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Can Surgeons Think and Operate with Haptics at the Same Time?

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Abstract Much effort has been devoted to incorporating haptic feedback into surgical simulators. However, the benefits of haptics for novice trainees in the early stages of learning are not clear. Presumably, novices have less spare attentional resources to attend to haptic cues while learning basic laparoscopic skills. The aim of this study was to determine whether novice surgeons have adequate cognitive resources to attend to haptic information. Thirty surgical residents and attendings performed a TransferPlace task in a simulator, with and without haptics. Cognitive loading was imposed using a mental arithmetic task. Subjects performed 10 trials (five with cognitive loading and five without) with and without haptics. Results showed that all subjects performed significantly slower (27%) when they were cognitively loaded than unloaded, but equally accurately in both cases, suggesting a speed–accuracy tradeoff. On average, subjects performed 36% faster and 97% more accurately with haptics than without, even while cognitively loaded. Haptic feedback can not only enhance performance, but also counter the effect of cognitive load. This effect is greater for more experienced surgeons than less experienced ones, indicating greater spare cognitive capacity in surgeons with more experience.

Keywords Haptic feedback · Cognitive loading · Surgical training

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Introduction

Laparoscopic surgery has very important advantages over open surgery to patients in that it minimizes tissue trauma, shortens recovery time, reduces the length of hospital stay, and hence health care costs. It is a preferred alternative to open surgery in many procedures. However, it presents considerable challenges for surgeons such as distorted haptic feedback from long-stemmed instruments, reduced depth perception caused by the loss of stereopsis, poor hand–eye coordination as a result of reduced degree of freedom of motion and the fulcrum effect created by the pivot point at the abdominal wall. In laparoscopic surgery, surgeons have learned to adapt to the reduced haptic and visual feedback. However, this process of adaptation is time-consuming and costly in terms of patient safety. Higher injury rates, compared to open surgery, have been documented.[1,2]

Recently, a transformation in the approach to surgical training has taken place, with technological innovation such as surgical simulators and virtual reality simulation playing an increasingly important role.[3–5] Simulators have emerged as the preferred choice for training environments for both practical and ethical reasons. For example, the simulator can be used over and over to practice the same skills without incurring the costs associated with animal models. Through advances in computer modeling techniques, virtual environments can be developed and modified to simulate unusual anatomy or rare scenarios. Another advantage of using simulation for training is that trainees can practice their skills in an ultimately safe environment. Furthermore, additional aids, such as navigational aids for colonoscopy or force feedback for laparoscopic tissue dissection, can be provided to the trainee to enhance the learning experience. A number of simulators (e.g., GI Mentor, ProMIS, LapSim Simulation, MIST-VR, XiTact SA) have been developed and marketed, and some have been validated by demonstrating successful transfer of skills to the OR environment.[4] The implementation of simulators into surgical training programs as part of a standard curriculum is expected in the near future.

One of the most controversial dilemmas in VR training simulator design is the incorporation of haptic feedback. The role of haptic feedback is of special interest because it is critical in the discrimination of healthy versus abnormal tissues, identification of organs, and motor control. In laparoscopic surgery, haptics is reduced and distorted by the long tools and the friction in the trocar seal.[6,7] Some surgeons maintain that they are able to determine shape, texture, and consistency even in the absence of visual feedback using laparoscopic tools,[8,9] whereas others attribute the large numbers of injuries to excessive forces being applied to the tissues as a result of distorted haptics.[2,10]

To improve the surgical performance in laparoscopic surgery, many researchers have attempted to restore haptic feedback by adding force sensors to the instrument,[11] or designing new laparoscopic tools with force feedback capabilities.[12] Also, much effort has been devoted to the integration of force feedback functions into VR surgical simulators.[13–15]

Although force feedback has been shown to improve performance for telemanipulation tasks, the benefits of force feedback for training are not clear.[16] For example, force feedback has been shown to improve robot-assisted knot-tying with fine suture.[17] Visual and force feedback together is better than only visual feedback or only force feedback for tissue grasping and pulling.[18,19] Other research comparing the performance between different force feedback gains also showed that force feedback improves performance by reducing the overall forces applied and the number of accidental incursions into sensitive structures, but the rate and precision of dissection were not significantly enhanced with force feedback.[20] A similar study indicated that the impact of force feedback is dependent on the task to be performed.[21] For example, when the mechanical efficiency is high, performance in determining tissue properties was improved, but performance in holding tissue was not.

