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Cognitive simulators for medical education and training

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ABSTRACT

Simulators for honing procedural skills (such as surgical skills and central venous catheter placement) have proven to be valuable tools for medical educators and students. While such simulations represent an effective paradigm in surgical education, there is an opportunity to add a layer of cognitive exercises to these basic simulations that can facilitate robust skill learning in residents. This paper describes a controlled methodology, inspired by neuropsychological assessment tasks and embodied cognition, to develop cognitive simulators for laparoscopic surgery. These simulators provide psychomotor skill training and offer the additional challenge of accomplishing cognitive tasks in realistic environments. A generic framework for design, development and evaluation of such simulators is described. The presented framework is generalizable and can be applied to different task domains. It is independent of the types of sensors, simulation environment and feedback mechanisms that the simulators use. A proof of concept of the framework is provided through developing a simulator that includes cognitive variations to a basic psychomotor task. The results of two pilot studies are presented that show the validity of the methodology in providing an effective evaluation and learning environments for surgeons.

1. Introduction

Simulation training in surgery is emerging not only as an innovative way to teach surgery, but as a method to also decrease the error rates in surgery and improve patient care and safety through evaluation. The Accreditation Council of Graduate Medical Education (ACGME) which is the governing body of medical curriculum in United States has provided detailed standards on medical competency. The toolbox for evaluation recommended by ACGME has listed simulation training as the most effective evaluation strategy for medical procedures and is included in the patient care competency [1]. In addition, simulation was listed as an effective evaluation tool for [1] investigatory and analytic thinking, [2] knowledge and application of basic sciences, [3] patient care management plan development and execution, and [4] ethically sound practice. Recognizing the benefits of simulation training, the American College of Surgeons has now made it mandatory for residents to complete a simulation course called Fundamentals of Laparoscopic Surgery (FLS) [2] in order to become a board certified surgeon. This is one of the many examples of the impact of simulation on medical education and its increased acceptance by the clinical communities.

Currently available simulator technologies, which include virtual reality simulators, box simulators, and mannequins, have focused on the honing of basic skills and procedural skills. Basic skills include psychomotor tasks such as grasping, tracking, moving, and suturing; all using surgical probes and instruments. Development of these skills is a very important part of surgical training given the limited maneuverability and usability of surgical devices and instruments [3]. Research with a variety of simulators has shown that novice surgeons as well as experienced surgeons can benefit by honing their basic skills on simulators like the ProMIS® simulator [4] and the Fundamentals of Laparoscopic Surgery (FLS) Simulator [2]. Simulators have also been designed for complete procedures like the hysterectomy simulator and the endoscopy simulators [5]. These simulators enable the users to practice complete procedures that can enable them to practice and hone their procedural skills (see [6] for an example mannequin trainer and scenarios it encodes). A significant amount of research has been devoted to developing basic skills simulators and procedural simulators. However the original vision of employing surgical simulation and simulator techniques for investigatory and analytic

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thinking requires simulators to go beyond providing simple basic skill improvement and procedural skill memorization. In order to fulfill this vision there exists first the need to understand the role of cognition in surgery, and then the next step is to design, develop and evaluate simulators that will enable training cognitive modalities required for investigatory and analytic thinking.

1.1. Cognition and surgery

Hall et al. [7] investigated the link between surgical proficiency and cognitive processes. In the article, surgery is not only viewed as a mechanical task based skill but an applied skill with both cognitive and psychomotor dimensions. The article states that ‘‘surgical competence combines the intellectual exercise of decision making with the ability to perform mechanical tasks”. Spencer [8] hypothesized that 75 per cent of the important events in an operation related to making decisions and only 25 percent to manual skill. Sir Frederick Treves wrote in 1891 (paraphrased from citation in [7]), ‘‘The actual manipulative part of surgery requires no very great skill and many an artisan shows infinitely more adeptness in his daily work... It is in the mental processes involved in an operation that not a few fail. There is some lack in... the capacity for forming a ready judgment, which must follow each movement of the surgeon’s scalpel” [9]. While the manual skill required in surgery has certainly increased with the advent of minimally invasive surgery, the relevance and importance of cognitive skill, reasoning and decision making in surgery has not diminished. In fact many surgeons and educators would argue the exact opposite for laparoscopic surgery, and studies seem to confirm that laparoscopic and robotic surgeries involve a considerable amount of cognitive skill and decision making [10]. It is hence logical to expect surgical teaching aids such as simulators to provide cognitive training to surgical residents. However in order to develop cognitive surgical simulators it is first important to understand the nature of cognition in surgery.

There are many approaches to understanding and modeling the nature of decision making in medical environments. Researchers study decision making and reasoning in clinical environments and have modeled these processes through a range of theoretical models from cognitive psychology (See Arocha, Wang, and Patel [11] for an insightful review). Many of these models were not empirically validated in the surgical environments and have focused extensively on critical care environments. However, it may be argued that the basic nature of many of these models apply to surgical decision making and reasoning. This claim has some validity as surgeons deal with similar decision making processes as other clinical professionals, and from a theoretical perspective, pure decision making and reasoning skills may not necessarily have different constructs in either surgeons or other types of physicians.

There is however one key aspect of surgical environments that may render it different as compared to other clinical environments. This aspect lies in viewing surgery as a *multitasking* environment. Research in cognitive psychology has shown that often the demands on cognitive faculty are a function of the extra activities the human is involved in or the complexity of the environment within which the exercises are performed. When people perform two or more tasks simultaneously, the tasks are often executed slower and with more errors than when they are carried out as single tasks. This is called *multi task interference* (or *dual task interference* in case of two tasks). While the exact mechanisms of task interference are a matter of intriguing scientific debate (see [12] for a review), it is widely accepted that tasks that behaviorally recruit common cognitive faculties and are performed simultaneously can have differential performance effects as compared to these tasks performed in isolation. Surgery requires performance of complex manual tasks in conjunction with decision making, reasoning and maintenance of high levels of focus and attention. This can be understood as a dual task interference scenario where a surgeon has to perform at both *psychomotor* and *cognitive* levels. For example, a surgeon may be conducting surgery on a patient thereby accomplishing both psychomotor and cognitive tasks on the patient while recommending intervention for another patient; a task that poses additional cognitive load. This type of interactions between decision making and psychomotor skills is a complex phenomena; one that is studied in domains such as aviation but with limited studies in clinical environments.

Significant research has been conducted to understand the relationships between task interference, learning and experience. In general, task interference is severe during learning periods but is reduced dramatically with practice. Levy and Pashler [13] showed that with practice, sets of tasks that are in preferred pairing will show a significant reduction in the effects of dual interference. Ruthruff et al. [14] validated this finding by showing that learning can reduce task interference albeit not completely eliminate it. It is plausible that this same cause and effect exists in surgery, wherein surgery residents can improve their ability to conduct multiple psychomotor and cognitive tasks by training in learning environments designed to present multitasking scenarios. Currently the prevalent practices of learning psychomotor procedures in pristine environments in controlled simulation and training centers may not form an adequate basis for learning and training of future surgeons, but will provide learning only to a certain skill development level. Providing users with simulations that challenge the user’s multitasking abilities may enable better and more robust learning and acquisition of skills for surgeons.

The authors argue that by limiting simulation based training to psychomotor acquisition the full potential of simulation based education cannot be realized. In fields such as the aviation industry simulation has emerged as an effective tool in imparting cognitive training, and in medicine there is a need to develop analogous simulators that focus on the cognitive training of clinical professionals. However development of such a simulator for surgery requires a comprehensive informatics driven methodology that can systematically integrate cognitive training in surgical simulators. This paper outlines a methodology for the integration of cognitive training in surgical simulators. The proposed methodology outlines the design, developmental, and evaluation strategies for cognitive surgical simulators. A proof of concept is presented by developing a simulator that modifies a validated task from the FLS Module [2] and includes cognitive variations. The construct validity of the developed simulator is established through two experiments geared towards evaluating surgeons’ proficiency and producing measurable learning of skills.

The remainder of the paper is organized as follows. The following section defines related work in developing cognitive simulators. The third section covers the theoretical foundations of design, development and evaluation of a cognitive simulator. The proof of concept simulator developed is discussed in the fourth section. The fifth section discusses the experiments and results to establish the validity of the simulator, and conclusions and future work are discussed in the last section.

