



3D presentation in surgery: a review of technology and adverse effects

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Abstract

A systematic review was undertaken to assess the technology used to create stereovision for human perception. Adverse effects associated with artificial stereoscopic technology were reviewed with an emphasis on the impact of surgical performance in the operating room. MEDLINE/PubMed library databases were used to identify literature published up to Aug 2017. In the past 60 years, four major types of technologies have been used for reconstructing stereo images: anaglyph, polarization, active shutter, and autostereoscopy. As none of them can perfectly duplicate our natural stereoperception, user exposure to this artificial environment for a period of time can lead to a series of psychophysiological responses including nausea, dizziness, and others. The exact mechanism underlying these symptoms is not clear. Neurophysiologic evidences suggest that the visuo-vestibular pathway plays a vital role in coupling unnatural visual inputs to autonomic neural responses. When stereoscopic technology was used in surgical environments, controversial results were reported. Although recent advances in stereoscopy are promising, no definitive evidence has yet been presented to support that stereoscopes can enhance surgical performance in image-guided surgery. Stereoscopic technology has been rapidly introduced to healthcare. Adverse effects to human operators caused by immature technology seem inevitable. The impact on surgeons working with this visualization system needs to be explored and its safety and feasibility need to be addressed.

Keywords Stereopsis · 3D presentation · Surgical performance · Adverse effects, human factors

Introduction

The past decade has seen a dramatic rise in the popularity of 3D media, moving beyond cinema into television, gaming, and portable devices [1, 2]. However, it is not confined to only being used for entertainment. Stereoscopic displays are starting to be implemented in different industries for many practical uses, such as in the healthcare field for minimally invasive surgery [3].

The theory behind stereovision involves presenting each eye with a slightly different view of an object. The brain combines the two images into a single image with depth perception. This concept has been utilized ever since the first public 3D film, *The Power of Love*, was shown in 1922 [4]. The popularity of 3D films peaked in 1952–1954, during the

“Golden Era” of 3D productions. Following this period, 3D films experienced a sharp decline, due to many technological and practicality issues, and were forgotten about until their mainstream resurgence at the turn of the century [5].

With the emergence of this new era of 3D, public health concerns are being raised. Individuals have reported adverse side effects to viewing 3D content [6]. The reports were non-specific and varied [7–10]. These reports spurred researchers to study the physiological effects of 3D viewing on humans [11–13]. In addition, researchers have tried to devise a theory to explain the cause of the adverse effects experienced by some viewers. Relatively little conclusive research has been done on this subject due to the recent nature of 3D sickness.

The purpose of this paper is to review the main types of stereoscopic displays and their technologies, the adverse health effects of 3D content and the current theories explaining these effects, and the application of stereoscopy in surgery. Our lab, the Surgical Simulation Research Lab, has conducted studies on the use of 3D monitors in minimally invasive surgery. We are interested in the applications of 3D technology in the surgical field and advancing this

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technology to improve surgical accuracy while minimizing adverse user effects.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were followed as a guideline for this study and reporting the findings [14].

Search strategy and data source

A literature search was conducted in August 2017, using MEDLINE (PubMed), PsycINFO (EBSCO), ACM Digital Library (Guide to Computing Literature), and IEEEExplore (Digital Library) databases. Papers published in English between 1987 and 2017 were included. Search strategy included five groups of key words/terms, which are (1) stereo* or 3-dimension*, (2) endosc* or laparosc* surgery, (3) binocular disparity or vision disparity, and (4) motion sickness or dizz*. Combining these four groups of keywords allows us to find papers up to date on the technology for creating stereoperception; potential impact on human performance, especially in the surgical settings; possible causes for adverse effects in human sensorimotor pathway; and possible solutions to improve the stereoperception technology. In addition, we carried out a hand search of the references cited in the papers to ensure literature saturation. A flow-chart is presented to show paper screening and selection process (Fig. 1).

Results

The technology of stereovision

To create stereovision on the screen, two basic steps are needed. The first is to capture or create images with binocular disparity and the second is to present the motion pictures to two different eyes of humans and allow fusion of the pictures into one stereo- image [5].

