Role of Haptic Feedback and Cognitive Load in Surgical Skill Acquisition

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Teaching novice surgeons to attend to subtle and often misleading haptic cues in minimally invasive surgery can be challenging. Haptic cues may even be distracting during initial skill acquisition stage. A controlled experiment with thirty surgical residents and attendings was conducted to test the hypothesis that haptic feedback is more useful to the expert than novice surgeon because of the difference in spare cognitive capacity resulting from experience. In general, surgeons cannot perform a cognitively demanding task and laparoscopic surgery at the same time. Haptic feedback not only enhances performance, but counters the effect of cognitive loading, especially in accuracy of task performance. Performance is faster with more experience. With more spare cognitive capacity available, experienced surgeons can better take advantage of haptic feedback to aid their performance.

INTRODUCTION

Laparoscopic surgery has very important advantages over open surgery to the patients in that it minimizes tissue trauma, shortens recovery time, reduces the length of hospital stay, and hence health care costs. However, it presents considerable challenges for surgeons, such as distorted haptic feedback from long stemmed instruments (Jambon, Vinatier, & Dubois, 2005; Perreault & Cao, 2006). Higher injury rates in laparoscopic surgery, compared to open surgery, have been documented (Strasber, Hertl, & Soper, 1995; Way et al, 2003). In laparoscopic surgery, surgeons have learned to adapt to reduced haptic feedback by relying on visual feedback to make decisions and complete procedures. Some surgeons maintain that they are able to determine shape, texture, and consistency even in the absence of visual feedback using laparoscopic tools (Bholat, Haluck, Murray, Gorman, & Krummel, 1999; Brydges, Carnahan, & Dubrowski, 2005), while others attribute the large number of injuries in laparoscopic surgery to excessive forces being applied to the tissues due to the distorted haptics (Way, Stewart, Gantert, Kingsway, Lee, Whang, et al, 2003; Tang, Hanna, & Cuschieri, 2005).

Recently, a transformation in the approach to surgical training has taken place, with technological innovation such as surgical simulators and haptic feedback playing an increasingly important role (Seymour, Gallagher, Roman, O'Brien, Bansal, Andersen, et al, 2002). Virtual reality simulators have emerged as the preferred choice for training environments for both practical and ethical reasons.

While novices in surgery are the major target group for training in virtual reality simulators (Hassan, Maschuw, Rothmund, Koller, & Gerdes, 2006), as VR simulators seem to be most useful for the early part of the learning curve (Aggarwal, Black, Hance, Darzi, & Cheshire, 2006), the benefits of force feedback for early training are not clear (Adams, Klowden, & Hannaford, 2001). To improve the training of laparoscopic surgeons through technological innovation, both in training simulators and surgical instruments capable of providing haptic feedback, we need to know if haptics is useful during the skill acquisition stage of training. We hypothesized that haptic feedback is more useful to the expert than the novice surgeon because of the difference in cognitive capacity due to experience. A controlled experiment was designed to test the hypothesis, using mental arithmetic problems to impose cognitive loading on subjects while they performed simulated laparoscopic tasks.

MATERIALS AND METHODS

The experiment was conducted in the Carl J. Shapiro Simulation and Skills Center at Beth Israel Deaconess Medical Center. This project was approved by the IRB.

Subjects

Thirty surgical residents and attendings (6 PGY1s, 6 PGY2s, 6 PGY3s, 6 PGY4+5s, and 6 fellows/attendings) participated in this experiment. Two of the subjects were left-handed, 27 subjects were right-handed, and one subject was ambidextrous.

Materials and Procedures

Two surgical simulators were used in this study (see Figure 1). The MIST-VR system is a virtual reality system which has no haptic feedback. It is made up of a computer, a monitor and laparoscopic tool base. The ProMIS system is a physical simulator consisting of a life size model of the upper torso with a light source, a computer, monitor and laparoscopic tools. The ProMIS provides haptic feedback similar to that in actual surgery.