2. Related work

There is very little reported work devoted to the development of cognitive surgical simulators. One FLS Module [2] includes decision making exercises that require residents to view a case history and decide upon a particular action. This module is delivered through an online program and does not require surgeons to perform any surgery while making decisions but rather focuses solely on decision making skills. This limits the realism of cognitive load that is provided by the simulator. Kohls-Gatzoulis et al. [10] conducted a double blind randomized study wherein a control group of residents was allowed five or six repetitions of a total knee arthroplasty. The experimental group of residents was exposed to fewer repetitions of a total knee arthroplasty, but was augmented by didactic training referred to in the paper as *cognitive training*. Cognitive training included techniques such as lectures by experts and professional handouts delivering information on various scenarios that can be encountered. The paper did not elucidate how the cognitive training was different from conventional didactic training. They also compared the groups in their performance on multiple choice tests that involved cognitive decision making. Results showed that the experimental group of residents performed better in follow up multiple choice question tests and procedure repetitions. While limited in scope, this experiment did demonstrate the value of including didactic training in addition to simulation training; but did not clarify the nature of cognitive training. Further, none of the reported studies provided cognitive tasks to residents in addition to psychomotor tasks. Most surgical errors are made while conducting the actual surgery that involves both psychomotor and cognitive dimensions and not necessarily during the planning stages which are purely cognitive in nature. It is feasible for cognitive simulator models to present multitasking environments for promoting learning in surgical residents.

Simulators and practice environments that require dual task execution have proven to be successful in the aviation industry [15] and neurorehabilitation and diagnosis fields [16], both for the measurement of dual tasking abilities as well as increasing learning. To date, surgical simulators have not benefited from these theoretical constructs to provide more robust learning induced by a realistic environment.

3. Generic methodology to design, develop and evaluate cognitive simulators

This paper aims to extend the capabilities of conventional simulators by including cognitive variations. In order to fully define our methodology; the conceptual understanding of design and evaluation of psychomotor simulators is briefly presented. This will help provide a better understanding and differentiation of our proposed methodology to design and evaluate cognitive simulators.

3.1. Psychomotor simulators

Traditional psychomotor simulators are composed of three logical modules. The sensory module contains sensors that can measure and analyze psychomotor features to determine psychomotor proficiency. Traditionally the simulators include mechanisms for sensing tool movements as research has shown a high correlation between tool movements and surgical proficiency [3]. However, recently some simulators have expanded the sensory module to include hand movements [17] which can not only be reliable measures for evaluation but also serve as an effective feedback mechanism to improve psychomotor skills. Following the sensory module, the simulation module contains the psychomotor exercises that train the user. These simulation exercises can be simple physical simulators or sophisticated virtual reality scenarios, carefully designed to produce learning in users. The sensory module measures psychomotor features while users perform the simulation within the simulation module. The third module is the feedback and monitoring module that provides users with feedback on their performance and often includes longitudinal tracking of their proficiency. A significant amount of research has been done on employing different types of techniques and solutions for each of the modules. For example, researchers have employed a series of pattern recognition and analysis algorithms for determining psychomotor proficiency from psychomotor features (see [20] for a review). Similarly, different types of simulation modules have been developed each suited to their particular application area and feedback modules have been developed using the auditory, visual and the haptic modalities.

3.1.1. Evaluation of simulators

Evaluation of psychomotor simulators is aimed towards four basic research questions.

Question 1. Does practice with the simulator tasks enable better performance on the simulator tasks themselves? This is an important validation methodology in simulators and has been employed in several studies [2,4,10,17–19]. The key aspect of this validation is to establish that some type of learning is being facilitated by the simulator. The experimental paradigm generally plots *learning curves* of residents over a specific period of time. By itself this type of validation does not necessarily imply that users are learning the intended skills. However, often this type of validation is considered a first step in evaluation of a simulator as often simulators focus on basic skills of tool movement or hand movement. The argument lies in understanding that such type of validation warrants further investigation and can potentially lead to skill acquisition that is generalizable.

Question 2. Can the performance metrics on the developed simulator reasonably separate experts and novices? This is an important step in validating the simulator. Often performance metrics in a simulator do not correspond to proficiency in real environments. One way of ensuring this connection is to develop performance metrics that can depict differences between known experts and known novices on the skill. The experimental methodology involves employing the proficiency measures of known experts as baseline scores and then comparing the scores of residents over a single trial or multiple trials. Through this methodology further validation is provided that the simulator indeed has tasks and skills that can differentiate between levels of expertise and can be employed for evaluation.

Question 3. Does practice with the simulator tasks lead to increase in proficiency on the real tasks? This type of validation is aimed at identifying whether practice with the simulator leads to skill development that transfers to real environments. The experimental methodology generally compares a control group of residents who do not practice with the simulator to an experimental group that is exposed to a simulator on a transfer task. Preferably the transfer task is actual surgery evaluated through some mechanism like multiple raters or an automatic method like computer vision based tracking through a camera in actual surgery. This methodology provides validation that the simulator is indeed developing the skills for which it was designed. Often this type of validation is limited by the need for a large number of participants for statistically significant results. As a result, many of the published studies do not necessarily aim for statistical significance in their results, but aim at showing the trends of the results. However some of the simulators such as the FLS Simulator [2] and ProMIS® [4] are validated rigorously and have included this step of validation with statistically significant results showing the positive impact of simulation education. Another accepted method for establishing simulator validity lies in dividing the participants into a control group and an experimental group as above, but testing their proficiency on a transfer task that is not actual surgery but a different validated simulator like the FLS or ProMIS®. The logical argument that guides this methodology lies in simply showing a transfer of learnt skills to another task. Although this approach is weaker than the complete validation with actual surgical tasks it has been used as a quick mechanism to validate skill transfer produced by a simulator.

Question 4. Are the skills learnt with the simulator retained over a period of time? This is an emerging validation question in simulation based education that is driven by growing demands for accreditation of clinical professionals. There are a limited amount of studies that have been conducted on validating the simulators in producing long term learning [20]. The experimental methodology involves establishing baseline proficiency during an initial phase, and then repeating tests on the same task or transfer tasks after a gap in training. This type of simulation validation can be a powerful tool in ensuring the longevity of simulators and as such simulators can be employed for a continued medical education like the paradigm for surgeons at a skills level.

3.2. Layered architecture for cognitive simulators

Multitasking simulations can be suitably modeled through a layered architecture wherein elements of the two layers interact to produce a systems' behavior. Our system is modeled to have two distinct layers: a *psychomotor layer* for psychomotor training and a *cognitive layer* for cognitive training.

The layered architecture is particularly suited to produce complex interactions between the psychomotor training modules and the cognitive training modules. An alternative model would be to organize the cognitive and psychomotor training modules interacting in a multithreaded manner. In such a formulation, the cognitive training module and the psychomotor training module will be modeled as independent threads, which share some elements of data through a well defined data usage and release protocol. However, in reality the psychomotor and cognitive modules need to interact in a more sophisticated manner to produce learning environments. Often the interactions between the psychomotor component and the cognitive component of learning will require more than a linear data sharing plan and the influence on each other through a variety of methods. For example, consider a simulator that is designed to provide training for suturing but incorporates noise in the environment to offer a realistic training environment. The psychomotor component of the simulator would deal with providing an environment for surgeons to learn how to conduct the suturing task. The cognitive component will deal with training surgeons on how to cope with noisy environments when accomplishing suturing tasks. If modeled as a multithreaded process then the noise measurement and noise simulation would occur independently of the suturing simulation interacting during set time intervals. Such type of interaction is adequate to simulate directed noise which is discrete, but simulation of ambient noise which is continuous in nature can be cumbersome. On the other hand, the layered architecture can easily incorporate both ambient noise in the environment through functional interaction between psychomotor cognitive layers as well as directed noise through similar interactions. Another important advantage of the layered methodology is that simulators can be designed with a subset of the functionality that the methodology facilitates, allowing designers to tailor simulators to their requirements and the environmental constraints. The key here is that a layered architecture allows for greater flexibility that provides an elegant solution for simulating certain types of surgical procedures as compared to strict multithreaded architectures that need explicit definitions of data sharing and interaction mechanisms.

Our proposed layered architecture is defined in Fig. 1. The architecture like the psychomotor simulators contains three modules:

(1) sensory module,
(2) simulation module and
(3) feedback and evaluation module.

