The Effect of Color-Contrasting Shadows on a Dynamic 3-D Laparoscopic Surgical Task

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***Abstract*—Laparoscopic surgery is performed using long instruments that enter the abdomen through small incisions while viewing the workspace on a video monitor. Because of the viewing limitations that are inherent in the imaging system, depth perception is severely limited compared to direct viewing in open surgery. Previous studies have demonstrated that the addition of shadows can improve performance in tasks under laparoscopic conditions. This study examined the effect of color-contrasting shadows on performance in a depth-perception-dependent laparoscopic task. It was hypothesized that the added contrast of colored shadows would make them more pronounced on the dark-red background found in the body, thus improving performance. Twenty-four novice participants performed a dynamic pick-and-place task under three different lighting conditions on two differently colored backgrounds. Results showed that the presence of both colored and black shadows improved performance by 10% compared to no shadows, but the colored shadows did not provide a significant advantage over the black shadows.**

***Index Terms*—Simulation, surgery, visualization.**

I. INTRODUCTION

IN LAPAROSCOPIC surgery, a surgeon uses long instruments to operate in the abdomen through small incisions while viewing the operative site on a video monitor. Despite its advantages over open surgery such as reduced scarring, recovery time, and cost, decreased depth perception in laparoscopic surgery can lead to accidental injuries in the patient. Way *et al.* [1, p. 460] stated that, "... errors leading to laparoscopic bile duct injuries stem principally from misperception, not errors of skill, knowledge, or judgment. The misperception was so compelling that in most cases the surgeon did not recognize a problem." It has been shown that observer-centered depth cues, which include binocular disparity, convergence, and accommodation, are not present in laparoscopic surgery, as they are in open surgery [2].

Other limitations in laparoscopic surgery include the decoupling of motor and sensory spaces because of the location of the monitor. It has been shown that optimal performance is achieved when the monitor is located at the hand level; however, the displays are normally situated in a convenient spot such as on top of a video cart rather than in an ergonomic one [3]. The reduced size of the endoscopic field of view reduces the surgeon's peripheral vision in the surgical area. Similarly, the magnification of the operative field affects the scope of the field of view, as well as the apparent speed of movements of the instruments. This forces the surgeon to adjust the speed of instrument movements, depending on the degree of magnification [2]. Limitations on the quality of the endoscopic image are also responsible for poorer task performance compared with direct binocular or monocular vision [4]–[6].

To make accurate movements in laparoscopic surgery, the surgeon relies on the pictorial depth cues that are available from the video display. It has been shown that there are individual differences in the use of depth cues, suggesting that people utilize various depth cues differently [7]. Despite these differences, however, it has also been shown that depth judgments are made with increased speed and accuracy when more depth cues are present, regardless of what they are [8]. The limited, yet useful, depth cues that are present in laparoscopic surgery are the monocular cues that are not lost in the 3-D to 2-D transition from the real image to the monitor and are not substantially degraded in the image from the laparoscope, such as interposition (the obstruction of the view of one object by another caused by overlapping) and relative size (if two objects are known to be the same size, then the one that appears smaller on the retina will be perceived as farther away) [9]. Although interposition is a useful cue for determining the relative depth of different objects, it reveals nothing about the relative depth of nonoverlapping structures. The relative size cue requires familiarity with the objects being viewed. This cue allows surgeons to judge distances and magnification from the appearance of organs and instruments in the field of view [6]. Linear perspective, height in the plane, aerial perspective, proximity–luminance covariance, and texture gradients are also present to some degree [2].