Figure 1. MIST VR (left) and ProMIS (right).

On each simulator, an identical transfer-place task was performed. Subjects used an instrument to grasp a ball, transfer it to another instrument and place in a box. The procedure was then repeated with the opposite graspers until a total of six error-free transfer-place tasks were achieved in each trial.

Cognitive load in the form of mental arithmetic problems were given to the subjects in half of the trials on each simulator. In the loaded condition, the subject was asked to solve medium level math problems (such as 21x11) while performing the transfer-place task.

Experimental Design

The experimental design was a 3 (haptics) x 2 (cognitive loading) x 5 (experience) mixed design. There were three haptic conditions used in the experiment: exaggerated haptics (EH), haptics (H) and no haptics (NH). Exaggerated haptics was achieved by weighing the ball being transferred to increase the feedback. The order of haptic conditions was counterbalanced. Two cognitive loading conditions were used (unloaded and loaded using simple 2-digit math problems). Each subject performed 10 trials in each haptic condition with 5 cognitively unloaded trials and 5 loaded trials. The order of cognitive loading conditions was ramdomized.

Data Analysis

Three performance measures were obtained from each simulator: time to task completion, errors, and number of math problems attempted. Performance data were analysed using ANOVA. Pearson correlation was used to examine the relationship between the number of math problems completed and time or errors.

RESULTS

Time to task completion

There were significant main effects for haptics ($F(2, 290) = 468.90$, $p<.001$), cognitive load ($F(1, 145) = 252.05$, $p<.001$), and experience ($F(4, 145) = 28.40$, $p<.001$) (see Table 1). There was a significant interaction between haptics and cognitive load ($F(2, 290) = 11.06$, $p<.001$), showing that when subjects were cognitively loaded, there

Table 1. Significant Factors

	Time to task completion										Error		
Factors	Haptics			Cognitive Load		Experience					Haptics		
Conditions	Exaggerated Haptics	Haptics	No Haptics	Unloaded	Loaded	PGY1	PGY2	PGY3	PGY4/ PGY5	Attending /Fellows	Exaggerated Haptics	Haptics	No haptics
Mean	54.24	57.57	85.49	57.93	73.60	81.06	69.74	65.46	55.31	57.27	0.05	0.07	0.98
Standard deviation	17.54	18.62	23.89	19.48	26.58	25.71	26.11	18.61	19.69	22.87	0.21	0.25	1.53
p	<.001			<.001		<.001					<.001		
F value	468.90			252.05		28.40					90.14		

was a larger increase in time to task completion without haptics than with haptics (see Figure 2). There was a significant interaction between haptics and experience (*F*(8, 290) = 2.37, *p*<.018) (see Figure 3), indicating that experienced surgeons showed greater improvement with haptics than less experienced surgeons.

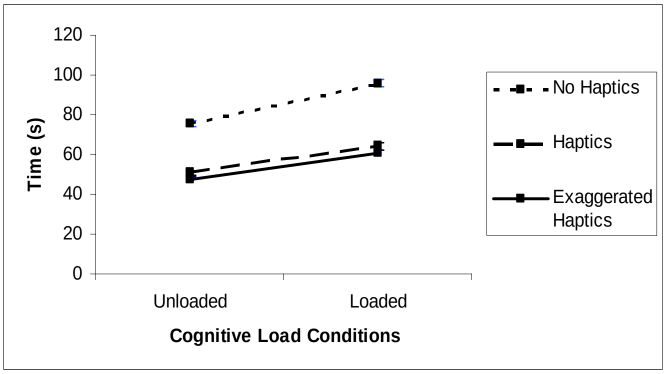

Figure 2. Interaction between Haptics variable and Cognitive Loading variable on time to task completion. Collapsed across Experience levels. Error bars represent standard error.