The cognitive layer works in tandem with the psychomotor layer in each of these modules. At the sensory level, the mechanisms for cognitive sensing can be incorporated in addition to the psychomotor sensing mechanisms. Cognitive sensing can be accomplished through a variety of means such as eye movement

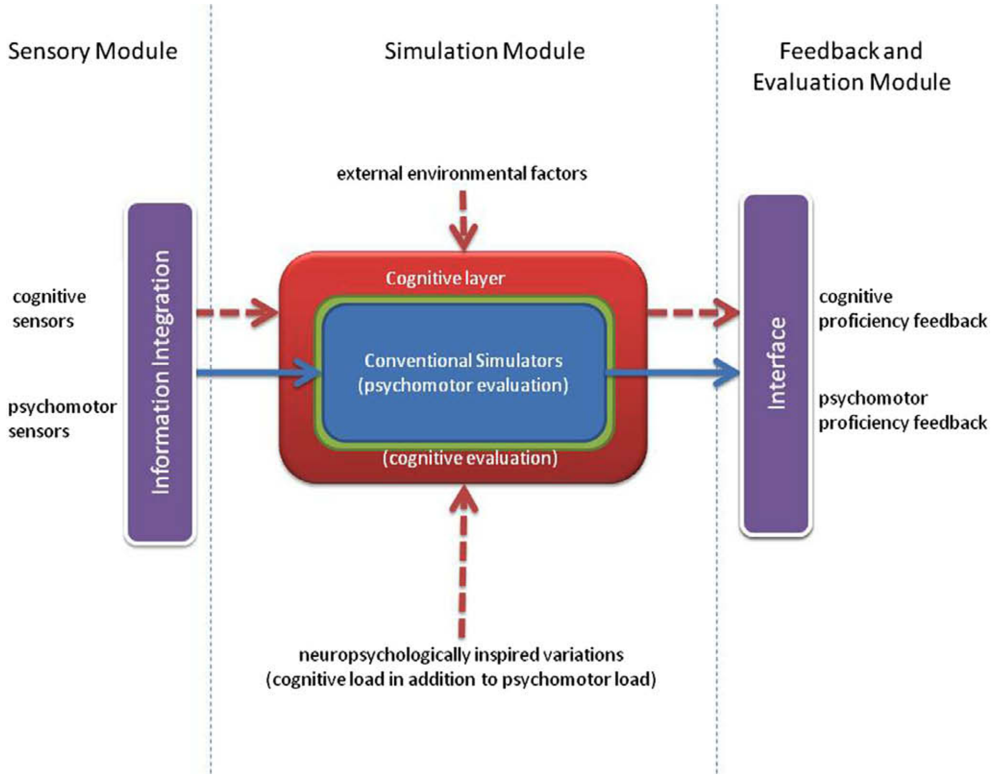

Fig. 1. Generic methodology to design cognitive simulators.

tracking, electroencephalogram measures, skin conductance measures and even biophysical measures such as cortisol levels to measure stress. As these measures are employed in addition to the psychomotor measures there is a need to measure the interaction between psychomotor and cognitive layer, and thus an information integration layer is included in the core architecture. These information integration layers are responsible for (a) ensuring synchronous behavior between the variety of psychomotor and cognitive signals and (b) filtering the individual data streams. These steps ensure that the simulation layer and the analysis layers can work with the signals to offer realistic simulation environments and feedback.

The simulation module produces the most sophisticated interactions between the cognitive layer and the psychomotor layer providing a learning environment that mimics the real environment conditions. With the addition of the cognitive layer, a variety of additional exercises can be produced. One particular type of variations can be produced by simulating external environmental factors. External environmental factors include all factors that influence the performance of a surgeon and would incorporate both clinical environmental factors as well as workflow related factors. Examples would include ambient noise, directed noise, and technical issues like an inverted camera and the patient history and treatment plans. For simulators that are based on team based activities, issues such as interpersonal communication and the lack of shared information can also be included in simulations to provide variations to the basic psychomotor tasks. Variations for complete procedure based simulators can include simulation of patient history and different treatment plans. These types of variations can provide realism to the simulation tasks and enable surgeons to master accomplishing complex tasks in demanding environments with high cognitive load. From a theoretical perspective, these variations are coherent with the notion of *embodied cognition*. Embodied cognition emphasizes the formative role the environment plays in the development of cognitive processes. The encyclopedia of philosophy [21] states that "The general theory (of embodied cognition) contends that cognitive processes develop when a tightly coupled system emerges from real-time, goal-directed interactions between organisms and their environment; the nature of these interactions influences the formation and further specifies the nature of the developing cognitive capacities." The provision to include variations that may be produced by environments is designed to allow for *embodiment training*. The embodied cognition theorists believe that the environment limits and guides the cognitive processes and learning that occurs in an individual. It is based on this ideal that the authors challenge the notions of purely psychomotor training in ideal environments for surgeons when in fact surgical procedures are conducted with cognitive load under high levels of environmental variations. Embodiment training simulations can smooth the transition of clinical professionals from learning environments to the challenging work environments like critical care units and trauma units.

The other type of variations that can be added to basic simulation tasks are specifically designed to evaluate and train individual cognitive modalities such as attention, memory and visio-motor coordination. The purpose of these types of variations is manifold. First, these variations can build on a large body of literature from neuropsychology [22] that includes descriptions of designed tasks especially suited to evaluation and training of cognitive modalities. Originally these tasks were designed as diagnostic aids for patients with neurological disorders. For example, a suite of memory and executive functioning tasks is employed for detecting amnesia [22]. Many of these tasks are purely cognitive in nature but can be modified by adding a psychomotor component to them. Another example is the combination of a memory task with a suturing task to present a multitasking environment. Such multitasking environments can be designed to mimic the cognitive load faced by surgeons in daily work and hence can serve as an important learning and habituation tool. These tasks also serve as an effective tool in establishing baseline scores of expertise in surgeons as pertaining to different cognitive modalities. Surgeons' performance on multitasking environments with memory tasks or attention tasks can serve as an important measure of surgeons' cognitive expertise as well as a measure of their current mental state, which may be adversely affected through factors such as fatigue.

The feedback and evaluation module is responsible for the presentation of the performance data to the users. This module can employ a variety of means to present and visualize the data from learning curves to bar graphs with error bars for comparison of groups. Further this module can be configured to deliver a *universal score* of proficiency that combines cognitive and psychomotor performance. This can be achieved by a linear or non-linear combination of individual proficiency scores combined in a weighted manner. The weights can be fixed by experts based on consensus. It is also possible to determine the weights through an empirical methodology. In this methodology the individual scores from different proficiency measures can be employed in a regression paradigm wherein the weighted sum of an individual's proficiency score should equal a universal score possibly gathered through independent trained raters.

The presented design methodology represents a configurable and generalizable paradigm to develop cognitive simulations. It provides a *design document* for simulation designers to modify existing simulators to include cognitive variations and design new simulators that have inbuilt mechanisms to support cognitive training. The application of framework to existing simulators and new simulators is discussed below.

Existing simulators as represented in Fig. 1 generally consist of psychomotor tasks. Cognitive variations can be added through mechanisms that do not require complete re-design of the software or hardware. Cognitive sensing can be facilitated through a cross platform cognitive sensing mechanisms. For example cognitive sensing can be accomplished through including eye movement tracking system to monitor the areas of the simulation environment upon which a user is focusing. Such a sensing mechanism would be cross platform as it could be employed for a range of surgical tasks and not focus on a single task. As represented in Fig. 1, a requirement would be to synchronize the cognitive sensing signals with the psychomotor sensing signals. This could be accomplished by either hardware synchronizing mechanisms or through software based synchronization.

The interaction of the cognitive and psychomotor layers in the simulation module can be complicated by simulators not providing Application Programming Interface (API) or mechanisms to modify their existing tasks. While this does limit the number of variations that can be offered by the simulators, simple scenarios can still be effectively simulated. For example a suturing simulator could be combined with a memory task that may require remembering patients' vital information. The user may be asked to make decisions based on vitals while conducting suturing, or simply be required to recall the vitals during the process or after it. Such a simulation may require an additional program that presents the memory task and requires decision making/recall based on those vitals. Another example lies in simulation of noisy environments. Programs could be written that simulate noise while requiring surgeons to accomplish a psychomotor task. Similar methodology may apply to generate simulations for both environmental variations as well as neuropsychological variations. The feedback modules for such an arrangement would generally present cognitive psychomotor measures separately as the feedback from existing simulators may not be accessible programmatically.