II. ADVANCES IN IMAGING

Two major systems have been developed to improve depth perception in minimally invasive surgery. One such solution was the use of 3-D monitors to reintroduce binocular disparity to the laparoscopic image. Most of these systems are based on rapid sequential imaging of the target area from slightly different angles. There are three primary ways of designing stereoendoscopes: 1) by using a two-lens system; 2) by using a single-lens system that splits the image into left- and right-eye images at the back end of the endoscope; and 3) by using a universal image converter that can be fitted onto any endoscope [10]. The video from the camera is then displayed on a video

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monitor, alternating each frame between the images obtained from the left and right cameras. The images may be polarized so that the surgeon can use passive eyewear to see the images from each camera with the corresponding eye. Although 3-D laparoscopic imaging systems do succeed in producing artificial binocular disparity, they have some notable shortcomings. First, the size restrictions of an endoscope can only allow a distance of 8 mm between the two lenses that are responsible for producing the disparate images in the two-lens system. Compared to the normal human interpupillary distance of about 60 mm, the disparity of the images from the 3-D imaging system is much different from what people are used to, leading to viewing discomfort. These problems are similar in the other two types of stereoendoscopes because the left- and right-eye images are taken from virtually the same point [10]. Second, 3-D displays have lower resolution than their 2-D counterparts. This decreased resolution results in a poorer image quality compared to traditional laparoscopic imaging systems. Several studies that compare 3-D with 2-D displays in laparoscopic cholecystectomy found no performance advantages in the 3-D endoscopic systems. Furthermore, visual strain, headaches, and facial discomfort were worse with the 3-D displays [11].

The second method, which is designed to improve depth perception in minimally invasive surgery, is the addition of shadows to the laparoscopic image. In the normal laparoscopic system, the location from which the light is emitted to illuminate the body and the lens through which the image of the operative cavity is received are both at the tip of the laparoscope. Using this setup, all of the shadows that are created from the light source are cast directly behind the objects that are creating them, putting them out of the line of sight of the lens. Numerous studies have shown that shadows are useful depth cues that humans begin to use from infancy [12]–[15], and another study concluded that shadows created in the laparoscopic image improve task performance [16]. The optimal luminance contrast range for shadows in laparoscopy was found to be between 22% and 42% [17], whereas more errors were associated with a higher contrast of 65%. It was postulated that the performance under a higher shadow contrast decreased because of poor illumination of the shaded areas. Currently, shadow-producing laparoscopic systems such as the Shadow Telescope II from MGB Endoscopy [18] use two points of illumination—a primary light source to illuminate the workspace and a secondary light source to produce shadows.

III. SHADOW AND COLOR PERCEPTION

Shadows are neither edges nor boundaries, which are extensively used in the visual system to denote the difference between an object and its surroundings. Rather, they create abrupt luminance changes in a scene and can be used to perceive depth [12]. There are two types of shadows: cast shadows and attached shadows. Attached shadows are created on surfaces of an object that are faced away from the light source, causing them to be under weaker illumination. These shadows give a 3-D appearance to the object and can be illustrated by the differences between a circle and a sphere, where each has the same boundary, but the sphere appears more 3-D because the attached shadows cause the part of the sphere that is faced away from the light source to appear darker. Cast shadows are created when an object blocks the illumination of a surface by obscuring a light source. They can either be extrinsic, i.e., projected onto a surface, or intrinsic, i.e., cast on a part of the object itself [13]. The shape of the cast shadow can provide clues to the object's shape and spatial arrangement. In addition, shadow motion caused by the movement of the shadow-casting objects or changing angles of illumination can give the observer important information about the trajectory of a moving object and is incorporated with the object movement to perceive depth as early as six months of age [14]. Because the movement of cast shadows can be caused by a moving object or a moving light source, the human visual system resolves this ambiguity by assuming that the light source is usually stationary and that the object is moving [15].

In addition to luminance contrast, the color of shadows may be important for depth perception because of its effects on the luminance contrast between the shadow and the background. Weber's law, which has been shown to accurately model detectable differences in physical stimuli, relates humans' ability to sense changes in stimuli intensity to the magnitude of the physical stimuli. It is described by the equation $\Delta I/I = k$, where ΔI is the just noticeable difference (JND) in intensity, I is the intensity of the original stimulus, and k is a constant of proportionality [19]. Based on Weber's law, we speculate that shadow perception is dependent on the intensity of the surrounding illumination and the difference in the intensity between the shaded and illuminated regions. However, a JND in the luminance between the shaded and illuminated regions would not necessarily be useful as a depth cue because the low contrast could still make the shadows difficult to see. Weber's law can be applied to color perception as well, where k is a constant of proportionality that determines the size of a JND in chromaticity between two adjacent objects.