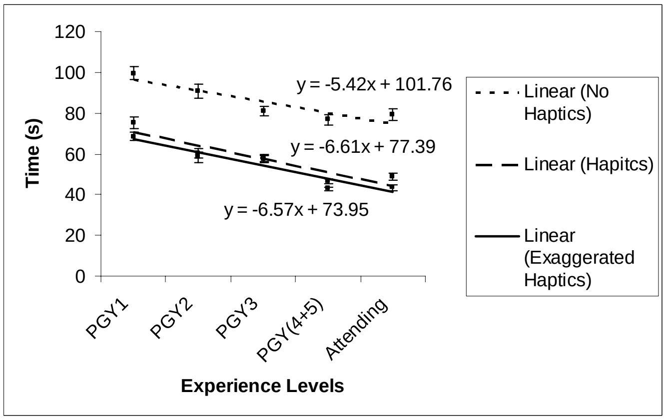

Figure 3. Performance of time to task completion in each haptic condition, collapsed across cognitive load conditions. Error bars represent standard error.

The slopes of linear regression of the performance in both haptics condition as a function of experience, across cognitive load conditions, were larger than the slope in no haptics condition (see Figure 3). There was also a significant interaction between cognitive load and experience (*F*(4, 145) = 5.95, *p*<.001) (see Figure 4).

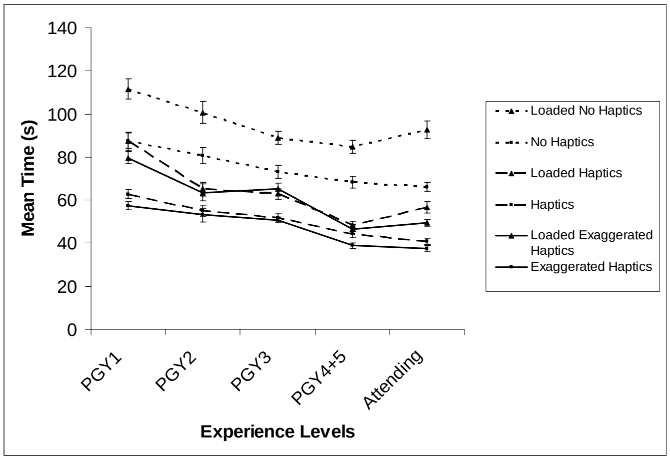

Figure 4. Effects of cognitive loading and haptics on time to task completion in simulated laparoscopic surgery. Error bars represent standard error.

Paired sample t-tests of haptics variable across cognitive loading showed a significant difference between each of the three pairs of means that were considered: EH and H, *t*(299) = 4.24, *p*<.001; EH and NH, *t*(299) = 26.91, *p*<.001; H and NH, *t*(299) = 24.58, *p*<.001.

Errors

There was a significant main effect for haptics, *F*(2, 290) = 90.14, *p*<.001, but not for cognitive loading (see Table 1). Paired sample t-tests of haptics variable across cognitive loading conditions showed significant difference between EH and NH, *t*(299) = 10.53, *p*<.001, and H and NH, *t*(299) = 10.17, *p*<.001, but not between EH and H.

Cognitive Loading

Pearson correlation showed significant positive correlations between time to task completion and the number of math problems attempted in exaggerated haptics condition (*p*<.003), haptics condition (*p*<.001), and no haptics condition (*p*<.04).

DISCUSSION

Effects of Haptics and Cognitive Load

In general, subjects performed significantly faster (37% with exaggerated haptics and 33% with normal haptics) and more accurately (95% with exaggerated haptics and 93% with normal haptics) with haptics than without. Haptic feedback plays an important role in improving the accuracy and the speed of task performance. Similarly, subjects performed significantly faster (21%) when they were not cognitively loaded, showing that the mental math problem was competing with the laparoscopic task for cognitive resources. However, subjects performed equally accurately in both cases, suggesting a speed-accuracy tradeoff. Indeed, it was observed that surgeons tended to pause work while mentally solving math problems. Similar results have been reported in the literature (Goodell, Cao, & Schwaitzberg, 2006). Although subjects who tended to pause their task would take longer to perform the task, movements during such a pause were slight and caused no error whatsoever. The shift of attention away from, and back to, the task did not lead to more errors. This is in contrast to the results of other studies where distractions that caused an attention shift led to increased errors in performance of both cognitive and motor tasks (Pool, Koolstra, Van Der Voort, 2003; Weerdesteyn, Schillings, van Galen, Duysens, 2003). Since the subjects were all surgeons, it may be presumed that accuracy in surgical performance was their priority, while speed of performance could be judiciously sacrificed. This result was reflected in the positive correlation between the number of math problems subjects attempted and the time to task completion in the haptics condition.

