Cognitive-Task-Analysis and its Role in Teaching Technical Skills

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Introduction

New demands in surgical education over the past decade have brought a new set of challenges to academic surgeons. The limitations associated with the apprenticeship model, the pressure to perform more procedures in a cost efficient manner, the rising cost and unavailability of operating room time, an increased complexity of procedures and devices, fewer patients available for teaching and the initiation of the 80-hour work week restriction have all contributed to the need to re-evaluate traditional mentor-based instruction.

A significant barrier to the mentor-based model of teaching is that it relies primarily on experts to teach. Recent studies investigating the teaching of complex knowledge have uncovered that experts who teach and curricula based on expert knowledge unintentionally leave out about 70% of the information students need to learn and perform successfully (1,2,3). This is termed the “70% rule” and causes serious problems in medicine because it forces learners to ‘fill in the blanks’ by trial and error learning. There appears to be two reasons for this problem. First, as physicians gain expertise, their skills become automated and the steps of the skill blend together. Automated knowledge is achieved by years of practice and experience wherein the basic elements of the task are performed largely without conscious awareness (4). Expert physicians rely heavily upon a rich set of flexible rules and automatic, unconscious
decision processes that result in greater speed and efficacy (5) and frees up the working memory to handle novel events (4). This causes experts to omit specific steps when trying to describe a procedure because this information is no longer accessible to conscious processes (1,4,6). Second, many physicians are not able to share the complex thought processes that accompany the behavioral execution of technical skills. Even surgeons who make an attempt to “think-out-loud” during a procedure often omit essential information because their knowledge is automated. Cognitive psychology theory tells us that it is difficult to capture expertise and identify the essential moments of a procedure where an expert makes critical decisions (7).

Unfortunately, the teaching of novice surgeons is heavily dependent on training programs and instructional materials derived from experts in the field. The fact that experts have limited conscious awareness of cognitive decisions and procedural steps leads us to believe that the critical information essential to teaching technical skills is not effectively conveyed to learners in surgical skills training. A potential solution to this dilemma is the use of interview methods that capture the underlying knowledge and skills experts use to perform complex procedures. Known collectively as Cognitive-Task-Analysis (CTA), these techniques enable us to extract implicit and explicit knowledge from experts to inform surgical instruction.

**Cognitive-Task-Analysis**

Cognitive-Task-Analysis is a strategy that can be used to unpack the mental models of experts to elicit the automated knowledge required to perform a given task (7). CTA uses a variety of interview and observational methods to gain access to the
cognitive decisions goals, knowledge, and strategies that underpin observable task performance (8). There are many different methods of CTA and a detailed description of each is beyond the scope of this chapter. (For a comprehensive review see Cognitive Task Analysis by J. Schraagen, S Chipman and V Shalin, (Eds), Mahwah, NJ, Lawrence Erlbaum, 2000). Although commonalities can be found among all methods, they will vary with respect to how they elicit, analyze and represent expert knowledge. The most widely used methods involve a series of structured, unstructured, individual or group interviews with three to five subject matter experts. During the interviews, the cognitive task analyst asks the experts to describe the actions and decision steps of a specific task, including the decision alternatives and criteria for deciding among them. The analyst also asks a series of probing questions to capture the experts’ assessment of a situation, critical cues, metacognition and potential errors a novice might make. Following the interviews, the transcripts are analyzed, formatted, and verified by each expert. Multiple experts are interviewed in this manner to capture the maximum amount of information required to perform a given task. The results of the multiple CTA interviews are aggregated and put into a document that describes the task, the conditions for performing the task, necessary equipment and materials and a step-by-step protocol that includes both the action and cognitive decision points that were identified throughout the procedure.

CTA emerged in the early 1980s as an extension of traditional behavioral-task-analysis (BTA) (9). BTA has been in use since the beginning of the century and has been described as was one of the most important training innovations during the Industrial Revolution (4). During this time, industrial managers observed highly skilled workers
and documented the activities that were required to perform a variety of jobs related to manufacturing. Task protocols were developed to train inexperienced workers more quickly and effectively (4). Task analysis methods have been so successful that they laid the foundation for the development of training objectives (4) and, in many forms, are still in use today.

