THE PERFORMANCE EFFECTS OF COLOR-CONTRASTING SHADOWS ON LAPAROSCOPIC SURGERY

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ABSTRACT. The viewing limitations inherent in laparoscopic surgery, severely limit depth perception compared to open surgery, sometimes leading to internal trauma caused by the laparoscopic instruments. Recently, the effects of shadows in laparoscopy have been studied and have shown promising results. Previous studies have found that the addition of shadows can improve performance in tasks under laparoscopic condition. Aiming to further improve depth perception in laparoscopic surgery, this study tested 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 should make them easier to see on the dark red backgrounds found in the body, thus improving performance. Twenty-four novice participants were included in the study, which compared performance under no shadows, black shadows, and colored shadows on two differently colored backgrounds. In all conditions, the task was performed on an oscillating platform. Results from this study showed that the presence both the colored shadows and the black shadows improved performance compared to no shadows, but the colored shadows did not provide a significant advantage over black shadows.

INTRODUCTION

In laparoscopic surgery, surgeons operate in the abdomen while viewing the workspace on a video monitor, with the image coming for an endoscope. There are a number of difficulties that surgeons must overcome, one of which is poor depth perception compared to conventional open surgery. The reason for the limited depth perception in laparoscopic surgery is the lack of depth cues present on the monitor. First, all of the depth cues that rely on the processing of the human visual system such as binocular disparity, convergence, and accommodation are not present in laparoscopic surgery. Thus, surgeons are forced to rely on other depth cues such as interposition, luminance covariance, and the relative size of the tools and organs (Gallagher, Ritter, Lederman, et al., 2005). One useful depth cue that has been absent from laparoscopic imaging systems until recently is shadows.

Previous studies aimed at improving depth perception in laparoscopic surgery have led to the development of two types of imaging systems, 3-D monitors and shadow-producing systems. Studies comparing 3-D imaging systems to conventional 2-D systems (Durrani & Preminger, 1995; Hanna, Shimi, & Cuschieri, 1998) repeatedly found no advantages supporting the use of 3-D systems in surgery. However, studies that tested surgical performance with the presence of shadows found significant performance increases associated with the presence of shadows compared to no shadows (Hanna, Cresswell, & Cuschieri, 2002; Mishra, Hanna, Brown, et al., 2004). It was also found that shadow luminance contrasts between 22% and 42% were associated with optimum performance, while high shadow contrasts were found to hinder performance. It was postulated that excessively dark shadows could have made areas under the shadow difficult to see (Mishra et al., 2004).

Shadow perception depends on two things: luminance contrast and color contrast. A shadow's luminance contrast describes the difference in brightness between the area under the shadow and the illuminated area around the shadow. A very dark shadow on an otherwise bright surface would be said to have a high luminance contrast. Color contrast refers to the difference in the proportion of color saturation of two images. Normally, shadows cast from a single light source and an obscuring object drop in color saturation evenly across the spectrum, yielding no perceptible color difference. However, when shadows are created by two separate light sources, as they are in shadow-producing laparoscopic systems, they can be designed to have color contrast as well as luminance contrast.

Human shadow perception can be described by Weber's law, which states that the just noticeable difference (JND) needed to perceive a stimulus is dependent on the intensity of the initial stimulus. Therefore, if the illuminated area around the shadow is very bright, the area under the shadow will need to be significantly darker to detect a difference between the two, and if the area around the shadow is somewhat dim, the JND would be smaller (Cornsweet, 1970). The same principle can be applied to the difference in color contrast between two areas. In order to take full advantage human color perception, the use of cyan shadows in was tested to add maximum color contrast between the shaded areas and the surrounding illuminated areas. Considering that the average color inside the body is red, which absorbs blue and green lights, cyan shadows were chosen.

In an experiment we conducted, we measured novice subjects' performance in a task under laparoscopic conditions under no shadows, black shadows and cyan shadows to test our hypothesis that cyan shadows would be associated with the best performance because of their added color contrasts and superior visibility on differently colored backgrounds.

MATERIALS AND METHODS

Participants

Twenty-four novice subjects, 12 male and 12 female, between the ages of 19 and 45 were selected to participate in the experiment. The mean age was 23 years. All subjects passed an Ishihara color blindness test consisting of 10 images with no errors. All subjects signed an IRB-approved informed consent form.