However, Higgins and Champion[22] noted in their review of aviation training literature that “irrelevant” stimuli in a high-fidelity simulation actually made task learning more difficult, as the novice trainee had to learn to ignore these stimuli. Experts, however, expect more realism and are likely to have more problems with immersion in abstract, low-fidelity environments. Some have suggested that the level of simulator fidelity be matched to the stage of skill acquisition. Low-fidelity simulators may be appropriate for cognitive stage learners as initial or sustaining training, whereas high-fidelity trainers may be appropriate for advanced or autonomous stage learners.[22,23] As current surgical training simulators are low in fidelity with respect to visual and task representation (i.e., using peas or graphical spheres to represent tissue), the notion of realistic haptic feedback may be treated as an “irrelevant” stimulus for the novice trainee. Presumably, novices have less spare attentional resources to attend to haptic cues while learning basic laparoscopic skills.

Therefore, to improve the training of MIS surgeons through technological innovation 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 as a result of experience. We expect that more experienced surgeons will be able to perform faster, with fewer errors, compared to less experienced surgeons. We also expect that the difference in performance measures caused by haptics will be greater as the subjects are more experienced. To test the hypotheses, we conducted a controlled experiment using two surgical simulators, one of which provided haptics, whereas the other did not. In addition, as cognitive capacity was presumed to be a covariate with experience, and the underlying mechanism in the utility of haptic information, we also varied the degree of cognitive loading on subjects while performing on the simulators.

Methods

The experiment was conducted in the Shapiro Simulation and Skills Center at Beth Israel Deaconess Medical Center. This project was approved by the institutional review board (IRB).

Subjects

Thirty surgical residents and attendings (six PGY1s, six PGY2s, six PGY3s, six PGY4/PGY5s and six fellows/

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

attendings) participated in this experiment. Two of the subjects were left-handed, 27 subjects were right-handed, and one subject was ambidextrous. All residents had no previous experience with the ProMIS simulator, and minimal to no prior experience with the MIST-VR simulator used in this study. All residents had approximately 10 hours' training annually in the Skills Lab on a box trainer and in the SAGES FLS program. Fellows and attendings had minimal to no experience in the Skills Lab.

Materials and Procedures

Two surgical simulators were used in this study. The MIST-VR system (see Fig. 1, left) is a virtual reality system, which has no haptic feedback. It is made up of a computer, a monitor, and laparoscopic tool base and costs approximately $35,000 USD. The ProMIS system (see Fig. 1, right) 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 offers haptic feedback similar to that in actual surgery. The base unit and software options cost approximately $50,000 USD.

A transfer-place task was used to compare the effect of haptics on performance as a function of subject experience. In the MIST-VR system, a graphical ball was grasped by one tool, transferred to another tool, and placed in a graphical box. The procedure was then repeated with the opposite tools until a total of six error-free transfer-place tasks were achieved in each trial. In the ProMIS system, a visually similar environment was constructed using metal ball bearings and cups as receptacles for placing the balls. These metal balls were covered in a layer of soft material for ease of grasp. At the beginning of each test session, a demonstration of the task was shown to the subject, accompanied by a verbal explanation by the researcher. Then, subjects practiced until one target drop error-free trial was achieved on each simulator.

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 as many medium-level math problems (such as 21× 11) as possible, while performing the transfer-place task. Each subject performed 10 trials in each haptic condition, with five cognitively unloaded trials and five loaded trials. The experimental session lasted approximately 1 hour.

Experimental Design

The experimental design was a 2 (haptics) × 2 (cognitive loading) × 5 (experience) mixed design. The order of haptic conditions (Haptics, and No Haptics) was counterbalanced, whereas the order of cognitive loading conditions was randomized.