While BTA may be one of the most successful training innovations in the past century; it has its limitations. First, BTA was developed during the behavioral psychology era and founded on the assumption that behavior can be explained by a linear series of single stimulus-response [S-R] units (10). BTA focuses solely on the overt execution of the task, with little or no attention to the underlying cognitive decisions and processes that accompany each skill (4). Second, BTA was not designed to capture the behavior of individuals performing complex tasks that require problem-solving and trouble-shooting. Many surgical training programs today are rooted in a culture of BTA. Many curricula have moved towards a more structured approach to teaching technical skills and have developed specific objective checklists that outline each step of the procedure. The problem is that many of these checklists were developed using BTA techniques and focus primarily on skill performance with little attention to the complex cognitive decisions that are made throughout the procedure. Even surgeons who attempt to “think-out-loud” and try to recall and document each step and decision of a procedure, are often not able to accurately describe their own thought processes due to the automated nature of their expert knowledge. Although a BTA can be descriptive of the necessary steps involved in completing a complex task, they fail to provide the qualitative suggestions on how to complete the task. The complexity involved with performing
surgical procedures makes BTA obsolete as a method to capture expertise and create curricular content.

In summary, CTA techniques allow us to gain access to the cognitive strategies of experts and yield information about the thought processes and goal structures that underlie observable task performance. In addition, it allows us to deconstruct the automated skills of experts so that they are broken down into concrete measurable steps that learners understand. In essence, CTA provides us with information about how decisions are made and, more importantly, what information or cues are used by the expert to make those decisions.

**Types of Knowledge: Declarative and Procedural**

In order to understand the CTA process and potential benefits, we need to first understand the different types of knowledge involved in the development of expertise and how these knowledge types are interrelated. In this section we will define the two types of knowledge, declarative and procedural, and describe the role that each plays on the continuum from novice to expert.

Declarative knowledge is information about *why, what, or that* (4,11). It is knowledge of facts and found primarily in the conscious working memory (12). Declarative knowledge helps us handle novel events (4) and represents abstract facts (13). Declarative knowledge can be further divided into concepts, processes, and principles (4,8). Concepts help you understand what something is and how it is defined, processes help you understand how something works or what its stages or phases are, and principles help you understand cause and effect (8). Since most declarative knowledge is
characterized by its conscious quality, the act of retrieving declarative knowledge from one’s long term memory is slow and taxing (13).

Procedural knowledge is about how to do something and includes information about the execution of actions and decisions (4,11). Anderson (13,14) suggests that procedural knowledge is divided into production rules; simple encodings of observed transformations in the environment. These production rules specify when a cognitive act should take place and are informed by goals and subgoals (14). A fair amount of procedural knowledge is implicit and cannot consciously be recalled or explained (12). It is for this reason that experts may not be able to describe all the steps in procedure -- it has become automated and is no longer accessible to conscious processes (4). Over extended periods of time and practice, procedural knowledge becomes highly accurate, automated, rapid, and efficient within the context or domain in which it was developed (4). These newly non-conscious mental processes frees up working memory space to handle novel events (6). In addition, as people repeatedly solve the same type of problem, they not only increase the speed at which they solve the problem but they often come up with new problem-solving processes that combine or skip steps (15). The hallmark of procedural knowledge is that it operates outside of conscious awareness and executes much faster than conscious processes (4).

**Acquiring Expertise**

An understanding of declarative and procedural knowledge, and the relationship between the two, is essential to grasp how an individual acquires expertise. Nearly all knowledge comes into one’s memory in the declarative form (16). As an individual’s
schema regarding a task develops to a level of an expert, the declarative knowledge
transitions into procedural knowledge and becomes automated and therefore non-
conscious to the individual expert (17). Automated basic skill acquisition occurs in three
phases: cognitive, associative and autonomous (18). During the cognitive phase the
learner is a novice. The novice interprets new incoming declarative knowledge in an
attempt to carry out a goal. This phase is guided by trial and error and retrieval of
knowledge is labor intensive and effortful. As learners practice the skill they enter the
associative phase where steps of the procedure blend together and declaratives cues begin
to drop out. Finally, with repeated practice, the autonomous phase is reached. During
this phase the skill is fine-tuned, gains speed of execution and ultimately loss of
conscious access.