In the laparoscopic environment, a surgeon encounters a wide range of colors inside the body, ranging from the light yellow color of fat to the dark-red color of blood. There is a marked difference in brightness between these two background colors in the body, giving rise to variations in shadow luminance contrast on the surfaces. In a simple image analysis of the luminance contrast of cast shadows on different surface colors, we found that luminance contrast decreased when the shadows were moved from a lighter surface to a darker surface. When a shadow with a luminance contrast of 20.5% on a white background was moved to a red background, the luminance contrast was reduced to 10.5%, which is nearly a 50% difference. To minimize this contrast variation in laparoscopic conditions, we proposed that cyan (a mixture of blue and green) light would produce shadows that offer color contrast in addition to a higher luminance contrast, making them easier to detect on both light and dark backgrounds. Cyan light was chosen because it does not contain wavelengths of light in the red spectrum. This would result in less light being reflected back from a red surface (organs) because the red pigments will absorb the blue and green wavelengths. A measurement of the luminance contrast of the cyan shadows showed that a 20% contrast on a white background remained essentially the same with a 21% contrast on a red background. An experiment was conducted to test the hypothesis that cyan shadows would enhance depth perception and improve the performance of a laparoscopic task compared to black shadows and no shadows.

IV. METHODS

A. Participants

Twenty-four participants, 12 male and 12 female, participated in the study. The subjects ranged in age from 19 to 45 years, with a mean age of 23 years. Nineteen were right handed, and five were left handed. The subjects' color vision was tested using images from Ishihara's color blindness test [20] displayed on a liquid-crystal display monitor that was similar to the one used in the experiment. None of the subjects had previous exposure to laparoscopic surgery or surgical simulators. All subjects signed an Institutional Review Board-approved informed consent form.

B. Task

The subjects performed an aiming, grasping, and placing task under three different shadow conditions of no shadow, black shadow, and cyan shadow on two different background images. These images were photographs of the inside of the abdomen that were predominantly yellow-orange (the light background) and dark red (the dark background). The task was performed in a surgical trainer box, which allowed the instruments and laparoscope to be inserted through small openings on the top cover of the box, but blocked the task space from the view of the subjects, as shown in Fig. 1.

The task space consisted of a plastic board fitted with six pegs of varying heights. Two small balls were placed on top of the first two pegs, and the subjects were required to transfer them from peg to peg in a prescribed order until both balls were on the last two pegs. The entire task consisted of four moves, two with each hand. The subjects were required to complete three error-free trials in each condition. The task completion time was electronically recorded by a button next to the task that was pressed by the subject with the grasper at the beginning and end of each trial. The task was placed on a moving platform, which oscillated up and down with a peak-to-peak amplitude of 0.75 in and a frequency of 0.4 Hz, or 24 breaths/min to simulate the patient's movement due to ventilation in laparoscopic surgery.

All subjects were given verbal instructions and a demonstration on how to perform the task before beginning their practice trial. All performance measures were explained along with all task procedures. The subjects were instructed to perform "as quickly and as accurately as possible."

C. Equipment

The shadowless condition was created using a single laparoscope, which was situated above and in front of the task space at a 60° angle from the horizontal, as the light source and viewing laparoscope. The black-shadow condition used the laparoscope from the shadowless condition as the main light source and viewing laparoscope and a secondary laparoscope to provide light for shadow casting, which was positioned above and to the right (from the user's perspective) of the task space at a 65° angle from the horizontal. The cyan-shadow condition was created using the black-shadow setup with light filters placed in the connection between the light cable and the laparoscope. Two Roscolux stage lighting filter gels were used to create cyan shadows. The primary laparoscope was fitted with a cyan light filter, and the secondary laparoscope was outfitted with a red filter. This caused two sets of shadows to be cast in the workspace. Red shadows, which are created by blocking the cyan light from the main laparoscope, were cast behind the objects from the point of view of the viewing laparoscope and were not seen on the monitor. The cyan shadows were created by blocking out the red light, causing the shaded areas to the left of the shadow-casting objects in the task to be illuminated only by cyan light.