New simulator designers can benefit from this architecture by designing each of the three modules in a manner wherein the cognitive psychomotor layers can interact freely. The sensing module should be designed to include both inbuilt mechanisms for synchronization of a variety of signals and be configurable to include newer measures. The module will also include routines to ensure consistency of data streams. The simulation module should be designed to include several variations for the learning and evaluation of neuropsychological measures of cognition. The environmental factors should be built in and provisions should be made to include both neuropsychological learning and evaluation and environmental factor based variations simultaneously. The key task of the simulation designer for this module would be to understand the surgical environment and then to develop a combination of psychomotor and cognitive tasks that closely simulate the surgical environment. The feedback mechanisms should include visualizations as well as a means to generate a universal score. An important feedback that should be included in the simulation would revolve around the users' ability to accomplish multitasking. This can be based on cognitive psychology research on multitasking and a variety of measures employed for depicting multitasking [13].

The evaluation of cognitive simulators can be performed in a manner similar to psychomotor simulators. The four research questions defined in Section 3.1.1 are adequate in establishing the validity of the simulators. In addition to these four types of validation, another type of validation lies in studying the difference between learning produced by psychomotor learning and learning produced by cognitive learning. This is an important testing mechanism which is not included in currently available simulators or other evaluation mechanisms. This can be accomplished by comparing groups of users exposed to different types of simulators.

4. Proof of concept cognitive surgical simulator for tool manipulation

As a proof of concept of the above described methodology, a cognitive simulator has been developed for a commonly employed practice exercise called the ring transfer [2]. This exercise is included in the FLS [2] module which is validated and now a required module to qualify as a board certified surgeons. The exercise has been used by residents to practice tool manipulation through laparoscopic probes. Presented in this paper are details of how a new simulator has been developed, and includes this exercise and its cognitive variations.

The simulation was implemented using the Sensable® Haptic joystick. The Sensable Haptic joystick allows for the generation of 3 degrees of force feedback in response to events in the virtual environment. OpenHL® programming API was used to design the simulation. The simulator's sensing module included both hand and tool movement measurements. The simulation allows for measurement of the tool tip in the virtual environment. Additionally the sessions could be played back in the software with traces (path) of the tool tip movement being shown at various speeds, allowing for visual analysis of movement. Additionally, while performing the simulated tasks the subjects wore the Cyberglove® and Polhemus Liberty Tracker® that allowed for the capture of the user's hand movements (see Fig. 2b).

As mentioned before, the developed methodology allows for simulators to add only a subset of functionalities possible. For the purposes of ring transfer, a cognitive sensing mechanism is not explicitly included. However provisions were made to include eye movement tracking as well as electroencephalogram readings in later phases of development. Further, we did not include environmental variations explicitly. These design considerations were made to isolate the effect of cognitive variations on proficiency. The simulation module included the basic psychomotor task and neuropsychological variations to measure cognitive modalities. These are described in detail below.

4.1. Psychomotor skills task

4.1.1. Sensorimotor coordination exercise

The basic ring transfer task can be described as follows. The simulation environment presents users with nine equally spaced pegs and a ring. In the virtual ring transfer task (shown in Fig. 2a, residents were tasked with grasping a series of a "virtual" rings and placing each on randomly highlighted pegs on a board. This basic task involved 10 rings (Fig. 2). After the participant places a ring on a highlighted peg, another peg is randomly highlighted for the participant to put the ring around the same. This is repeated till all 10 rings are correctly placed. The time taken for completing the task is displayed on the bottom middle part of the screen for the participant to follow. This basic ring transfer task is a psychomotor task employed in many simulators to hone tool manipulation skills. An error is marked for every time a ring is placed on the wrong (non-highlighted) peg. *The simulation considers this error to be a cognitive error as it is generally a result due to a lapse of judgment or attention on the part of the user.* It may be noted that the simulation does not allow placement of the ring on a wrong peg and the user must continue until the correct peg is

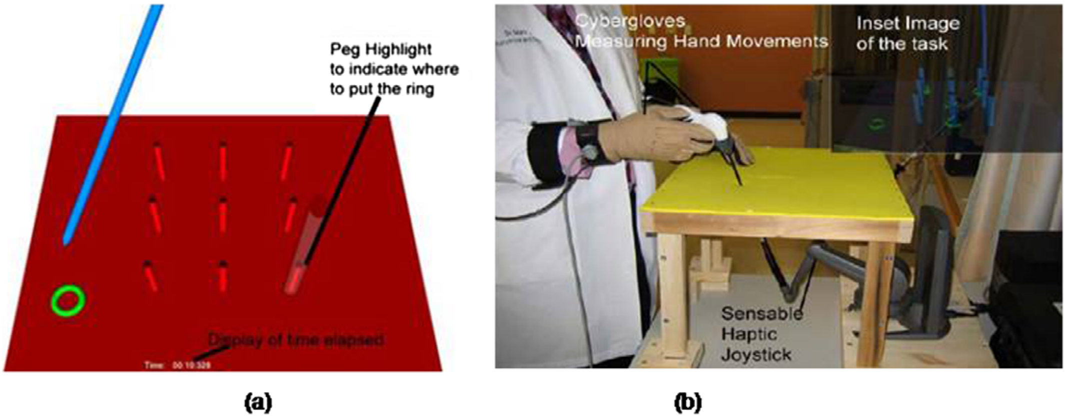

Fig. 2. (a) Ring transfer task implemented using the Sensable Haptic joystick. The simulation requires the participant to pick the ring and then place it on the highlighted peg. The movement of the tool and hands are measured in the process. (b) Shows a subject using the system. It may be noted that the hand movement data capture gloves can be worn with any simulator and be potentially employed for evaluation in actual surgery.

chosen. It is primarily a sensorimotor coordination task that involves visual perception and motor actions and errors of misplacing ring generally occur only during habituation phase wherein subjects are familiarizing themselves with the apparatus and task. Sensorimotor coordination in this task is primarily measured through movement smoothness of the surgeons' hands as well as the tool movement smoothness. It may be noted that this test is similar to the Purdue Pegboard Test which measures hand movement dexterity [23]. Purdue pegboard test is a validated task for neuropsychological assessment and rehabilitation and its adaptation to surgery enables measurement of dexterity in surgical residents.

4.2. Cognitive skills task

The psychomotor ring transfer task described above is available in a variety of simulators. As a design consideration, a key point of interest is the development of cognitive variations of this task to provide a richer learning environment. Four cognitive modalities were chosen for which variations were designed. These four modalities were (1) movement planning (2) preparatory attention (3) working memory and (4) intermodal transfer. These modalities were chosen as they can influence surgical performance significantly. These modalities and their nature are described below.

Movement planning has been a source of several investigations by neuroscientists and cognitive psychologists. Complex motor behavior is composed of serial movements. To plan serial movements, sensory information is often transiently stored in working memory and converted to a movement program with the help of multisensory stimuli [24]. Often studies revolve around monitoring a subjects' ability to plan a combination of simple atomic (basic) motions to accomplish sophisticated tasks. In surgery, movement planning is critical in ensuring patient safety. In a neuropsychological assessment, tasks to evaluate movement planning abilities involve the subjects' ability to monitor movement, predict trajectories and then accomplish certain actions. These activities evaluate how well a subject can track certain activities, plan motion to respond and finally execute the response.

Mesulam [25], defined attention as "preferential allocation of limited processing resources and response channels to events that have become behaviorally relevant." Laberge [26] further categorizes attention into several processes including *selective attention*, *preparatory attention* and *sustained attention*. In any perceptual task, the first activity from a behavioral standpoint lies in selecting the appropriate goal from an array of alternative goals and selecting the operation(s) associated with achievement of that goal. This process is known as *selective attention*. In theory selection can be random. However research has shown that humans are able to perform nonrandom selections and that both short-term and long-term learning can enhance selective attention (for a more detailed review please see Kruschke [27]). *Preparatory attention* is the elevation of activity in the corresponding perceptual or action brain area that speeds the processing of stimuli or actions when the appropriate triggering event occurs. *Preparatory attention* follows selective attention and allows humans to hone in on cues and environmental triggers that allow for achievement of goals. *Sustained attention* is produced following successful preparatory attention and is characterized by maintenance of enhanced levels of activity over long duration of time. Tasks and protocols have been designed to measure each of these processes, and from a surgical perspective all types of attention described above are of interest for simulation. However, for a proof of concept, preparatory attention was chosen as research has shown that learning can significantly enhance preparatory attention [22].