The transition of declarative knowledge into automated procedural knowledge
occurs through deliberate practice within a particular domain (4,19). Deliberate practice
is intense, highly structured and comprised of activities that have been found to be most
effective in improving performance (19). The number of hours spent in deliberate
practice determines the level of expertise (19); however, it is generally agreed that
expertise takes 10 or more years to develop (13,19). While declarative knowledge is
flexible and adaptable, procedural knowledge, once automated, becomes inflexible and
experts are often characterized as having rigid mental models. Experts are described as
people who have a high level of conceptual abstraction, solve problems deductively, have
superior working memory and apply automated procedures without conscious thought
20). Each of these aspects improves expert performance, leading to effectiveness and
efficiency within a domain.
Although experts have greater cognitive, technical, and reasoning skills, the automaticity that develops through repeated deliberate practice interferes with their ability to articulate these non-observable strategies. Research indicates that experts are unable to break down this non-conscious automated knowledge into discrete steps, and can omit up to seventy percent of critical actions and decision points when training novices (1). As mentioned previously, this is termed the “70% rule” (1, 6) and has been documented in the literature. Clark and colleagues (1) interviewed ten trauma surgeons and asked each to describe how to perform an emergency femoral shunt procedure. One surgeon was interviewed using a CTA protocol while the other nine provided an unaided description of the procedure (non-CTA). Results of the study indicated that the surgeon interviewed using the CTA protocol provided greater accuracy and completeness when compared to the gold standard, where as the other nine surgeons omitted nearly 70% of the essential steps and decisions. Similar findings were revealed by Sullivan and colleagues (3). In this study, three subject matter experts were videotaped teaching a colonoscopy procedure to second year surgical residents. The videotaped transcriptions were compared to a CTA-based gold standard protocol that was developed by the same three subject matter experts. Results indicated that the surgeons omitted an average of 65% “how to” steps and critical decisions when teaching the procedure to residents.

Another instructional limitation of expertise is that rigid mental models result in inaccurate recall of procedures (20). In the domain of medicine, it has been documented that the relationship between expertise level and recall is not linear. A consistent finding in clinical case representation studies is that an inverted U-shaped relationship exists (21). This has been termed the “intermediate effect” and supports the idea that teachers
at an intermediate level of expertise are better able to recall and articulate details of a
procedure better than a novice or an expert. Rikkers and colleagues (21) asked
neurologists, 2nd and 6th year medical students to diagnose, recall, and explain signs and
symptoms of four clinical cases. Results supported the “intermediate effect” and
demonstrated that the neurologists diagnosed the cases faster and more accurately than
the students; however the 6th year students remembered more information and produced a
more detailed explanation for the signs and symptoms than were described than both of
the other groups. This concept was further supported by Hinds (22) who found that
varying levels of expertise determined the effectiveness of instruction to meet the
educational needs of novices. Individuals with intermediate experience were better able
to accurately assess the experience of novices than experts. A later study by Hinds (23)
showed that trainees who received explanations from experts performed better on transfer
tasks than trainees who received their explanations from non-experts. The experts
provided explanations that were significantly more abstract and theoretically oriented
than those of the non-experts, so learners in the expert-to-novice instructional condition
were able to solve transfer problems more quickly and effectively than their counterparts
in the non-expert-to-novice instructional condition. However, conceptual knowledge
alone is insufficient for generating effective performance. The non-expert instructors in
the study provided more concrete, procedural explanations, which facilitated higher
performance by trainees when they attempted to perform the original target task. The
abstractions provided by the experts lacked key details and process information necessary
for optimal performance. This finding is consistent with many others in the training
literature suggesting that the most effective learning occurs when all necessary information is available to the learner in the form of instruction and/or prior knowledge.

To review, research has shown that while experts demonstrate superior performance in a specific domain, this expertise does not always translate into effective instruction for learners. Due to automaticity and rigid mental models, experts are not able to accurately recall or describe their thought processes and therefore have difficulty providing accurate instruction to novice learners. Surgeons are not immune to the difficulty associated with recall of expertise and the transference to instructional materials. With this in mind, it would seem that CTA may be an effective tool that can be used by surgical experts to capture the knowledge associated with performing complex procedures.

**Using Cognitive-Task-Analysis to Capture Expertise for Training**

CTA has emerged as a promising knowledge elicitation technique that can be applied to training programs. One of the essential features of CTA is its use of multiple experts to produce a complete mental model of a specific procedure. The effectiveness of using multiple experts was documented by Chao and Salvendy (2) when they systematically documented the rates at which experts omit cognitive skills from self-reports. Six expert programmers were asked to complete a series of challenging troubleshooting tasks, and all of their actions were recorded. The programmers were then asked to explain their decisions using a variety of different knowledge elicitation methods. No single expert was able to report more than 41% of their diagnostic actions, 53% of their debugging actions, or 29% of their interpretations, regardless of the
knowledge elicitation method used. However, when the researchers began compiling the elicited explanations from different experts, they found that the percentage of actions explained increased. When explanations from all six experts were aggregated, the percentages of verbalization for each category of actions increased to 87%, 88%, and 62%, respectively. The improvement in information elicited reflects the experts’ individual differences in which sub-goal productions had been automated to greater and lesser extents.