Dependent Measures and Data Analysis

Three performance measures were obtained: time-to-task completion, number of errors, and the total number of math problems completed. The independent factors were haptics (haptics and no haptics), cognitive load (loaded and unloaded), and experience (PGY1, PGY2, PGY3, PGY4/PGY5, fellow/attending). Performance data were analyzed using analysis of variance (ANOVA). Pearson correlation was used to examine the relationship between the number of math problems completed and time or number of errors.

Table 1 Significant Results

	Time-to-Task Completion (Seconds)									Error (Frequency)	
	Haptics		Cognitive Load		Experience					Haptics	
	Haptics	No haptics	Unloaded	Loaded	PGY1	PGY2	PGY3	PGY4/5	Attending/ fellows	Haptics	No haptics
Mean	54.24	85.49	57.93	73.6	81.06	69.74	65.46	55.3	57.27	0.05	0.98
Standard deviation	17.54	23.89	19.48	26.58	25.71	26.11	18.61	19.69	22.87	0.21	1.53
F value	631.59		192.32		22.42					95.35	
p value	<.001		<.001		<.001					<.001	

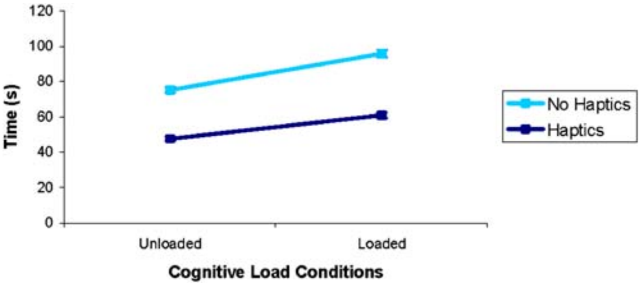

Figure 2 Interaction between haptics variable and cognitive load variable on time-to-task completion, collapsed across experience levels. *Error bars* represent standard deviation.

Results

Time-to-Task Completion

There were significant main effects for haptics [*F*(1, 145) = 631.59, *p*<.001], cognitive load [*F*(1, 145) = 192.32, *p*<.001], and experience [*F*(4, 145) = 22.42, *p*<.001] (see Table 1). There was a significant interaction between haptics and cognitive load [*F*(1, 145) = 13.50, *p*<.001], showing that when subjects were cognitively loaded, there was a larger increase in time-to-task completion without haptics than with haptics (see Fig. 2). There was a significant interaction between haptics and experience [*F*(4, 145) = 3.16, *p*<0.016] (see Fig. 3), indicating that experienced surgeons showed greater improvement with haptics than the less experienced surgeons. The slope of linear regression of the performance in haptics condition as a function of experience, across cognitive load conditions, was larger than the slope in no-haptics condition (see Fig. 3). There was also a significant interaction between cognitive load and experience [*F*(4, 145) = 2.48, *p*<0.046] (see Fig. 4).

Errors

There was a significant main effect for haptics [*F*(1, 145) = 95.35, *p*<0.001] (see Table 1), but not for cognitive load.

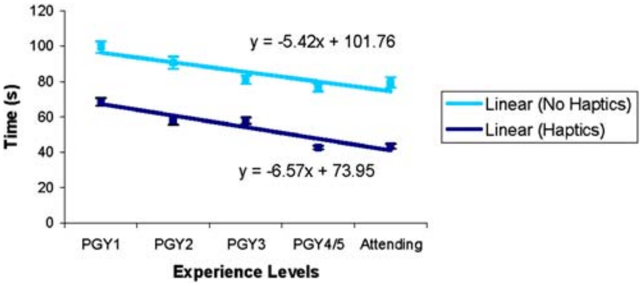

Figure 3 Performance of time-to-task completion in haptics and no haptics conditions, collapsed across cognitive load conditions. *Error bars* represent standard deviation.

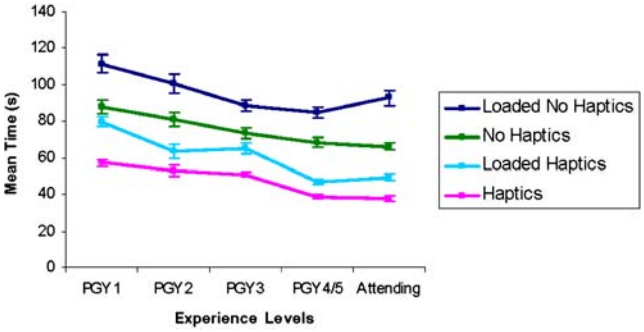

Figure 4 Effects of cognitive loading and haptics on time-to-task completion in simulated laparoscopic surgery. *Error bars* represent standard deviation.