Working memory may be defined as the system for the temporary maintenance and manipulation of information which is necessary for the performance of such complex cognitive tasks such as comprehension, learning and reasoning. It can be deduced from the definition that working memory plays an important role in multitasking and hence is of direct relevance to surgery. Many researchers have already explored working memory capacity. G.A. Miller [28] in a seminal paper summarized evidence that people can remember about seven chunks in short-term memory (STM) tasks. Since that paper however, considerable debate in psychological and neurological literature has led to the consensus that that capacity limit is smaller, and Cowan [29] in a summary article put the number at four with all other performance constraints accounted. The most basic working memory test is known as the digit span test (DST) which involves subjects perceiving a sequence of characters and recalling the sequence after a delay [30]. Using this test and its variations, researchers have shown that working memory capacity can vary according to level of expertise [31] and level of fatigue [32].

In everyday life as well as specialized environments, exchanges between individuals and environment are multimodal. A key perceptual process lies in the human ability to perceive varied perceptual information from different modalities and coordinate it into unified wholes to produce adequate responses to each situation. The act or the ability of humans to coordinate information from various modalities to produce unified perceptual experiences is known as *intermodal coordination* [33]. In *intermodal transfer*, information provided by one modality is employed or processed by another modality. An everyday life example of intermodal transfer lies in predicting haptic characteristics of an object by only viewing the object. Humans are adept at transferring information learned in one modality (like vision) to another modality (like haptics) [33]. In surgery, the ability to transpose knowledge and information from visual stimuli to haptic sensations is a key skill. Surgeons have to often rely on experience in order to interpret visual stimuli from a camera and decipher tactile property of organs. There is no reported literature on warm-up and its ability to enhance basic functions like intermodal transfer and coordination. However, including tasks that specifically target intermodal coordination and transfer skill may have a beneficial effect on surgical proficiency and help elucidate the mechanisms of warm-up for cognitive and psychomotor arousal.

Table 1 outlines the exercises designed to specifically target these modalities in addition to the psychomotor tasks. These tasks are described below and a descriptive video for each of the tasks is available from www.public.asu.edu/~kkahol/nibib.htm.

4.2.1. Slow 2-dimensional tracking task

In addition to the basic ring transfer task three variations of the task were designed to target *movement planning*. In the sensorimotor coordination exercise, the ring is stationary and can be grasped and picked up from a fixed location. To include more manipulations and greater range of motion, a variation of the basic simulation was designed where the ring moved slowly (approximately 25 pixels per second on an 1124 × 1048 pixel display) in the environment. This speed was chosen based on informal experiments with senior surgeons. This variation required the participants to track the ring movement and grasp and pick it up while it is in motion. In this variation, the ring moved in the plane of the pegboard. This task is inspired by visio-motor tracking tasks that primarily involve motor planning resources but also recruit attentional resources and working memory resources [22]. Some simulators such as ProMIS$^{®}$ include such variations.

4.2.2. Fast 3-dimensional tracking task

In this variation, the ring was allowed to move anywhere in a 3D environment at a faster rate (approximately 50 pixels per second on an 1124 × 1048 pixel display). This speed was chosen based

Table 1
Exercises and the primary cognitive and psychomotor faculty engaged.

Cognitive and Psychomotor faculty	Exercises						
	Sensorimotor coordination	2 dimensional tracking	3 dimensional tracking	Orientation	Preparatory attention	Working memory	Visio haptic transfer
Sensorimotor coordination	X	X	X	X	X	X	X
Working memory		X	X	X		X	
Movement planning		X	X	X			X
Preparatory attention		X	X	X	X	X	X
Intermodal transfer				X			X

on informal experiments with senior surgeons. This task requires more sophisticated tracking in 3 dimensions with the ring in a variable orientation recruiting the same resources as the slow 2-dimensional tracking task but with higher complexity.

4.2.3. Orientation task

In this variation of the pegboard task, the entire pegboard moves slowly, creating different orientations in which the surgeons need to place the ring on the highlighted peg. The speed and orientations were chosen based on informal experiments with senior surgeons. This task recruits movement planning resources efficiently as the user has to divide their resources between tracking rings and the pegboard and placing them on the correct peg in a continuously changing orientation. It trains the user to accomplish the tasks in different orientations; and is well matched to actual surgical procedures where the tissues or organs may actually be slightly moving. In addition, it also allowed for capture of rotation movements of the wrist which is generally not required in the psychomotor ring transfer task.

4.2.4. Preparatory attention task

In the primary sensorimotor task, a peg is lit up throughout the simulation, providing users with constant visual feedback on the peg where the ring should be placed. In order to make this a preparatory attentional task, a randomly chosen peg is highlighted only for 500 ms after which the highlight is removed. This task requires the user to pay attention to the peg that lights up and then execute the ring transfer to the selected peg. This task requires users to pick visual cues to identify the correct peg and then execute the motion engaging preparatory attentional circuits in addition to recruiting processes for accomplishing the basic sensorimotor coordination task.

4.2.5. Working memory task

In the working memory task, a sequence of randomly chosen pegs light up instead of a single peg. Each peg lights up for only 500 ms requiring the user to memorize the sequence. Two variations are programmed. The first variation presents a sequence of 3 randomly chosen pegs while the second variation presents a sequence of 4 randomly chosen pegs. This test is inspired by the digit span test which requires users to memorize a sequence of numbers and then recall it [22]. This test combines working memory recruitment with motor processes to offer a challenging exercise for surgeons. Such variations of digit span test have been designed for measuring visio-spatial attention and working memory in neuropsychological evaluation (the Korsi Block Tapping Test, in Lezak et al. Neuropsychological Assessment [30]). This test reveals that the digit span in multiple tasks scenario runs one element lower than conventional digit span task [29]. A maximum of 4 pegs were highlighted based on previous work that suggests 4 items to be the limit of working memory [29]. Informal tests conducted with senior surgeons (who did not participate in the final study) confirmed that a span of more than 4 pegs leads to considerable increase in errors in judgment of correct pegs.

4.2.6. Visio-haptic transfer task

A surgical simulation task that requires intermodal transfer in conjunction with sensorimotor coordination was developed. In the visio-haptic transfer task, much like the attentional task, a peg is randomly chosen and highlighted for 500 ms with the task being to put a ring on the highlighted peg. However, after the peg is highlighted, the entire pegboard appears and then disappears from the visual display every second. During the appearance of the pegboard, the user can both see and palpate the entire board and ring. However, during disappearance of the board from visual stimuli, haptic sensations of the board and ring continue to be present in the simulation. The user has to now rely solely on the sense of haptics to place the ring on the correct peg. This task requires the user to memorize spatial location of the pegboard and individual pegs learned from visual display. In order to effectively accomplish this task, the information learned from the visual display needs to be transferred to haptic modality which allows the user to place the ring on the pegboard even in the absence of visual stimuli. This is a novel task which is designed to specifically measure and promote intermodal transfer.

These exercises represent the simulation module of the cognitive simulator. It is important to note that all the simulations were based on validated neuropsychological assessment and such tests are a valuable resource for the simulation community to incorporate cognitive exercises.

4.3. Feedback and evaluation module

The feedback and evaluation module in the proof of concept simulator employs the cognitive errors as marked in the simulation modules as the measure for cognitive evaluation. The simulator employs hand movement and tool movement capture systems and their variables as parameters for psychomotor evaluations.

Tool movement measured as the movement of the tooltip in a virtual environment is a validated measure for surgical proficiency [3,18]. Kahol et al. [34] introduced hand movement measured through the Cyberglove® and Polhemus Liberty® Tracker as an effective measure of surgical proficiency. Both tool movement and hand movement is representative of economy of motion and overall smoothness in execution. The smoothness of tool movement was calculated as using the following formula:

$$\text{Tool movement smoothness} = 1 - \text{normalized (tool acceleration)} \tag{1}$$

Tool acceleration was calculated for the entire duration of a task and normalized in a range of 0 through 1. Smoothness of tool movement as predicted through this measure is 1 when overall acceleration is close to 0. This is generally the case in well executed motion with controlled accelerations. On the other hand, jerky motions show higher normalized acceleration and hence lower smoothness. Similarly the hand movement smoothness is calculated using the following formula:

$$\text{Hand movement smoothness} = 1 - \text{normalized}\,(\text{wrist acceleration}) \tag{2}$$

The data capture setup shown in Fig. 2b depicts the wireless Cyberglove® glove and the Polhemus Liberty® tracker. The wrist acceleration is calculated through tracking of the sensor placed on the wrist. In regards to tool movement smoothness, jerky hand motions lead to less smoothness while controlled movements lead to increased smoothness. For every simulation exercise the time required to complete a task is also recorded. These objective measures are then supplemented with a gesture level proficiency measure which is an effective psychomotor measure. It is based on the technique of task decomposition that has emerged as a validated measure of surgical psychomotor proficiency [3,34]. In this approach, hand movement or tool movement is decomposed into smaller gestures (such as in, out, grasping or rotation). Each individual gesture is analyzed and based on its similarity to an optimal occurrence of a gesture (determined by modeling an experts group performance of that gesture), is given a proficiency rating (please see [20]] for a complete description of the modeling process). For this paper, hand movement was used for task decomposition. The algorithm for this purpose was described by Kahol et al. [34] and was shown to correlate highly with subjective proficiency ratings obtained by senior surgeons. The algorithm employed here generates a score between 0 and 10 for an entire exercise. Zero implies least proficiency in accomplishing the task while 10 implies highest proficiency. This measure is estimated through a combination of time elapsed and kinematic analysis of hand motion. These five measures (gesture level proficiency, hand movement smoothness, tool movement smoothness, time elapsed and cognitive errors) provide a broad framework for the evaluation of proficiency.