In the medical arena, CTA has been proven to be an effective method to elicit expert knowledge not captured by other means. In 1993, Crandall and Getchell-Reiter (24) investigated the procedural knowledge of expert nurses specializing in neonatal intensive care for newborn or premature babies. The participants were 17 registered nurses who averaged 13 years of overall experience and 8.1 years of specialization. The nurses were asked to provide an un-aided (non-CTA) recall detailed accounts of critical incidents they had experienced or measures they had implemented which they believed had positively influenced an infant’s medical condition. The nurses were asked to be as specific as possible about the assessment parameters, diagnostic cues, and clinical judgments that they used in the incident. After completing the free recall phase, the researchers used CTA to identify additional relevant information that the nurses did not articulate. Analysis of the transcripts revealed that the CTA probes elicited significantly more indicators of medical distress in the babies than were otherwise reported. Before CTA, the nurses’ explanations of the cues they used were either omitted or articulated vaguely. In contrast, 25 of the 70 diagnostic cues identified through CTA that were important in the nurses’ diagnosis of problems had not been reported during free recall.
Comparison of the elicited cues to those articulated in available medical and nursing training at the time revealed that more than one-third of the cues used by expert nurses to correctly diagnose infants were not included. These cues spanned seven previously unrecognized categories that were subsequently used to train novice nurses entering neonatal intensive care (25).

**Evidence for CTA-Based Instruction**

Research evidence indicates that the accurate identification of experts’ cognitive processes through CTA can be adapted into training materials that are substantially more effective than those developed through other means. For example, Schaafstal and colleagues (26) compared the effectiveness of a pre-existing training course in radar system troubleshooting with a new version generated from cognitive task analysis. Participants in both versions of the course earned equivalent scores on knowledge pretests. However, after instruction, students in the CTA-based course solved more than twice as many malfunctions, in less time, as those in the traditional instruction group. In all subsequent implementations of the CTA-based training design, the performance of every student cohort replicated or exceeded the performance advantage over the scores of the original control group.

Merrill (27) compared CTA-based direct instruction with a discovery learning (minimal guidance) format and a traditional direct instruction format in spreadsheet use. The CTA condition provided direct instruction based on strategies elicited from a spreadsheet expert. The discovery learning format provided authentic problems to be solved and made an instructor available to answer questions initiated by the learners. The
traditional direct instruction format provided explicit information on skills and concepts and guided demonstrations taken from a commercially available spreadsheet training course. Scores on the posttest problems favored the CTA-based instruction group (89% vs. 64% for guided demonstration vs. 34% for the discovery condition). Further, the average times-to-completion also favored the CTA group. Participants in the discovery condition required more than the allotted 60 minutes. The guided demonstration participants completed the problems in an average of 49 minutes, whereas the participants in the CTA-based condition required an average of only 29 minutes.

In an extensive meta-analysis, Lee (28) demonstrated the effectiveness of CTA-based training and performance-improvement studies in a variety of organizations that focused on different types of tasks. She reported an overall median percentage of post-training performance gain effect size of 1.72 (an average increase of 44% on outcome performance measures) for CTA-based instruction when compared to more traditional instructional design using behavioral task analysis. Most outcome measures reviewed emphasized application of learning rather than recall or recognition tasks.

Although in an infancy stage, there is evidence that CTA-based instruction is effective in the surgical domain. In 2004, Velmahos, et al. (29) performed a prospective randomized controlled study investigating the effectiveness of a CTA-based course to teach central line placement to surgical interns. Twenty six interns were randomly assigned to either a CTA-based course or to the control group. Scores on the pre-test indicated equivalency of groups. Results revealed that the CTA-based group outperformed the control group on the knowledge post-test and the 14-item procedural checklist. In addition, the CTA group required fewer attempts to find the vein and
trended toward less time to complete the procedure. A similar study design was followed by Sullivan and colleagues (30) comparing CTA-based instruction to traditional methods while teaching percutaneous tracheostomy placement amongst PGY 2-4 surgical residents. Results indicated that the CTA group performed significantly better than the control group on the procedural checklist at one month and at six months post-instruction. In addition, the CTA group demonstrated cognitive strategies during the “think-out-loud” assessment protocols that were significantly superior to those of the control group.

In 2008, Luker et al. (31) investigated the effectiveness of a CTA-based multimedia program to teach surgical decision making. Ten plastic surgery residents were instructed how to perform a flexor tendon repair using traditional and CTA-based instruction. Residents were evaluated upon three occasions. Traditional instruction took place between the first and second trial and served as the control. CTA-based instruction was then introduced as an intervention between the second and third trial. Results indicated that after being trained using the CTA-based instruction the residents showed a statistically significant improvement in decision-making skills.