Number of Math Problems Solved

Pearson correlation showed a slight positive correlation between time-to-ask completion and the number of math problems in haptics condition (r=0.24), and in the no-haptics condition (r=0.26).

Discussion

Effects of Haptics and Cognitive Load

In general, subjects performed significantly faster (37%) and more accurately (95%) 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

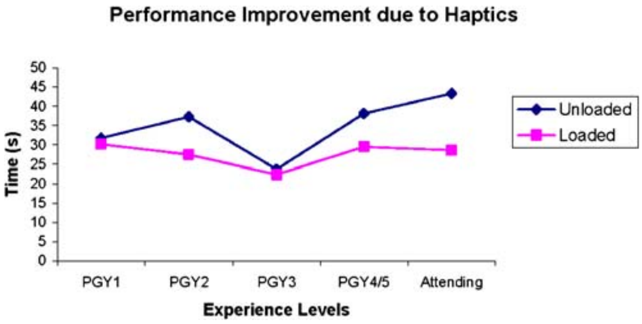

Figure 5 Performance improvement (time-to-task completion) as a result of haptics when cognitively loaded and unloaded.

literature.[24] 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.[25,26] As the subjects were all surgeons, it may be presumed that accuracy in surgical performance was their priority, whereas speed of performance could be judiciously sacrificed. This result was reflected in the positive correlation between the number of math problems subjects solved and the time-to-task completion in the haptics condition.

When not cognitively loaded, subjects performed 37% faster and 94% more accurately with haptics than without. Interestingly, even while cognitively loaded, subjects performed 36% faster and 97% more accurately with haptics than without, suggesting that haptics not only enhances performance, but counters the effect of cognitive loading (see Fig. 4).

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 Fig. 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 as a result of haptics, indicating that the haptic information was not fully utilized. Conversely, when not cognitively loaded, the performance improvement with haptics was much greater for the more experienced surgeons than the less experienced surgeons (see Fig. 5), suggesting that experts had more spare cognitive resources to utilize the haptic information. 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 are still in the learning stages and may not have the spare cognitive capacity to utilize, or benefit from, the subtle force feedback in the system. However, the only group that did not conform to this trend was the PGY3s. The residents in this group of residents 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.

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 simple surgical training task performance. Experienced surgeons are able to take more advantage of the haptic feedback in the system. Based on these results, it is unclear whether it would be worthwhile to provide haptic feedback in surgical training simulators to novice trainees, especially when learning complex surgical tasks, such as suturing, for the first time. Future research to investigate the utility of haptic information during early stage learning is warranted.

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References

1. Strasber SM, Hertl M, Soper NJ. An analysis of the problem of biliary injury during laparoscopic cholecystectomy. J Am Coll Surg 1995;180:101–125.
2. Way LW, Stewart L, Gantert W, Liu K, Lee CM, Whang K, Hunter JG. Causes and prevention of laparoscopic bile duct injuries—Analysis of 25 cases from a human factors and cognitive psychology perspective. Ann Surg 2003;237:460–469.
3. Scott DJ, Bergen PC, Rege RV, Laycock R, Tesfay ST, Valentine RJ, Euhus DM, Jeyarajah DR, Thompson WM, Jones DB. Laparoscopic training on bench models: Better and more cost effective than operating room experience? J Am Coll Surg 2000;191(3):272–283.
4. Seymour N, Gallagher A, Roman S, O'Brien M, Bansal VK, Andersen DK, Satava RM. Virtual reality training improves operating room performance: Results of a randomised, double-blinded study. Ann Surg 2002;236:458–463.
5. Sutherland LM, Middleton PF, Anthony A, Hamdorf J, Cregan P, Scott D, Maddern GJ. Surgical Simulation: A systematic review. Ann Surg 2006;243(3):291–300.
6. Perreault JO, Cao CGL. Effects of vision and friction on haptic perception. Hum Factors 2006;48(3):574–586.
7. Picod G, Jambon AC, Vinatier D, Dubois P. What can the operator actually feel when performing a laparoscopy? Surg Endosc 2005;19:95–100.
8. Bholat OS, Haluck RS, Murray WB, Gorman PJ, Krummel TM. Tactile feedback is present during minimally invasive surgery. J Am Coll Surg 1999;189:349–355.
9. Brydges R, Carnahan H, Dubrowski A. Surface exploration using laparoscopic surgical instruments: The perception of surface roughness. Ergonomics 2005;48(7):874–894.
10. Tang B, Hanna GB, Cuschieri A. Analysis of errors enacted by surgical trainees during skills training courses. Surgery 2005;138:14–20.