The evaluation and feedback module included routines for plotting learning curves, bar graphs with error bars, ANOVA plots and MANOVA plots. A weighting mechanism that allowed for the generation of universal score was also included.

5. Validation of the ring transfer simulator with cognitive variations

As defined in Section 3.1.1 validation of simulators involves four basic research questions. For initial experiments, the primary focus was on validating the simulator with regards to question 1 and question 2 described in Section 3.1.1. In addition, the difference between cognitive training and psychomotor was also evaluated All the experiments were conducted after approval by the Institutional Review Board of the concerned institutions. Subjects were not compensated for the studies and participated in them on a voluntary basis. The results of the experiments were not shared with program directors of the residency programs so as to not influence the evaluation of performance in their residency program.

5.1. Experiment 1. Evaluation of cognitive and psychomotor abilities of surgeons with cognitive simulators

The first two levels of validation as defined by Section 3.1.1 were the subject of study for this experiment. The primary goal was to establish that residents who practice with the simulator improve in their skills to complete the simulation tasks. Secondly this experiment also validated whether the designed simulator can produce a measurable difference between participants with varying levels of expertise.

5.1.1. Subjects

Baseline demographic data were obtained from thirty-seven (19 female) trauma surgery and obstetric residents, 25 of whom were junior level (PGY-1 or -2) house officers and 12 of whom were senior level (PGY-3 or higher) residents. In addition, 10 attending trauma surgeons (1 female) with over 5 years of experience in post residency training were involved in the experiments. These groups of surgeons and residents defined the main participant group.

5.1.2. Experimental protocol

Each participant was involved in eight sessions. Each session was held pre-call before the residents performed their night call to eliminate the effect of fatigue. In each session, three exercises were performed after filling in the fatigue questionnaire. These three exercises were randomly chosen from the eight exercises defined above. Each exercise was repeated 2 times. During each session the subject wore the Cyberglove® and Polhemus Liberty® tracker on their dominant hand. In the first session, the glove was calibrated to a participants hand and the calibration was stored. For every session performed by a participant, the calibrated glove was used to accurately record hand movements and wrist movements. Each session lasted approximately 15–20 min. Tool movement smoothness and hand movement smoothness in an exercise were calculated using formulae (1), (2), respectively for each exercise. Proficiency in an exercise was calculated by passing the captured hand movements through the task decomposition algorithm that generated a single proficiency score for each exercise performed. Time elapsed and cognitive errors were noted during the recording of the session by the designed software.

5.1.3. Data analysis

The learning curves of participants grouped according to their experience were plotted over the eight sessions. The mean proficiency level for the five proficiency measures in each session was determined for the following groups; PGY1; PGY2; PGY3 and senior surgeons. The percentage increase in proficiency was calculated by comparing the mean proficiency scores on the last session and the first session. The standard deviations were calculated for each of the groups. MANOVA analyses tool was employed to evaluate the separation between groups in the first and the last trial.

5.1.4. Results

Fig. 3 shows the learning curves. Overall all the groups showed significant increase in proficiency scores over the eight sessions (mean increase in proficiency scores being 64.09%, 64.49%, 58.7% and 63.09% for the PGY1, PGY2, PGY3 and Senior Surgeon groups). Standard deviations within groups decreased with increase in number of sessions which suggests a learning trend that repeats across subjects. In the first trial, each of the groups showed a statistically significant difference ($p < 0.05$ was obtained on MANOVA test for all the proficiency variables except time elapsed). By the last trial the difference between PGY3 and Senior Surgeons ($p < 0.59$) were less defined as were the differences between PGY1 and PGY2 group ($p < 0.7$).

5.1.5. Discussion of results

Analyses of the results clearly suggest the validity of the simulator in producing a learning effect. All the groups showed improvement with practice with the simulators. PGY1 group showed significant improvements with practice on reducing cognitive errors (91% reduction in mean errors in the last session). This is an important result as one of the main aims of the developed simulator was to enable residents to improve their cognitive skills. While all the proficiency scores showed consistent trends, the elapsed time had unpredictable behavior. This is expected as often during learning stages, time elapsed can vary and is not necessarily a good variable for surgical proficiency [35].

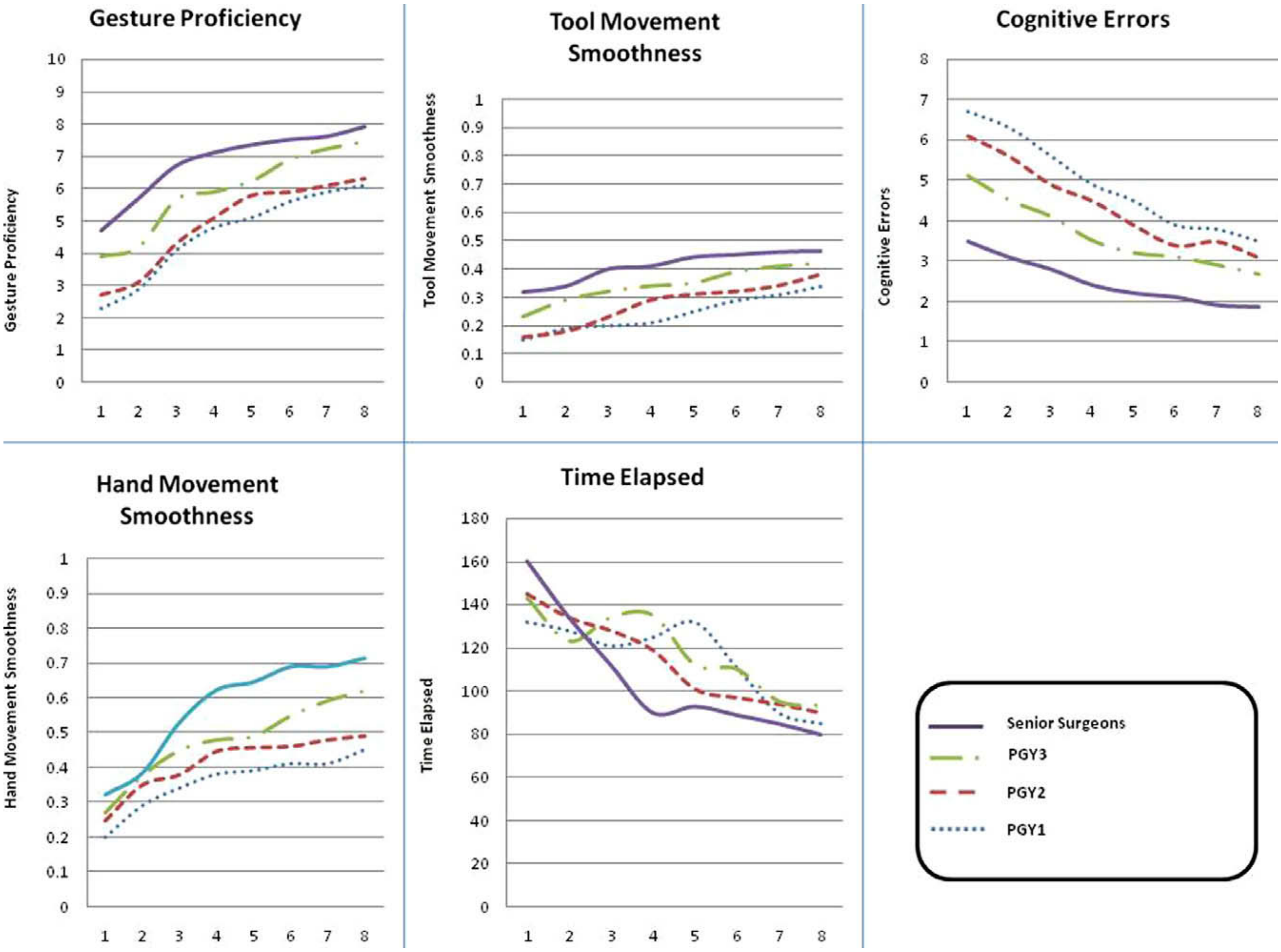

Fig. 3. Results of experiment 1.