Technically, the capture and creation of images can be achieved with a two-lens camera. The technological difficulty is on how to present these two sources of video images to human eyes.

The earliest form of 3D display used the *anaglyph* method. Anaglyph stereoscopy uses two complimentary colour filters to encode the two images [1, 4, 9]. The colours are commonly a combination of red and green, red and blue, or red and cyan. The optical glasses contain different coloured filters on each eye that filters out the identical coded colour on the screen and renders the complimentary colour [1]. The first 3D films used this form of stereoscopy

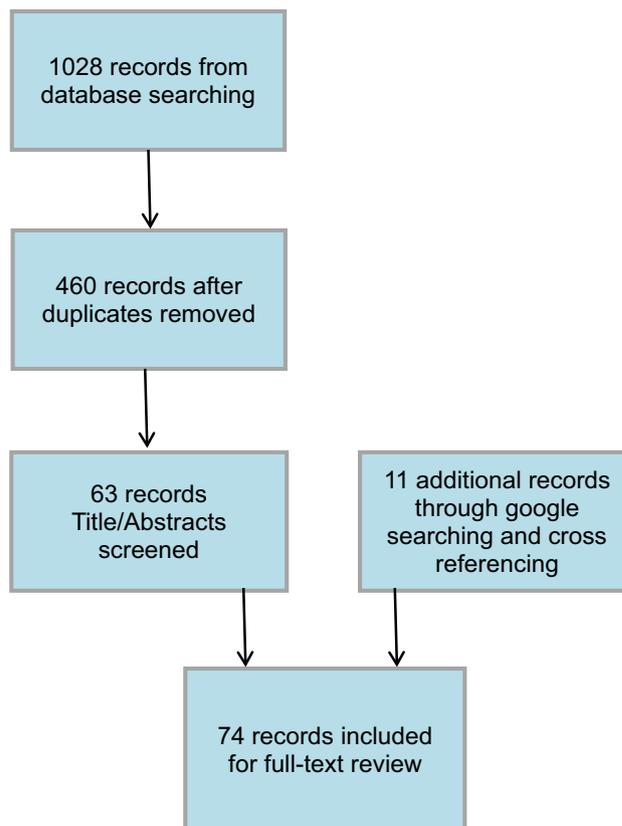


Fig. 1 Literature search strategy

due to the ease of image processing and inexpensive cost of the glasses. However, ghosting (one eye seeing a portion of the other eye's image) occurred frequently due to poorly adjusted colours that were not filtered completely, causing headache and nausea. This method of 3D encoding is rarely used in movies now [5]; it is predominantly used in comic books. The modernized version of anaglyph stereoscopy is featured in the use of *interference filter* technology. Instead of the aforementioned two-colour combinations, it uses three narrow bands of specific wavelengths (50 nm) of red, blue, and green [15]. Different wavelengths are used for each eye, which are filtered out by glasses containing filters with the corresponding wavelengths. This provides a foundation for a higher quality stereoscopic presentation when wearing appropriate glasses to view images.

A large number of 3D films shown in the past few years have used *polarization* stereoscopy and this has become one of the most common forms of 3D display [1, 5, 9]. It has also been adapted for use in 3D televisions, along with active shutter and autostereoscopic displays. The two images are differentially projected through a polarized filter and are superimposed. Polarization filters are used in the optical glasses, which allow the corresponding polarized image to pass through each lens. The lenses filter out the

polarized image intended for the other lens. The lenses are usually polarized at 90° angles (45° for one eye and 135° for another). However, circular polarization allows a wider range of head movement without distorting or losing the stereoscopic effect [5, 6, 9]. The image that is perceived is darker because the polarizers absorb a portion of the light. The projections must also be done on a screen made of silver or aluminum because ordinary display screens cause the light to lose its polarization.