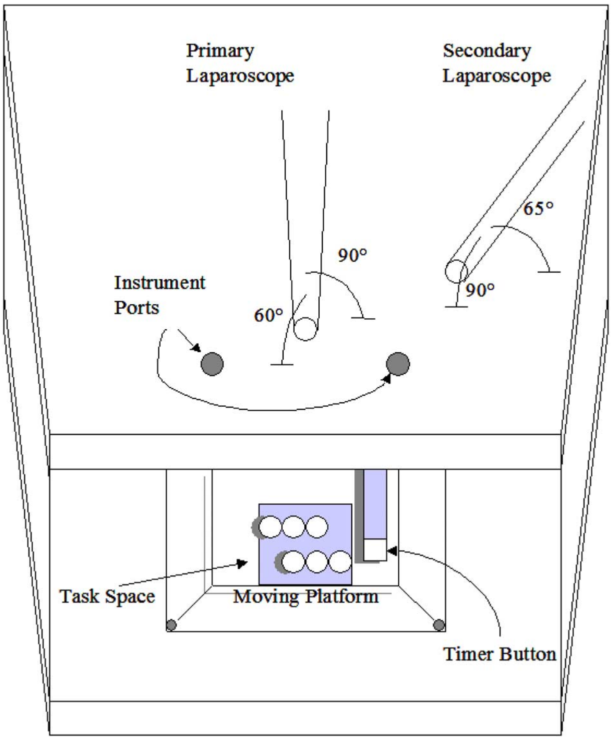

Fig. 1. Experimental setup. The bottom panel shows the task space that was hidden from the subject's direct view.

For the cyan-shadow-containing condition, the light sources for the main and secondary laparoscopes were adjusted so that the white balancing of the image was optimal. The luminance contrast was measured using Adobe Photoshop and was found to be 20% on a white background. Images of shadows created by a laparoscopic grasper on red and white backgrounds were taken from the camera box using a Sony digital camcorder via an s-video cable and loaded into Photoshop. The grayscale value of 0 (whitest) to 100 (blackest) was displayed at each pixel. The high value of the grayscale contrast range was calculated by taking the highest (darkest) value under the shadow of the instrument minus the lowest (brightest) value in the nearby illuminated area. The low value of the range was measured by taking the lowest (brightest) value in the shadow minus the highest (darkest) value in the surrounding area. These values

TABLE I
MEAN AND STANDARD ERROR FOR TASK COMPLETION TIME, ERRORS, AND PERCEIVED DIFFICULTY

	Light/None	Light/Black	Light/Cyan	Dark/None	Dark/Black	Dark/Cyan
Task Completion Time	54.2 ± 1.70	47.0 ± 1.82	48.7 ± 1.85	52.6 ± 2.03	49.2 ± 1.38	47.0 ± 1.22
Errors	1.9 ± 0.39	2.0 ± 0.46	1.7 ± 0.34	2.4 ± 0.59	1.7 ± 0.37	2.5 ± 0.74
Perceived Difficulty	6.0 ± 0.41	4.6 ± 0.53	5.0 ± 0.49	6.7 ± 0.49	5.5 ± 0.43	5.4 ± 0.42

were then averaged to obtain the average luminance contrast of the shadow in the image. For the black-shadow condition, the light sources for the two laparoscopes were adjusted to create shadows with an average luminance contrast of 20.5%, which is virtually the same as the luminance contrast of the cyan shadows. All shadow conditions had similar overall brightness levels because of the automatic brightness control on the digital camera box.