When not cognitively loaded, subjects performed faster (37% with exaggerated haptics and 32% with haptics) and more accurately (94% with exaggerated hatics and 95% with haptics) with haptics than without. Interestingly, even while cognitively loaded, subjects performed faster (36% with exaggerated haptics and 33% with haptics and more accurately (97% with exaggerated haptics and 91% with haptics) with haptics than without, suggesting that haptics not only enhances performance, but counters the effect of cognitive loading (see Figure 5). This is true regardless of the magnitude of the haptic feedback.

Effects of Experience

In general, more experienced surgeons performed faster (p<.001) but not more accurately than less experienced surgeons. Our results suggest that haptics is beneficial even to less experienced surgeons, but more experienced surgeons are able to better take advantage of haptics (see Figure 3). Our hypothesis that novice surgeons have relatively limited spare cognitive resources available to utilize haptic information was supported.

Indeed, when cognitively loaded, all surgeons showed similar improvement with haptics, indicating that the haptic information was not fully utilized when cognitively loaded. Conversely, when not cognitively loaded, the performance improvement with haptics was much greater for the more experienced surgeons than the less experienced surgeons (see Figure 5), suggesting that experts had more spare cognitive resources to utilize the haptic information. In other words, more experienced surgeons, having mastered the surgical skills to the level of automatic responses, have the spare cognitive resources to attend to the subtle haptic cues. Given the myriad of difficulties associated with performing laparoscopic surgery, less experienced surgeons still in the learning stages may not have the spare cognitive capacity to utilize, or benefit from, the subtle force feedback in the system. Notably, the only group that did not conform to this trend was the PGY3s. The residents in this group were classified as PGY3, but in reality, had only completed 2 years of surgical residency and were working on research during their third year in the program. Therefore, it is possible that their smaller performance improvement with haptics was a function of lack of practice with surgical techniques over the last 6 months.

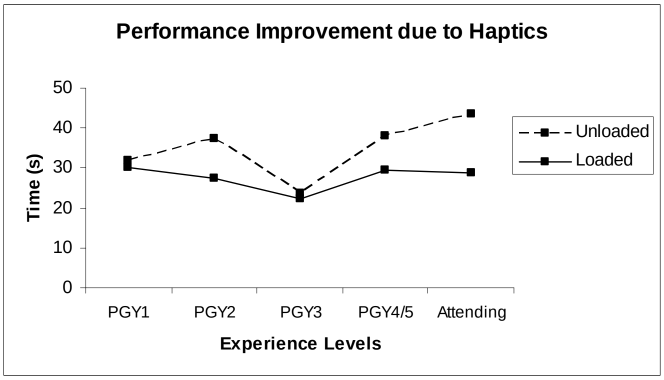

Figure 5. Performance improvement (difference in time to task completion) due to haptics (compared between exaggerated haptics and no haptics condition) when cognitively loaded and unloaded.

Conclusion

In general, haptic feedback not only enhances performance, but also counters the effect of cognitive loading. Haptic feedback plays an important role in improving the accuracy and the speed of task performance. Haptics is beneficial for the simple surgical task examined in this study. Based on these results, it seems worthwhile to provide haptic feedback in surgical training simulators to novice trainees. However, for learning more complex tasks, such as suturing, haptics may or may not interfere with learning. Future research to investigate the utility of haptic information during early stage learning of complex tasks is warranted.

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