A major advantage of the polarization system is the low cost of the glasses. Additionally, the glasses are lightweight and not cumbersome unlike the glasses of active shutter systems [1, 5, 6]. The major disadvantages of polarization systems are the low screen resolutions with narrow vertical viewing angles and the costly silver screens. The low screen resolution is a consequence of both images being superimposed on the same screen, resulting in seeing only “half” of the image with each eye. Viewers must be within a narrow vertical range of the display to correctly see the picture [6]. This means that viewers cannot watch the television while lying in bed due to a misalignment of the polarizing filters.

Another widely used method of 3D display is *active shutter* technology. The previously mentioned systems are passive systems, while this system is considered an active system due to electronics in the viewing glasses that interact with the display. The display is set to rapidly alternate between two separate views (left and right eye views) of an image. The active glasses use a liquid crystal cell to open and close shutters alternately at high speeds [16]. When the image for the left eye is displayed, the right shutters are closed and vice versa. Modern high-definition televisions can reach speeds of up to 144 images per second, which helps to reduce the chances of image crossing between two eyes, creating a better experience of stereopsis. The glasses must be synchronized with the display before each use.

Compared to polarization systems, active shutter allows for a higher screen resolution and a wider vertical viewing angle. However, the tradeoff for the higher resolution is that the display must essentially double the frames per second of a polarized display to achieve the same frame rate due to separately displaying each eye view. If the refresh rate is too low, such as on some improperly designed or low-cost systems, the viewer may experience flickering. The major disadvantage of active shutter systems is that the electronic glasses are very heavy and expensive relative to passive glasses and must be recharged after usage.

Autostereoscopy has rapidly become one of the most popular forms of 3D in recent years and is expanding rapidly due to its practicality to be used in mobile phones, gaming devices, televisions, computer monitors, and tablets [17–20]. The Nintendo 3DS is a well-known gaming device that employs autostereoscopic technology. Viewing glasses are not required to perceive the stereoscopic image

in autostereoscopic displays. This eliminates the inconvenience of using uncomfortable viewing glasses. The two main types of autostereoscopic displays are parallax barrier and lenticular lens systems [17–21]. In both types, the left and right eye images on the display are arranged in alternating narrow vertical strips. Parallax barriers use a slit barrier in front of the LCD or plasma screen to block the strips so that each eye sees the correct strips [22]. Lenticular lenses achieve the same effect by using lenses to refract the strips to the correct eye. Half of the screen is visible to the left eye while the other half is visible to the right eye.

The main drawback of autostereoscopic displays is the narrow viewing range due the fact that each eye must be in a correct “viewing zone” [20]. This may be a problem in various situations such as comfortably viewing the display with multiple people sitting on a couch. Some autostereoscopic displays employ head tracking technology that detects the position of the head and alters the image to fit the eyes to the correct viewing zone [21]. However, this only works if there is a single viewer, such as for a computer screen or a gaming device.

Multiview autostereoscopy has been developed to improve the viewing range. Multiview displays provide a number of different views of the image so that viewers perceive a unique view depending on where they are sitting relative to the screen [18]. Viewers may move their heads left and right without distorting the 3D effect. A slanted lenticular screen may provide 7–15 views [18, 21]. Other experimental technology has been designed to improve autostereoscopy such as multi-projector, time-sequential, and super-multiview systems. These systems have not been commercially released yet and still require further testing.

Adverse effects of stereovision

The above-mentioned technologies are called reconstructed stereovision in this paper to separate them from natural stereoperception by humans via two eyes and a complex visual neuro-pathway. Although reconstructed stereovision is built based on our knowledge of human stereoperception, it is different in many subtle ways to natural stereoperception. Long-term exposure to reconstructed stereoscopy may lead to adverse effects to human users.

As people began to immerse themselves in stereoscopic media, news reports documenting side effects started appearing [23]. In 2010, technological giant Samsung released a document that outlined the dangers and risks of 3D viewing [24]. This document had guidelines on 3D television use and listed potential side effects, such as motion sickness, eye strain, nausea, and disorientation. There were some bizarre warnings stating that elderly, sleep deprived, intoxicated, and pregnant individuals should avoid watching 3D television. Samsung claim that document served as precautions

for a small percentage of people who are unable to see 3D properly and to avoid unnecessary excitement in the sick and pregnant [24, 25]. Although the claims were largely unfounded, Samsung's document sparked many studies on the subject to determine if 3D viewing does indeed cause adverse side effects [6, 19, 23, 25, 26].