The results also show the validity of the simulator in producing measurable differences between groups of different expertise levels. By the end of the trial PGY1 had attained skill levels similar to the PGY2 group and the relation held for PGY3 and the senior surgeons group. This result is expected for basic skills like the ones simulated by the ring transfer exercises this are expected. The difference between performances is shown at an absolute level in each of the sessions with the senior surgeons group consistently outperforming the other groups. It is also noticeable in the change of proficiency scores over eight sessions with the proficiency scores of the senior surgeons stabilizing at a faster rate than other groups. It was also seen that the number of cognitive errors made was a reliable measure to differentiate between the groups of participants and could function as an effective evaluation tool.

The key findings in these studies were that it is possible to develop simulations that target cognitive faculty evaluation and training. Learning was recorded in exercises and the proficiency measures showed results consistent with expectations of the effect of experience. The second experiment was conducted as a follow up experiment to experiment 1. In this experiment, the difference between conventional simulators and cognitive simulators in producing a learning effect is studied.

5.2. Experiment 2. The effect of practice with cognitive simulator on procedural surgical tasks

Experiment 2 was conducted to study the effect of basic practice with the eight exercises and their effect on learning of procedural skills. In addition this experiment allowed for studying the difference produced between psychomotor learning and cognitive learning exercises. The experiment was performed after approval from Institutional Review Board of the involved institutions.

5.2.1. Subjects

10 PGY3 residents were recruited for this study (4 females, 6 males; 3 OBGYN, 7 general surgeons).

5.2.2. Experimental methodology

Five residents were allowed to practice with the sensorimotor coordination exercise 48 times and formed the control group. They performed these iterations on the ProMIS® Simulator ring transfer exercise. This is a commercial off the shelf simulator offering simulation exercises using both conventional and virtual reality training. It has been validated and is employed for basic laparoscopic training and is the equivalent of the FLS course which is recognized by the American College of Surgeons [2].

The remaining five residents were exposed to six iterations of each of the eight exercises and formed the experimental group (48 practice sessions overall). Both the groups performed the exercises over four sessions (12 exercises per session) on four consecutive days.

After a gap of 24 hours, both the groups were required to conduct the electrodiathermy exercise in the ProMIS® Simulator while wearing Cyber Gloves®. The electrodiathermy task is a procedure that requires removal of the gall bladder from its bed in undersurface of the liver through electrosurgery. The ProMIS® simulator includes this exercise as a virtual simulation. The objective proficiency in the ProMIS® Simulator was measured as time elapsed for completion of task, path smoothness (a variable from ProMIS® Simulator), Gesture proficiency (through CyberGloves worn during performance of the task) and hand movement smoothness. The diathermy task was repeated three times by each participant in both the groups.

5.2.3. Data analysis

A level of analysis was performed to study the difference of learning produced in the psychomotor exercises and the cognitive exercises. This analysis was concerned with the 48 practice trials of the control group and experimental group performed. The comparison of the gesture proficiency measure between both the simulators was chosen as it was a reliable measure and common in both the ProMIS® simulator and the cognitive simulator across the forty-eight learning trials. Learning curves were plotted for gesture proficiency levels. The increase in proficiency produced by each of the types of exercises was also compared as shown in Table 1. This was calculated as a percentage increase in proficiency for each of the exercises.

ANOVA was performed to study the differences in control group and experimental group on the proficiency measures in electrodiathermy tasks for each of the three iterations of the task. This provided a measure of the transfer of skills from the cognitive simulator to a complete diathermy procedure.

5.2.4. Results

The learning curves for the control group and experimental group over forty eight trials are shown in Fig. 4. The maximum increase in proficiency was shown by the movement planning exercises (67% improvement). The lowest increase in proficiency was reported for the working memory task (48% improvement). The ANOVA plots for the comparison of experimental group and control group (gesture proficiency) over three trials of electrodiathermy task is shown in Fig. 5. A statistically significant difference was seen in control group and experimental group ($p < 0.05$).

5.2.5. Discussion of results

The learning curves for the control group and experimental group showed that the cognitive simulators led to higher levels of proficiency. This could be attributed to the variations built into the simulator that offered higher degree of exposure to residents and allowed for users to practice their skills in a variety of environments. It is also an example of how the cognitive variation actually influences and improves psychomotor performance. These variations are designed to enable users to perform psychomotor tasks under different types of cognitive load. The results suggest that practice with these variations as compared to simple psychomotor exercises can enable faster and higher volumes of learning.

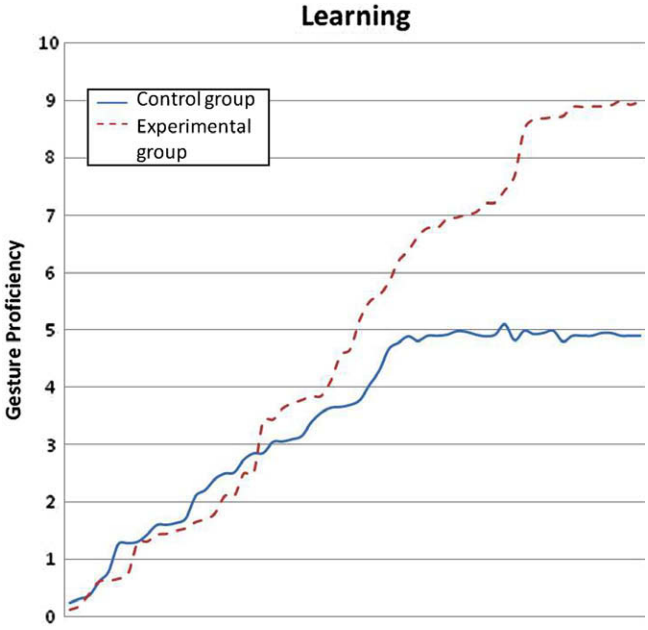

Fig. 4. Learning curves for experiment 2.

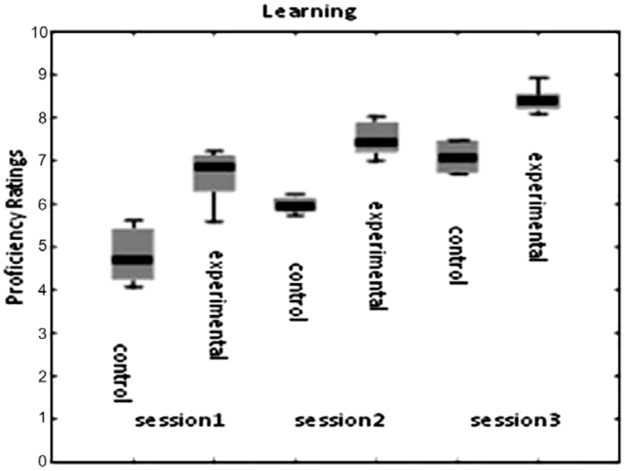

Fig. 5. Control group and experimental groups box plots in experiment 2.

The movement planning exercises showed the highest improvement over six learning trials. This result is consistent with the existing literature in cognitive science on improvements in movement planning with experience. The working memory on the other hand has shown to be of fixed capacity and hence only a limited amount of improvements are possible.

The experimental group was able to perform the task in lesser duration and with higher hand movement smoothness, tool movement smoothness and gesture proficiency. This comparison showed that skills learned by the cognitive exercises are able to produce higher proficiency in the procedural skills like diathermy when compared to conventional simulators.

These two experiments are presented as proof of concept that (a) cognitive simulators produce a learning effect, (b) cognitive simulators can distinguish between groups of different levels of expertise, (c) cognitive exercises produce a better learning effect than psychomotor simulators and (d) the learning produced with cognitive simulators can transfer to other types of sophisticated surgical procedures. While these results need to be verified with larger trials, the data clearly points to the validity of the simulator. The experiments also provide an example of how the generic methodology proposed in Section 3 is generalizable and can be applied to the development of cognitive simulators even with limited sensor, simulation and feedback modules. This is an important consideration in that it shows that sophisticated cognitive simulations can be developed without expensive sensing or presentation mechanisms.