11. Menciassi A, Eisinberg A, Carrozza MC, Dario P. Force sensing microinstrument for measuring tissue properties and pulse in microsurgery. IEEE/ASME Trans Mechatron 2003;8(1):10–17.
12. Rosen J, Hannaford B, MacFarlane MP, Sinanan MN. Force controlled and teleoperated endoscopic grasper for minimally invasive surgery: Experimental performance evaluation. IEEE Trans Biomed Eng 1999;46(10):1212–1221.
13. Ottensmeyer MP, Salisbury JK. In vivo mechanical tissue property measurement for improved simulations. Proc Soc Photo-Opt Instrum Eng (SPIE) 2000;4037:286–293.
14. Hassan I, Maschuw K, Rothmund M, Koller M, Gerdes B. Novices in surgery are the target group of a virtual reality training laboratory. Eur Surg Res 2006;38:109–113.
15. Aggarwal R, Black SA, Hance JR, Darzi A, Cheshire NJW. Virtual Reality simulation training can improve inexperienced surgeons' endovascular skills. Eur J Vasc Endovasc Surg 2006;31:588–593.
16. Adams RJ, Klowden D, Hannaford B. Virtual Training for a manual assembly task. Haptics-e 2001; 2(2), retrieved October 17, http://www.haptics-e.org.
17. Kitagawa M, Okamura AM, Bethea BT, Gott VL, Baumgartner WA. Analysis of suture manipulation forces for teleoperation with force feedback. In Dohi T, Kikinis R, eds. MICCAI 2002, LNCS 2488, pp 155–162.
18. Tholey G, Desai JP, Castellanos AE. Force feedback plays a significant role in minimally invasive surgery. Ann Surg 2005;241:102–109.
19. Lamata P, Gomez EJ, Sanchez-Margallo FM, Lamata F, Antolin M, Rodriguez S, Oltra A, Uson J. Study of laparoscopic forces perception for defining simulation fidelity. In Westwood JD, ed. Medicine Meets Virtual Reality, vol. 14. IOS Press, 2006, pp 288–292.
20. Wagner CR, Stylopoulos N, Howe RD. The role of force feedback in surgery: Analysis of blunt dissection. Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, FL, March 2002, pp. 68–74.
21. Heijnsdijk EAM, Pasdeloup A, Van der Pijl AJ, Dankelman J, Gouma DJ. The influence of force feedback and visual feedback in grasping tissue laparoscopically. Surg Endosc 2004;18: 980–985.
22. Higgins GA, Champion HR. The military simulation experience: Charting the vision for simulation training in combat trauma, US army medical research and material command, Fort Detrick, MD DAMD17-99-9028, 2000.
23. Gandsas A, Adrales GL, Park AE. Simulation in general surgery. In Loyd GE, Lake CL, Greenberg RB, eds. Practical health care simulations. Philadelphia: Elsevier Mosby, 2004.
24. Goodell KH, Cao CGL, Schwaitzberg SD. Effects of cognitive distraction on performance of laparoscopic surgical tasks. J Laparoendosc Adv Surg Tech 2006;16(2):94–98.
25. Pool M, Koolstra C, Van Der Voort T. Distraction effects of background soap operas on homework performance: An experimental study enriched with observational data. Educ Psychol 2003;23:361–380.
26. Weerdesteyn V, Schillings A, van Galen G, Duysens J. Distraction affects the performance of obstacle avoidance during walking. J Mot Behav 2003;35:53–63.