Ujike and Watanabe performed an experiment using 34 adults with normal or corrected-to-normal visual acuity to test the effect of 3D presentation on human subjects. Their subjects watched a 10-min virtual simulation of walking down a street (with simulated turns and rotations) in either 2D or 3D on a polarized screen. A questionnaire was provided that asked subjects to describe their comfort level each minute throughout the experiment. They concluded that stereoscopic images created more visually induced motion sickness than 2D images [27].

Read and Bohr followed up the previous experiment by recruiting 433 subjects to watch *Toy Story 3* in either 2D or 3D. Initially, there were three groups: A (active shutter), B (polarized), and C (2D) [28]. The subjects were asked to rate the appearance of the film, the realism of 3D depth, and if they experienced any uncomfortable symptoms. The preliminary results were heavily skewed towards 3D causing adverse effects and led Reid and Bohr to believe there was a "nocebo" effect, in which individuals in the 3D groups reported negative effects because they expected to experience symptoms. Two more groups were created, D and E, in which subjects wore 3D glasses (active and polarized, respectively), but observed the 2D film. Surprisingly, the subjects in groups D and E were not aware the film was being displayed in 2D. The results showed that 2% of people reported symptoms after viewing 2D, an additional 8% of people reported symptoms after viewing the 2D film with 3D glasses, and an additional 14% of people reported symptoms after viewing 3D [28].

Solimini conducted a similar study in which participants were asked to watch 2D and 3D films in the cinema [29]. This was a prospective observational study. Information about each individual was collected, such as history of headaches, corrective lenses, car sickness, anxiety levels, video game usage, and socio-economic variables. There were no controls for the movie title, show time, seat location, and attention paid to film, so this data was also collected. The subjects were scored on a simulator sickness questionnaire where 16 symptoms corresponding to three categories (nausea, oculomotor, and disorientation) were scored from 0 to 3, depending on the severity. These questionnaires were provided before and after each movie. Solimini concluded that 54.8% of viewers reported some sickness after viewing a 3D film, compared to 14.1% after viewing a 2D film. Symptom intensity was also reported to be 8.8 times higher than baseline after viewing 3D, compared to two times higher than baseline after viewing 2D [29].

After it was concluded that stereoscopic viewing causes adverse side effects, Solimini et al. [30] conducted a study to determine the specific symptoms that result from 3D viewing. They designed a 20-item questionnaire, which they asked 38 subjects to answer after viewing a commercially released 3D film. Results showed that symptoms from 3D viewing included (from most common to least) eye fatigue, headache, dizziness, nausea, and double vision [30].

Yang et al. [25] expanded on the previous study by asking 203 subjects to view a movie in theatres in either 2D or 3D while sitting at different angles and distances to the screen. Questionnaires were answered before and after viewing the movie. They discovered that 3D viewing induced greater and more frequent episodes of double vision, blurred vision, dizziness, disorientation, and nausea compared to 2D. Additionally, they found that older viewers (age 46+) reported greater ocular, visual, and motion sickness symptoms in 2D, while younger viewers (age 24–34) reported greater visual and motion sickness in 3D. The results also showed that sitting in an oblique position to the screen decreased motion sickness symptoms, but also diminished depth immersion [25].

Theories behind stereoscopic visually induced motion sickness

Although there are a few generally well-accepted theories of why viewing reconstructed stereoscopy causes visually induced motion sickness, no definitive explanation has been discovered currently. Hwang and Peli [31] hypothesized that motion sickness symptoms occur due to two factors: depth wobbling and mismatch of angular rotation. They described depth wobbling as an expansion or compression of depth due to breaks in relative angular disparity. Relative angular disparity is the difference between the two views seen separately by each eye; in reality, relative angular disparity remains the same when looking at an object with depth even if you move your eyes.