Task

The experimental task was placed in a laparoscopic trainer box that blocked the task from the direct view of the subjects. The task involved aiming, grasping, and placing small balls on moving targets. The subjects were required to move the balls in a prescribed pattern, involving two moves with each hand. The task was outfitted with two separate background images taken from a laparoscopic surgery. The images were identical except for the colors. The light background was mostly yellow-orange, while the dark background was dark red to black. The different colors were used to simulate the wide range of colors that would be encountered in a laparoscopic surgery. The task was mounted on a moving platform, which oscillated at a rate of 0.2 Hz, or 24 breaths/min to simulate a patient on a ventilator. Pilot testing found that the use of a moving platform widened the performance differences between the different visual conditions. A button in the task space that was pressed with the right laparoscopic grasper was used to start and stop the task timer in order to record the task time.

Equipment

A plastic laparoscopic trainer box was used to enclose the apparatus and keep it out of the direct view of the subjects. Two laparoscopic graspers were inserted through holes in the top of the box. The amount of friction was very low because trocars were not used. Two laparoscopes were used, one for the main light source and imaging , and one for the secondary shadow-producing light source. The experimental setup is shown in figure 1. The primary imaging laparoscope was set in front with the center of the task and at a 60° angle from the horizontal. The secondary laparoscope was set to the right of the task in order to cast shadows directly to the left of the objects that were creating them.

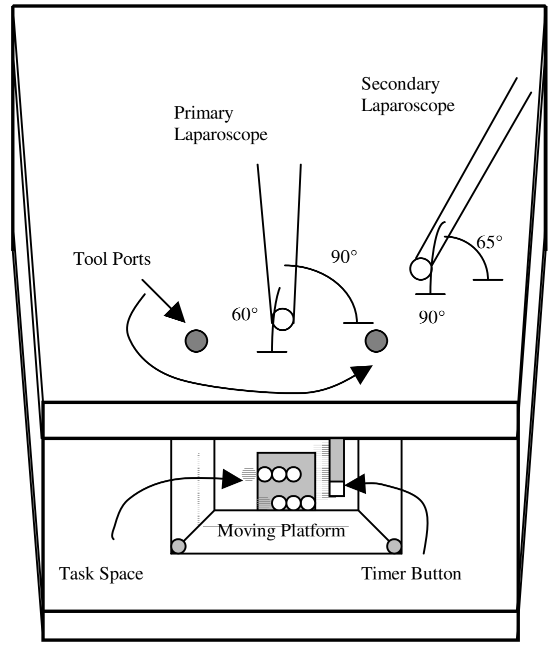

Figure 1. The experimental setup.

The different lighting conditions were created using a one or both laparoscopes. Identical 250 watt Quantum 3000 light sources were connected to the laparoscopes to illuminate the workspace. For the condition with no shadows, the secondary laparoscope was turned off and only the primary laparoscope was used. This caused all of the shadows that were created by the light source to be cast directly behind the objects that were creating them, preventing them from being seen on the monitor. To create black shadows, both laparoscopes were used with white lights, casting the shadows to the left of the targets. The black shadows had a luminance contrast of 20.5% when measured on a white background.. To create cyan shadows, both laparoscopes were used as they were to create the black shadows. However, absorption light filters were placed in the junction between the light cable and laparoscope in order to illuminate the workspace with a mixture of two different colors. The cyan shadows had a luminance contrast of 20% on a white background. However, these shadow contrasts were not the exact contrasts that were encountered during the experiment, as it was noted that the level of luminance contrast of shadows dropped as they were moved onto darker backgrounds (see Table 1), and the heterogeneous background colors of the two task backgrounds ranged from light yellow to nearly black.

Table 1. Average luminance contrast of black and cyan shadows on white and red backgrounds.

Average Luminance Contrast		
	Background Color	
	White	Red
Black Shadows	20.5%	10.5%
Cyan Shadows	20.0%	21.0%

Table 2. Average red saturation contrast for black and cyan shadows on white, yellow, and red background

Average Red Saturation Contrast			
	Background Color		
	White	Yellow	Red
Black Shadows	22.1%	19.5%	1.0%
Cyan Shadows	41.5%	40.2%	21%

The light filters that were used to create the cyan shadows condition were Roscolux stage lighting gels. The *fire* filter was used to create the red light, and the *calcolor cyan 90* filter was used to create the cyan light. When the red and cyan lights mixed, they created a near-white color. There were two sets of shadows (red and cyan) that were created from this lighting combination, but only the cyan shadows were visible from the point of view of the imaging laparoscope. The contrast advantages of the cyan shadows were two-fold. First, the luminance contrast of the cyan shadows remained stable between the white and red backgrounds (see Table 1), due to the absorption of blue and green wavelengths by red backgrounds. Second, the cyan shadows had a much higher red saturation contrast than the black shadows, as shown in Table 2. Note that the 22.1% red saturation contrast for the black shadows on the white background is indicative of the proportional drop of all wavelengths due to the reduced intensity of the light in the shaded area. However, it can be seen that the cyan shadows still have a significant red saturation contrast on the red background, whereas the black shadows' red saturation is negligible.