D. Experimental Design

A within-subjects repeated-measures design was used to examine the performance differences between no shadows, black shadows, and cyan shadows on two differently colored backgrounds. To counteract the learning effect, which was inherent in the task that was used, the experiment was counterbalanced. The subjects proceeded through the experimental conditions in a pseudorandomized order, similar to a Latin square design, where no shadow or background condition could be consecutively repeated. Therefore, if a subject started with no shadows on a light background, the next condition was cyan shadows or black shadows on a dark background.

E. Data and Analysis

The two independent variables were shadow conditions (no shadows, black shadows, and cyan shadows) and background colors (light yellow-orange and dark red). The dependent measures were the task completion time, the total number of errors committed in each condition, and the subjects' perceived difficulty of each condition on a ten-point discrete nominal scale where 1 represented "no difficulty" and 10 represented "extreme difficulty."

Two-way analyses of variance (ANOVAs) were conducted. Tukey's Honestly Significant Difference (HSD) test was the *post hoc* test used. Preplanned paired t-tests were used to compare the shadow conditions. Our statistical analyses were considered significant for p-values lower than 0.05.

V. RESULTS

The task completion time ranged from 18.6 to 112.4 seconds. Table I and Fig. 2 show the average values for the time, error, and perceived difficulty ratings in all shadow/background conditions. A two-way ANOVA showed a main effect due to shadows on the task completion time [$F(2, 426) = 6.989$, $p = 0.001$]. However, there was no difference in the task completion time as a function of background colors, nor was there an interaction between the shadow and background variables. Tukey's HSD test showed that the subjects performed significantly faster in the two shadow conditions than in the shadowless condition. The mean time for the black-shadow-containing condition was 10% faster than that in the shadowless condition, whereas the mean time for the cyan-shadow condition was 10.4% faster than that in the shadowless condition. There was no significant difference in task times between the two shadow conditions.

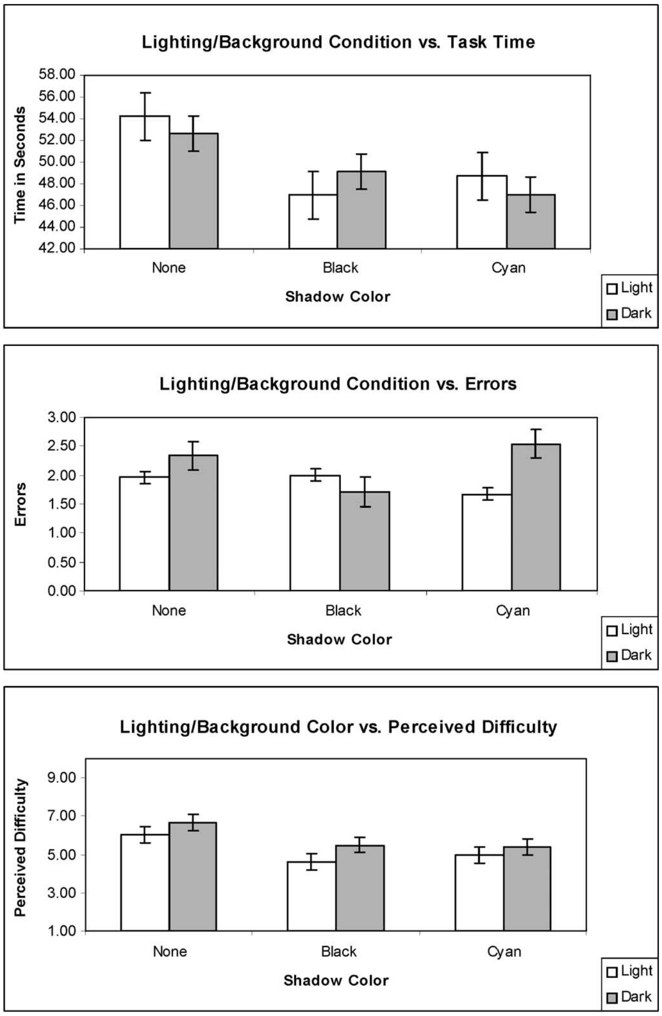

Fig. 2. (Top) Average task time for each shadow and background condition. (Middle) Average number of errors committed in each condition. (Bottom) Average perceived difficulty ratings. All error bars represent ±1 standard error of the mean.