6. Discussion

The above results suggest that cognitive simulators that are designed to challenge both cognitive and psychomotor resources of surgeons may offer adequate basis for effective training and evaluations. The presented system lays a generic methodology to include cognitive dimensions in surgical simulations. While presented for ring transfer, this methodology could be extended to other surgical exercises. The simulation designers' task revolves around choosing the right performance measures to include the development of cognitive and environmental variations and feedback systems for information presentation.

For example, let us consider another exercise called rope transfer in which a rope needs to be passed through an orifice. The sensor module could include a variety of psychomotor and cognitive measures. In the simulation module, including multiple orifices in the simulation can easily provide the variations that can measure and evaluate cognitive measures such as attention and working memory. In the case of more complex surgical tasks such as suturing and electrosurgery, dual task interference can be simulated through addition of noise to the simulations as an environmental factor. Another example of cognitive extensions would be including variations that require users to make surgical decisions. In one scenario, emphasis could be placed on development of simulations that require users to shift attention between multiple polyps to be treated using electrosurgery for accomplishing the goals of the exercise. In the simulation, each polyp will have an individual importance factor which will determine the order in which the subject needs to remove the polyp. Realistic behavior like rupture of polyps, blood loss or abnormal palpitations could be built into the simulations for allowing subjects to perceive if the polyp requires immediate attention. The simulations will require subjects to remove polyps of varying sizes requiring different level of expertise and different levels of attention (parameters of the haptic models can easily be adjusted to change the polyp density and size.) In another variation, the subjects could be exposed to a dual task scenario, where along with conducting electrosurgery the subjects will be required to perform another concurrent task such as to recall patients' vital signs and/or order treatment protocols for another patient. Additionally, such extensions of simulators could also be designed for complete procedures.

The importance of cognitive skills in surgery is an undeniable fact. Simulators that can hone cognitive skills as pertaining to laparoscopic surgery can have a beneficial impact. Such simulators can be built by designing simulators based on multitasking constructs. The proposed methodology builds on existing simulator hardware and software to add a layer of cognitive exercises in laparoscopic surgery that will challenge the residents' individual and combined cognitive faculty leading to better and faster learning. The proposed methodology also includes provisions for offering "embodiment training" wherein surgeons are encouraged to learn in realistic environments enabling a faster transfer to actual work environments. Future work in this direction will include the development of other types of cognitive simulators which will include environmental variations in the simulators. We will also include cognitive sensing mechanisms and work towards the development of a universal score that combines psychomotor and cognitive measures to realistically and objectively measure a surgeons' proficiency.

References

[1] ACGME. ACGME competencies: suggested best methods for evaluation [document on the Internet]. ACGME; 2000 Sept. [cited 2007 Dec. 12] Available from: http://www.acgme.org/Outcome/assess/ToolTable.pdf 2000.
[2] FLS. Fundamentals of laparoscopic surgery [Homepage on the Internet]. Los Angeles, CA: FLS Program; c2005 [cited 2007 Dec 12]. Available from: http://www.flsprogram.org/ 2005.
[3] Rosen J, Brown J, Chang L, Sinanan M, Hannaford B. Generalized approach for modeling minimally invasive surgery as a stochastic process using a discrete Markov model. IEEE Trans Biomed Eng 2006;53(3):399–413.
[4] HAPTICA. Haptica [Homepage on the Internet]. Dublin 2, Ireland: Haptica Ltd.; c2002–2007 [updated 2007 Nov 7; cited 2007 Dec 12]. Available from: http://www.haptica.com/ 2007.
[5] Immersion. Immersion [Homepage on the Internet]. San Jose, CA: Immersion Corporation; c2007 [cited 2007 Dec 12]. Available from: http://www.immersion.com/ 2007.
[6] Meti. SimMan [Homepage on the Internet]. Wappingers Falls, NY: Laerdal Medical; c2001–2007 [cited 2007 Dec 12]. Available from: http://www.laerdal.com/document.asp?docid=1022609. 2007 [cited; Available from: www.laerdal.com.
[7] Hall J, Ellis C, Hamdorf J. Surgeons and cognitive processes. British Journal of Surgery 2003;90(1):10–6.
[8] Spencer F. Teaching and measuring surgical techniques – the technical evaluation of competence. Bull Am Coll Surg 1978;63:9–12.
[9] Treves F. A manual of operative surgery. London: Cassell; 1891.
[10] Kohls-Gatzoulis J, Regehr G, Hutchisonm C. Teaching cognitive skills improves learning in surgical skills courses: a blinded, prospective, randomized study. Can J Surg 2004;47(4):277–83.
[11] Arocha J, Wang D, Patel V. Identifying reasoning strategies in medical decision making: a methodological guide. J Biomed Inform 2005;38:154–71.
[12] Meyer D, Kieras D. A computational theory of executive cognitive processes and multiple-task performance: I. Basic mechanisms. Psychol Rev 1997;104(1):3–65.
[13] Levy J, Pashler H. Is dual-task slowing instruction dependent? J Exp Psychol. Hum Percept Perform 2001;27(4):862–9.
[14] Ruthruff E, Hazeltine E, Remington R. What causes residual dual-task interference after practice? Psychol Res 2006;70(6):494–503.
[15] Lee A. Flight simulation: virtual environments in aviation. Hampshire, England: Ashgate Publishing, Ltd.; 2005.
[16] O'Shea S, Morris M, Iansek R. Dual task interference during gait in people with Parkinson disease: effects of motor versus cognitive secondary tasks. Phys Ther 2002;82(9):888–97.
[17] Kahol K, Smith M, Tripathi P, Ferrara J, Panchanathan S, Leibowitz A. Gesture based hand movement analysis and haptic feedback for surgical training (selected as best poster). Medicine Meets Virtual Reality, vol.14. CA: Long Beach; 2006.
[18] Gallagher A, Richie K, McClure N, McGuigan J. Objective psychomotor skills assessment of experienced, junior and novice laparoscopists with virtual reality. World J Surg 2001;25(11):1478–83.
[19] Gallagher A, Ritter E, Champion H, Higgins G, Fried M, Moses G, et al. Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training. Ann Surg 2005;241:364–72.
[20] Stefanidis D, Korndorffer J, Sierra R, Touchard C, Dunne J, Scott D. Skill retention following proficiency-based laparoscopic simulator training. Surgery 2005;138(2):165–70.
[21] The encyclopedia of philosophy. Embodied Cogn. Available from: http://www.iep.utm.edu/e/embodcog.htm 2007.
[22] Lezak M, Howieson D, Loring D. Neuropsychological assessment. New York: Oxford; 2004.
[23] Tiffin J. Purdue pegboard examiners manual. Rosemont, IL: London House; 1968.
[24] Miller G, Galanter E, Pribram K. Plans and the structure of behavior. New York: Holt; 1960.
[25] Mesulam M. Spatial attention and neglect: parietal, frontal and cingulate contributions to the mental representations and attentional targeting of salient extrapersonal events. Phil Trans R Soc Lond B 1998;354:1325–46.
[26] Laberge D. Attentional processing: the brain's art of mindfulness Boston: Harvard University Press; 1995.
[27] Kruschke JK. Attention in learning. Curr Trends Psychol Sci 2003;12(5):171–5.
[28] Miller GA. The magical number seven, plus or minus two: some limits on our capacity for processing information. Psychol Rev 1956;63:81–97.
[29] Cowan N. The magical number 4 in short-term memory: a reconsideration of mental storage capacity. Brain Behav Sci 2000;24:87–185.
[30] Lezak MD. Neuropsychological assessment. New York: Oxford; 1995.
[31] Barbara K, Nespoulous J. Working memory performance in expert and novice interpreters. Interpreting 2006;8(1):1–23.
[32] Hodge M. Factors affecting cognitive function in acute care nurses working 12 hour shifts. Abstr Acad Health Serv Res Health Policy Meet 2002;19:6.
[33] Hatwell Y, Streri A, Gentaz E. Touching for knowing: cognitive psychology of haptic manual perception. Amsterdam, Philadelphia: John Benjamins Pub; 2003.
[34] Kahol K, Balasubramanium V, Krishnan C, Panchanathan S, Smith M, Ferrara J. Measuring movement expertise in surgical tasks. 14th Annual ACM International Conference on Multimedia. CA; Santa Barbara; 2006. p. 719–22.
[35] Kahol K, Leyba MJ, Deka M, Deka V, Mayes S, Smith M, et al. Effect of fatigue on psychomotor and cognitive skills. Am J Surg 2008;195(2):195–204.