Experimental Design

There were six conditions in the experiment, which were combinations of the three shadow conditions and the two background colors. Subjects proceeded through all of the trials in an order determined by a Latin square, and were required to complete the task in each conditions three times without errors before moving on to the next condition. The experiment was counterbalanced and practice trials were given to account for and minimize the learning effect. No single shadow or background condition was repeated consecutively to help to prevent a subject from getting accustomed to any single condition.

Data and Analysis

Three types of data were collected in this experiment: task times, errors, and perceived difficulty for each of the shadow and background color combinations. The task times, which were recorded electronically when a button was pressed before and after the task, consisted of the three error-free trials in each conditions; therefore, no confounding factors were introduced from time lost due to errors. The numbers of errors that were recorded was the number of unsuccessful trials needed to complete three error-free trials in each condition. After the subjects completed each experimental condition, they were asked to rate the difficulty of the task from 1 (easiest) to 10 (hardest), relative to the difficulty of the other conditions. This data provided information on the subjects' preferences for the different conditions.

Data analysis was performed using 2-way analyses of variance (ANOVA), Tukey's Honestly Significant Difference (HSD) test, and paired t-tests.

RESULTS

The average task times, errors, and perceived difficulty ratings can be seen in figure 2 below.

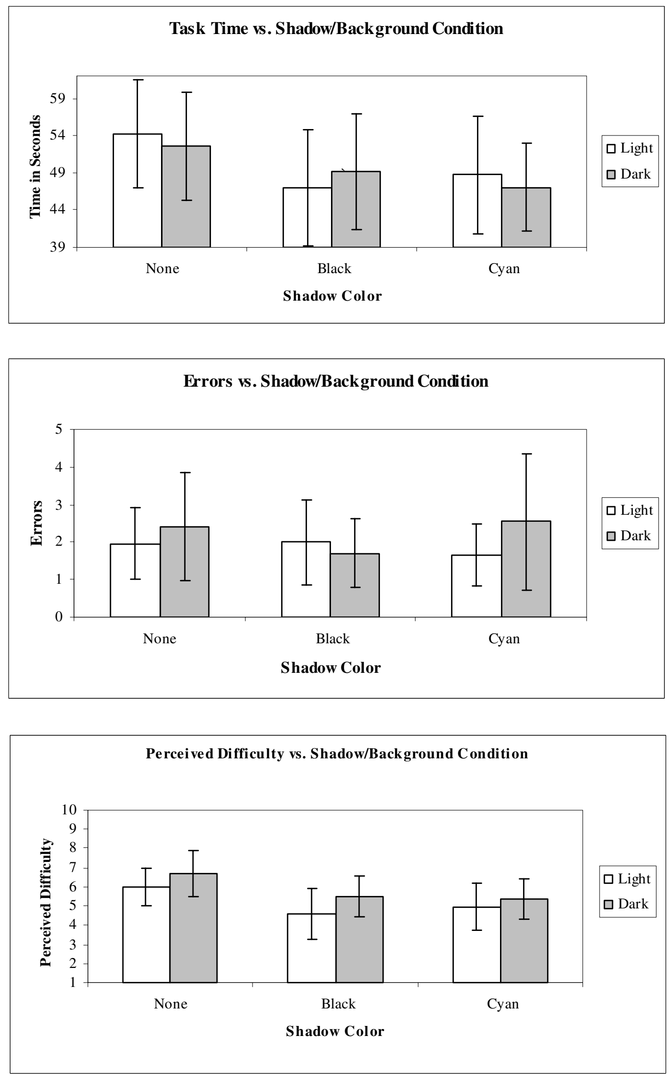

Figure 2. Average values for task times, errors, and perceived difficulty ratings. The error bars represent ±½ standard deviations from the mean.