The cameras used to capture the film in 3D are unable to replicate this effect and relative angular disparity breaks in an unnatural way, resulting in depth wobbling. Other visual cues, such as perspective and object size, remain the same while the depth deviates, causing conflicting messages to be sent to the brain. In addition, when a viewer's head shifts laterally while looking at an object in reality, the object appears to rotate in the opposite direction from the viewer. This does not occur in 3D settings; instead, the object follows the viewer's eyes, which results in the illusion of the object rotating with the viewer's head. Points on the object also rotate at the same speed regardless of distance from the viewer, breaking realistic motion parallax. This effect is described as mismatch of angular rotation [31].

A widely accepted model of visually induced sickness from 3D viewing is the vergence–accommodation theory. There is a point in space where both eyes must converge to, to foveate the object onto the retina; this is described as the vergence distance. To bring the image of the object to sharp focus and to avoid double vision (maintain single binocular vision), a viewer must accommodate (lens optical power) to a certain distance; this is described as focal distance [32].

In reality, vergence and focal distances are always synchronized while looking at an object. This does not happen in the reconstructed stereo presentation, where the focal distance is always at the virtual screen. While watching 3D image in the reconstructed stereo scenario, vergence distance changes with the apparent position of the 3D image in space and usually falls somewhere behind the screen [32, 33]. The vergence–accommodation synchronization is disrupted and blurred or double vision occurs. In addition, symptoms such as eyestrain, visual fatigue, and headaches may result from the eyes and brain attempting to resolve this conflict [32, 33].

The above notions were not accompanied with solid study data. The only validation study we could find was done by Hoffman et al. in 2008 [34]. Hoffman et al. [34] conducted a study which found four properties of correct vergence–accommodation: reduced time to identify stereoscopic stimuli, increased stereoacuity, reduced distortion of depth, and reduced viewer fatigue and discomfort. As increasing amounts of 3D media will be introduced to our daily lives, the impact of reconstructed stereovision on humans' visual perception and health welfare needs to be investigated. In some areas where stereovision is deeply integrated with motor control, such as image-guided surgery and remote manipulation, careful studies are required before introducing stereoscopic technology.

Stereoperception in surgery

In September of 1985, the first laparoscopic cholecystectomy was performed by Dr. Erich Muhe in Boblingen, Germany [35]. The operation was guided by a single lens scope. Since then, the number of laparoscopic procedures began to increase exponentially due to lesser tissue trauma and shorter recovery time. As laparoscopic procedures became widely accepted and performed by more surgeons, the reduction of depth perception due to the monocular laparoscopic view posed a problem and required technological improvement. Another German surgeon, Dr. Gerhard Buess reported the first laparoscopic cholecystectomy case done by a stereoscope with two cameras, two optical channels, and two eye pieces [36, 37]. Binocular disparity is thus generated and perceived by the human operator as stereoscopic video images [38]. Van Bergen et al. [39] confirmed that the two-channeled stereoscope provides the surgeon with richer depth cues than the single-channeled counterpart.

Since Becker et al. [36] announced the possible applications of stereo display technology in laparoscopy, several researchers sought to find the effects of the *3D monitors* on laparoscopic performance [39–43]. A number of studies found increased accuracy of performance and greater participant preference in the use of 3D visualization over the conventional 2D system [12, 44–46]. In the 1999 study, van Bergen [39] concluded that operators with normal spatial capability can work faster and more accurately under 3D vision. The results indicated that the use of this visualization system increased the accuracy of performance, with reported enhanced depth perception [47]. Pietrzak et al. [48] concluded in their research that the superiority of the 3D systems over the 2D systems is well documented, but still needs to be proven.

Despite the significant advantage of 3D imaging in terms of better depth presentation, 3D systems have not been extensively used. Surgeons often complained about the poor quality of the 3D image and discomfort of wearing 3D glasses, which includes visual strain, headache, nausea, and fatigue [49–54]. Several papers reported that 3D systems were not superior to 2D systems in terms of surgical performance [41, 55–57]. Instead, it was confirmed that surgeons experienced eye strain, facial discomfort, and headaches immediately after operations [39, 43]. Hanna and Cuschieri [43] argued that surgeons can use monocular depth cues such as shades and relative size when they perform laparoscopic surgical procedures with a single lens scope. Hofmeister et al.'s [58] review of papers comparing 2D and 3D video systems showed that only 50% of the reported studies found a significant benefit of stereoscopic visual systems. These findings spurred some scientists to explore 3D presentations that were directed more towards the operating site.

