement parallax systems such as a HMD. Some of these aids are commercially available, but not all of them have proven to have advantages over a conventional equipment. Nearly all the research on depth perception in laparoscopy is focused on stereovision. Many authors have an incomplete background in visual perception and do not seem to be aware of other depth information sources, such as shadows and movement parallax. Many references confuse stereovision with 3D vision and refer to stereo-endoscopes as 3D endoscopes. However, stereovision is only one of the many depth information sources and probably not the most important one. Experiments reported by several groups[51,73,79–81] have proven movement parallax to be a very important depth information source. It is the authors' belief that the addition of shadows and movement parallax may have a much larger impact on the surgeon's depth perception than the use of a stereo-endoscope. However, systems that realize shadows and movement parallax are still in their infancy.

The advantage of the half-moon endoscope[29] and the shadow endoscope[38] is small, as the distance between the light source and the endoscope lens is too short. The illumination cannulas[29] could not be evaluated because they are not used in the hospitals that are cooperating with the MISIT program. Movement parallax can in principle be realized by means of an active endoscope positioner that is controlled by the surgeon's head movements. The only commercially available head-controlled endoscope positioner is the EndoSista.[36,37] Although it is controlled by head movements, this robot realizes movement parallax only to a limited extent because it does not compensate for the endoscope's limited freedom of movement. This makes it impossible to observe the anatomic structure from different sides while keeping the viewpoint in focus.

Compared with a human camera assistant, the only real advantage of current active endoscope positioners is that they stabilize the picture. This can be very useful in time-consuming operations, but a passive endoscope positioner can also be used for this purpose, and these systems are smaller, much cheaper, and simpler in construction. The only real drawback of a passive endoscope positioner is that the surgeon has to release an instrument to move the endoscope into another position. It is arguable whether this drawback is more important than the advantages and whether the strongly technologically driven research on active endoscope positioners is really as useful as it seems.

A more extensive background on visual perception, as given by Gibson[8] and Rock,[10] can lead to a better understanding of surgical observation and to more useful aids than stereo-endoscopes or current active endoscope positioners. It is the authors' opinion that active endoscope positioners will become really useful only when they can be used to realize movement parallax with a centered viewpoint in the camera picture. The development of a smoothly working movement parallax system and the addition of shadows to the endoscopic camera picture are considered by the authors to be two of the most important topics for future research on observation in laparoscopic surgery. The development of such aids is one of the spearheads of the MISIT program.

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