**Implications for Surgical Programs**

CTA is a method for capturing highly complex performance expertise where many covert decisions are linked with difficult overt actions. The use of CTA has the potential to improve current surgical training methods in four tangible ways. First, CTA allows us access to the covert cognitive strategies that expert surgeons utilize during procedures. In our education programs, little attention is paid to the complex thought processes that accompany the behavioral execution of technical skills. Many of the
checklists and training materials used in surgical education are developed using BTA methods. BTA may overlook the hidden cognitive aspects of a task and may oversimplify a complex task (4). Now that we are in the cognitive psychology era we have the means to access the cognitive components of procedural skills.

Second, CTA provides a method to deconstruct the automated procedural skills of experts so that they are more easily understood by the resident (4). As a surgeon develops expertise, the procedural steps of a task become blended and automated. Expert physicians rely heavily upon a rich set of flexible rules and automatic, unconscious decision processes that result in greater speed and efficacy (5) and frees up the working memory to handle novel events (4). As mentioned previously, due to this automaticity, experts leave out up to 70% of essential information that novice surgeons need to learn procedural skills (1). CTA allows us to dissect out the procedure into concrete measurable steps that residents understand.

Third, CTA can increase the learning curve and accelerate the acquisition of expertise (4,32) by giving students access to all of the knowledge types they need in order to successfully and efficiently accomplish a task or implement a procedure. It has been shown that training programs that have utilized CTA methods have been able to decrease the training time and improve the performance of tasks (4,32). One of the most dramatic claims was made by Means and Gott (32) who speculated that the equivalent of five years of job knowledge could be transmitted in 50 hours of training based on CTA.

Lastly, CTA can be used to develop curricular content; decreasing the need for training to rely solely on experts. With information acquired from surgical experts, CTA can be used to construct curricular modules for use in surgical education. These modules
can then be given to junior faculty to assist with teaching procedural skills by providing them with an outline of each step of the procedure and the critical decision points that need to be discussed with the learners. This will allow learners to develop the needed conceptual understanding of the task and begin formulating the procedural steps and decision points. By applying CTA to surgical procedures, we can focus instruction on the decision-making steps and component parts of a procedure that differentiate an expert from a novice surgeon.

**Limitations of CTA**

Although there are clear benefits to using CTA methodology; there are also limitations. Clearly the biggest barrier is the time involved with conducting a CTA. The manpower required to design, conduct, and participate in a CTA can be demanding. The time commitment involved depends on the number of experts that must be interviewed, the CTA expertise of the interviewer, and the complexity of the decision steps that characterize the knowledge being captured (4). It has been estimated that the capturing of one hour of focused expertise requires about 30-35 hours of effort of trained CTA designers (4). Although one can speculate that the upfront efforts invested to conduct a CTA translate in less faculty time on the back end, there are very few studies that investigate the cost/benefit analysis of CTA methodology. In the seminal article by Clark and Estes (4), Clark describes the results of a cost-effectiveness study of CTA methods that he performed within a European company. Clark designed a new training course for managers based on CTA methodology. The original course continued to be offered to managers and served as the comparison group. The objectives for both courses were
identical. The old course required two days for managers to complete, while the new CTA course required only one day attendance to achieve the same performance results. Clark concluded that the overall financial benefit obtained from the CTA course was estimated to be equivalent to 2.5 years of an average manager’s salary.

Another limitation to applying CTA to surgical training is that there are very few individuals trained to conduct CTA studies and design instructional materials to inform surgical skills training. In addition, there are very few resources available that describe how to conduct a CTA in a step-by-step fashion. The current method of gaining CTA experience is through traditional mentor-based instruction.

Summary

As the demands in surgical education continue to rise and we are faced with the economic and developmental pressures to limit the length of training in many specialty programs, CTA may serve as an important tool to improve instruction regarding surgical skill training. Traditional methods for educating novice surgeons has created a culture for teaching and learning that is rooted in behavior task analysis, and that has relied on experts to teach. Current research efforts have highlighted the fact that these methods may omit essential information that novices need to perform complex tasks. CTA was first developed to facilitate the rapid and effective acquisition of expertise in complex cognitive technical skills; surgery is arguably one of the most, if not the most, domains where complex technical skills are required. The time is right for the surgery and educational psychology field to unite and develop a collaborative research effort to capture expert decision making and cognitive strategies, use the information to inform
surgical skills training, and evaluate its effectiveness. Although CTA can be time
intensive, the insights and information that can be gained may make the effort worth the
investment.
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