When the Da Vinci Robotic system (Intuitive, California, USA) was approved by the FDA (Food and Drug Administration) in 2000, it became well-accepted by surgeons who performed minimally invasive surgery, especially by urologists. The Da Vinci Robotic system contains two cameras that capture two separate views of the surgical site and displays them separately to the left and right eyes of the surgeon simultaneously, without the need for shuttering or polarizing images. The company claimed a better stereopsis experience for surgeons working on the system. Assessment of surgical performance in the simulated tasks supported that the Da Vinci system resulted in shorter task time and reduced performance errors (multiple citations).

Instead of displaying images on liquid crystal TV screens, stereo images can also be displayed on special head-mounted displays. Images taken from an endoscope can be displayed on two small screens in head-mounted goggles worn by the operator [59]. This technology claimed to provide the operator with more natural line-of-sight as it enables the surgeon

to look down on the operative field while performing open surgery [59].

Wearing head-mounted goggles allows for the development of the augmented reality display technique. The see-through goggle was reported by Bajura et al. [60] where ultrasound images were displayed on top of a patient's abdominal organs. Moreover, the ultrasound images appeared stationary when the surgeon walked around the patient. Patient information such as vital signs and intra-abdominal pressure can be overlaid on top of the video images produced from these technologies [61]. This type of augmented reality goggles allowed interior anatomic structures to be created by 3D algorithms from CT or MRI images. These structures were displayed during laparoscopic surgery, hidden beneath tissue and organ surfaces [60, 61].

Head-mounted goggles displayed both video and augmented images to surgeons, which posed new challenges in the understanding of stereoperception in the operating room [62]. Operators needed to adjust to vertically displaced viewpoints more frequently in order to execute tasks. Subjects may misjudge the distance of the moving target when wearing the head-mounted display [63]. Discomfort and somatic symptoms were reported with the use of the head-mounted display, including headaches, fatigue, nausea, and dizziness [64]. The impact on surgical performance and patient safety still requires further studies. Besides, we should be aware that these systems are costly and not easily accessible for operators [65–67].

Conclusion

Advancements in recent years have brought 3D to the forefront of modern technology. An understanding of the different mechanisms of displaying 3D is ideal for working with this technology; it is no longer confined to being used only for entertainment. Stereoscopy is currently being employed in minimally invasive surgery in various different ways. As the technology improves, so does the effectiveness of 3D displays. As advances in surgical technology continue to occur, increasing evidence is collected from simulation lab-based settings, supporting the use of 3D imaging system for realistic views of the surgical site. We expect to see more evidences from clinical settings in the near future as we believe that maximizing the effectiveness of stereopsis may lead to improvements in surgical accuracy and performance.

Currently, there are different high-tech visual devices, including virtual and augmented reality, available for surgeons through the use of head-mounted displays. This allows surgeons to operate with reconstructed three-dimensional visual guidance. Stereopsis can assist surgeons when they need visual judgment on depth. While we welcome the adoption new stereo technology into the operating theatre for

better patient care, we also need to investigate the impact of these technologies on human operators. It has been found that stereoscopic viewing causes adverse side effects related to motion sickness. Theories have been devised to explain the sickness, but no definitive explanation has been determined. Further study into the adverse effects of stereoscopy may allow insight into the prevention and treatment of these effects.

In conclusion, we believe that the possible advantages of the 3D imaging in regard to surgical performance is outweighed by the negative visual effects on the surgeons, even with the diminishing side effects of newer systems. Making 3D more user-friendly is crucial for applications in the surgical field.

Compliance with ethical standards

Conflict of interest Mr. Tianqi Wang declares that he has no conflict of interests. Dr. Bin Zheng declares that he has no conflict of interests.

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