The numbers of errors committed in the various conditions ranged from 0 to 14, and in all cases, the standard deviations were equal to or greater than the mean values. An ANOVA revealed no significant sources of variation. Two outlying data points that were greater than three standard deviations away from the mean were removed and replaced with the average number of errors committed by that subject, and the analyses were repeated; however, no significant variations were found.

An ANOVA on the difficulty ratings given by the subjects upon the completion of each condition revealed significant differences because of the shadow conditions [$F(2, 138) = 4.684$, $p = 0.011$] but not background colors. There was no interaction between the background color and shadows. Tukey's HSD test showed that regardless of the background color, the shadowless conditions were rated significantly more difficult than the shadow-containing conditions. The difficulty ratings of the black- and cyan-shadow conditions were not significantly different.

Paired t-tests also showed no significant differences in difficulty ratings between the black- and cyan-shadow conditions. A *post hoc* paired t-test comparing the light and dark background conditions found that the dark background was perceived to be significantly more difficult than the light background [$t(71) = 2.293$, $p = 0.025$].

A linear regression analysis was performed on the data for correlations between the three performance measures of task times, errors, and perceived difficulty. The squared correlation coefficient (R^2 value) between task times and errors was 0.0329, with an increase of 29.6 seconds for each additional error. Similarly, the R^2 value between task times and perceived difficulty was 0.038, with an increase of 28.7 seconds for each additional difficulty point. The correlation between errors and perceived difficulty was higher, with an R^2 value of 0.223 and an increase of 0.461 difficulty points for each additional error.

VI. DISCUSSION

The presence of shadows, whether they were black or cyan, aided in task performance and was perceived by the subjects to create easier working conditions. These results support the conclusions from previous studies [16], but it appeared that the cyan shadows had no performance advantages over black shadows on either the light or the dark background. This suggests that the shadow's level of luminance and color contrast may not be as important to depth perception as we surmised. On the other hand, it may be that this particular task did not require more depth information than that offered by the black shadow and, thus, could not take advantage of the additional color contrast of the cyan shadows. Although the shadow contrast in the black-shadow condition was chosen in the suboptimal range, shadows were clearly visible and enough to improve the subjects' performance and perceptions of the task compared to working without shadows.

A contrasting explanation for the lack of difference between the use of cyan shadows and black shadows is that the difference in the shadow–luminance and color contrasts may have been below the JND threshold for the test subjects. If this were the case, then it is expected that the subjects would see both shadow conditions as equal and would perform similarly under both conditions. Furthermore, if the JND to detect the chromaticity difference between shadows created by the absence of white light and shadows created by the absence of red light was a large one, then it may be more difficult to create any colored shadow that would affect performance differences in laparoscopic surgery. It may also suggest that reductions in the shadow–luminance contrast of up to 50% are insignificant.

The difference in perceived difficulty ratings between the light and dark background colors suggested that the background color had a large enough effect on the difficulty of the task to offset the performance advantages gained from the presence of shadows.

The effect of shadows on the accuracy of depth judgments is inconclusive. The error data contained large variations between conditions for each individual and between subjects. In four of the six conditions, the standard deviations of the error data were larger than the mean values, and in the other two conditions, they were equal to the mean. Removing two outliers did not help remove any ambiguity from the results. This suggests that the number of errors committed may have been affected more by other factors not related to the shadow conditions or background colors such as the difficulty of the task.