The task times ranged from 18.6 seconds to 112.4 seconds, resulting in the large standard deviations in the top graph of Figure 2. A 2-way analysis of variance revealed that the shadow conditions were a significant source of variation, whereas the background colors were not ($F(2, 426) = 6.989$, $p = 0.001$). Subsequent analysis using Tukey's HSD test found that the presence of shadows was associated with a significant improvement in task times, but no significant difference was found between the black shadows and cyan shadows. The mean time for the black shadows and cyan shadows were 10% and 10.4% faster than the shadowless condition.

An ANOVA on the error data found no sources of variation due to the wide distribution of the data, which ranged from 0 to 14 errors. It can be seen from the middle graph in Figure 2 that the standard deviations for the error data were the same size as or larger than the average values. Further paired t-tests did not show any significant differences between any of the conditions.

An ANOVA on the perceived difficulty data revealed that the shadow conditions were a significant source of variation ($F(2, 138) = 4.684$, $p = 0.011$), whereas the background color was not ($F(1, 138) = 3.076$, $p = 0.082$). Tukey's HSD test showed that both shadow conditions were associated with a lower difficulty rating than the shadowless conditions. On average, the black shadows were found to be rated 1.3 points or 20.4% lower than the shadowless condition, while the cyan shadows were rated 1.2 points, or 18.5% lower than the shadowless condition. No significant differences were found between the black shadow and cyan shadow ratings. Because of the borderline significant results from the background color from the ANOVA, paired t-tests were performed to compare the difficulty ratings of the background colors regardless of the shadow conditions. It was found that the light task background was rated significantly easier than the dark background ($t(71) = 2.293$, $p = 0.025$). The average rating for the light background was 0.67 rating points, 11.4% lower than the dark background.

DISCUSSION

The significantly improved performance in task times for conditions with shadows compared to conditions with no shadows can be directly attributed to the presence of shadows in the scene. However, no significant task time differences could be found between the black shadows and cyan shadows, indicating that the added contrast of the cyan shadows did not create any advantages for the subjects. A likely explanation for this is that the shadows in all conditions were clearly visible to the viewer, and that was all that was needed to achieve better depth perception. This would mean that the actual contrast level needed for the shadows to be useful is well below those tested by Mishra, et al. (2004). Additionally, it was noted in Mishra's study that very high contrast levels were associated with a drop-off in performance, and postulated that the dark shadows may have obscured some details from the scene. Regardless of the mechanism, it was shown that there is a tradeoff between shadow visibility and visibility of the area under the shadow that acts at the high end of the shadow contrast range. However, the low end of the shadow contrast range has thus far shown no performance disadvantages compared to high-contrast shadows. This study, which used shadow contrasts well below 22%, which was the lowest shadow contrast tested in Mishra's (2004) experiment, found that task times were not affected by the background color, which was shown to reduce the shadow contrast by up to half in the case of black shadows. Performance with shadows in these low contrast ranges was superior to performance without shadows, and was statistically equivalent to performance with higher contrasts. One theoretical weakness to shadow inducing systems is the poor illumination of the shaded areas, and this has been shown to have practical consequences at higher contrast levels in a depth perception-dependent task (Mishra, 2004). However, if low shadow contrasts allow for performance improvements equal to those under midrange shadow contrasts, low-contrast shadows could offer better illumination of the general workspace without sacrificing anything and may be optimal for use in surgery.

On average, the subjects preferred the shadow-containing conditions over the shadowless conditions. This was congruent with the task time results, which also favored shadows. However, the subjects' lower perceived difficulty of the light background compared to the dark background revealed that the background color had an impact on the subjects' perception of the task that was not reflected in the performance results (time and errors). There were three main differences between the light and dark background. First, the lighter background was able to reflect more light back to the lens of the laparoscope, creating a brighter picture. Second, the Background color was different, giving the overall image on the screen a different hue. Third, the shadow contrasts were higher on the light background, causing the shadows to be more pronounced. The combination of a bright yellow field of view combined with highly contrasting shadows was more desirable than a darker red background with lower-contrasting shadows. However, the fact that these differences in the scene did not have any significant impact on the task performance indicates that shadows can be used at very low contrast levels without sacrificing any of its advantages.

Although cyan shadows were not found to have any advantages over black shadows, they could still be used to create easily detectable shadows at luminance contrasts lower than those that could be produced with plain black shadows. Ideally, a shadow-producing laparoscopic system would produce shadows without obscuring any detailsof the image under dark shadows. Color-contrasting shadows could provide the extra source of contrast necessary to achieve this. Future research may be focused on establishing the minimum luminance contrast level at which shadows are useful in laparoscopic surgery, aiming to improve depth perception while preserving clarity of the full image.

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