The correlations between the task times and errors and between the task times and perceived difficulty ratings were small but borderline significant for the 124 data points used to calculate each one. However, because of the very small slope, it is difficult to conclude the existence of any positive relationship between these variables such as a speed–accuracy trade-off. The correlation between the number of errors and perceived difficulty, however, was much larger, indicating a positive linear relationship between difficulty ratings and errors, with each error being associated with an increase of 0.461 difficulty points.

A. Experimental Limitations

The ability and motivation of the participants were likely to be important modulating factors in this experiment. These would have affected the subjects' performance, leading to the large standard deviations in the error data, as shown in Table I.

The experimental task had a high degree of difficulty, causing some subjects to commit disproportionately large numbers of errors. The task required a high level of manual dexterity, as well as depth judgments from 2-D cues. Novices, who were not familiar with using laparoscopic instruments and the visuomotor constraints associated with laparoscopic surgery, were required to adapt to a new 2-D viewing perspective to track their movements, a new type of instrument, an unfamiliar task, and the fulcrum effect introduced by the insertion of the instruments into the trainer box. This created the possibility of adding frustration as another modulating factor. However, these widely varying results could not be avoided because a few of the subjects committed very few errors under these conditions. Other inherent differences between subjects, such as age and gender, were not controlled in this study. It is conceivable that age and prior experience with similar tasks could have affected the subjects' performance. For example, the younger subjects may have had more experience with video games and, thus, are adept at eye–hand coordination tasks.

The white balancing of the cyan-shadow condition using the light filters was less than ideal. This was because the light filters were not perfect complements to each other, meaning that the summation of light transmitted through both filters did not result in a balanced spectrum of light. Instead, the illumination was weighted more heavily in the red wavelengths than in the green wavelengths, causing the image to appear slightly pink under the cyan-shadow condition. It is not clear whether this may have affected the subjects' perception of the difficulty of the task and their viewing comfort.

The difficulty of white balancing the cyan and red lights could pose a problem in the practical implementation of color-contrasting shadows in a laparoscopic imaging system. This is because properly proportioned cyan and red lights can combine to be perceived as white light to the human eye, but computers will detect two separate wavelengths, making it impossible to digitally white balance the image using the Stryker 988 camera box. To counteract this effect in cyan-shadow-inducing systems, it would be necessary to carefully control the intensities of the two light sources to make sure that the colors balance properly, or a new white-balancing function would need to be developed. Another alternative would be to design a system, similar to MGB Endoscopy's Shadow Telescope II, which has a set proportion of fibers going to the main light source and to the secondary light source in the laparoscope. Each light source could be outfitted with custom light filters that would combine to produce a well-balanced white light.

B. Practical Implications

One practical design implication from this experiment could be gearing shadow-producing systems toward the lower end of the contrast spectrum to achieve shadows while providing better illumination in the shaded areas. Future work on color-contrasting shadows should address the problem of reduced illumination of shaded areas by examining the possibility of using very low luminance contrast and high color contrast shadows. This could create shadows that are easy to see while providing strong illumination in shaded areas. Further experimentation could compare laparoscopic task performance under the low luminance and high color contrasts to higher luminance contrast black shadows. In addition to making surgical performance easier, color-contrasting shadows could add an effective depth cue to the unnaturally flat images in normal laparoscopic surgery. The addition of these shadows in the workspace could make it easier to detect bumps, lesions, and other abnormalities in exploratory laparoscopy.

C. Conclusion

Considering the results from this experiment, we have accepted the null hypothesis that cyan shadows created by a cyan light and a red light do not have any significant advantages in this task over black shadows created by two white lights. Nevertheless, cyan shadows and black shadows have appeared to be equally effective in improving depth perception and task performance compared to no shadows. However, based on the results of the task completion time and the perceived difficulty ratings, combined with the results from Mishra *et al.*'s [17] experiment, which showed that performance decreased under a high shadow contrast, we have postulated that contrast levels below those used in this experiment could be more beneficial in laparoscopic conditions. If this is true, color-contrasting shadows may prove to be easier to see than black shadows at very low luminance contrast levels.

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