Cognitive load theory as a framework for simulation-based, ultrasound-guided internal jugular catheterization training: Once is not enough

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CLINICIAN'S CAPSULE

What is known about the topic?
Cognitive load theory can be used to guide simulation-based training for procedural skills.
What did this study ask?
How can cognitive load theory be used to overcome the challenges of learning ultrasound-guided internal jugular catheterization?
What did this study find?
All trainees approached or exceeded expert benchmarks, with evidence of retention over time.
Why does this study matter to clinicians?
This curriculum may better prepare trainees for performing this important procedure in the clinical setting.

ABSTRACT

Objective: The main objective of this study was to use the principles of cognitive load theory to design a curriculum that incorporates a progressive part practice approach to teaching ultrasound-guided (USG) internal jugular catheterization (IJC) to novices. A secondary objective was to compare the technical proficiency of residents trained using this curriculum with the technical proficiency of residents trained with the current local standard of a single simulation session.
Methods: The experimental group included 16 residents who attended three 2-hour sessions of progressive part practice in a simulation lab. The control group included 46 residents who attended the current local standard of a single 2-hour simulation session just prior to their intensive care unit rotation. Technical proficiency was assessed using hand motion analysis and time to procedure completion.
Results: After three sessions, median scores for right hand motion (RHM) (34.5; [27.0-49.0]), left hand motion (LHM) (35.5; [20.0-45.0]), and total time (TT) (117.0 s; [82.7-140.0]) in the experimental group were significantly better than the control group ($p<0.001$). Results for eight experimental group residents who were assessed for retention at a later date revealed median scores for RHM (45.0; [32.0-58.0]), LHM (33.5; [20.0-63.0]), and TT (150.0 s; [103.0-399.6]), which were significantly better than those of the control group ($p=0.01$, $p<0.01$, and $p=0.02$, respectively).
Conclusion: These results support multiple sessions of progressive part practice in a simulation lab as an effective competency-based approach to teaching USG IJC in preparation for the clinical setting.

RÉSUMÉ

Objectifs: L'étude avait pour objectif principal d'appliquer les principes de la théorie des capacités cognitives dans l'élaboration d'un programme d'apprentissage visant à intégrer la méthode de la pratique progressive-fractionnée à l'enseignement du cathétérisme échoguidé de la jugulaire interne (JI) à des débutants. L'étude avait également pour objectif secondaire de comparer la compétence technique des résidents formés selon le nouveau programme avec celle des résidents formés selon la formule habituelle d'enseignement, appliquée à l'échelle locale, consistant en une seule séance de simulation.
Méthode: Le groupe expérimental comptait 16 résidents, qui ont participé à 3 séances de pratique progressive-fractionnée, de 2 heures chacune, dans un laboratoire de simulation; le groupe témoin, quant à lui, comptait 46 résidents, qui ont participé à 1 seule séance de simulation, d'une durée de 2 heures, juste avant leur stage au service de soins intensifs, selon la méthode habituelle d'enseignement. L'habileté technique des participants a été évaluée à l'aide d'une analyse des mouvements de la main et du temps d'exécution de l'examen.
Résultats: Après 3 séances de formation, les résultats médians relatifs aux mouvements de la main droite (MMD) (34,5 [27,0-49,0]), à ceux de la main gauche (MMG) (35,5 [20,0-45,0]) et au temps total d'exécution (TT) (117,0 s [82,7-140,0]) dans le groupe expérimental étaient significativement

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meilleurs que ceux obtenus dans le groupe témoin ($p < 0{,}001$). Par ailleurs, 8 résidents dans le groupe expérimental, soumis à une évaluation de la capacité de rappel des gestes à une date ultérieure, ont obtenu les résultats médians suivants: MMD (45,0 [32,0-58,0]), MMG (33,5 [20,0-63,0]) et TT d'exécution (150,0 s [103,0-399,6]); ces chiffres sont nettement meilleurs que ceux enregistrés dans le groupe témoin ($p = 0{,}01$, $p < 0{,}01$ et $p = 0{,}02$, respectivement).

Conclusion: Les résultats obtenus confirment l'efficacité des séances fractionnées de pratique progressive, en laboratoire de simulation, comme méthode d'enseignement du cathétérisme échoguidé de la JI, axée sur les compétences, en vue de la préparation des étudiants au milieu clinique.

Keywords: cognitive load theory, competency, medical education, simulation

INTRODUCTION

In recent years, simulation has emerged as an important educational tool that is being used to improve training and enhance patient safety.[1,2] With the growth and widespread adoption of simulation, there has been a call for research to move from "Does it work?" to "How does it work?" – along with a call for curricular design that is supported by a contemporary learning theory.[3,4] Cognitive load theory (CLT) provides a useful conceptual framework for understanding learning processes and can be used as a guide for teaching procedural skills in the simulated setting.[5,6] In this paper, CLT is used to describe the challenges inherent in learning ultrasound-guided (USG) internal jugular catheterization (IJC), and to explain the rationale for using a progressive part practice approach to learning this important critical care skill.

CLT is based on a model of human memory where learning is a process of forming schemas in long-term memory (LTM) and, with practice, of moving learned procedures from conscious to automatic processing.[7] A schema is a cognitive construct that allows information to be organized in a meaningful way, and schema development and transfer of skills from controlled to automatic processing is considered the most important determinant of expertise in any skill.[8] Under CLT information enters the mind through the sensory memory system and, if raised to awareness, is processed in working memory (WM), where it is encoded into schemas that are stored in LTM. A central assumption of CLT is that learning will be impaired if the total cognitive load of a task exceeds the individual's WM capacity.[5]

Three sources of cognitive load are identified in CLT: intrinsic load, extraneous load, and germane load.[5] Intrinsic load refers to the cognitive demands specific to learning a task and depends on the complexity of the task and the learner's level of skill for the task. It is important to note that, while the complexity of a task is relatively static, a learners level of skill will change over time with practice. Compared to a true novice, a learner with previous exposure to a procedure will have a pre-existing schema that reduces the intrinsic load that they experience while performing that procedure. It follows that the intrinsic load experienced by an individual learner for a given task can be expected to decrease over time with practice and automation of schemas.[5]

Extraneous load occurs when demands on WM are increased by the design of the educational format, but learning is not enhanced.[5] Noisy environments, poor lighting, and poor equipment setup can all contribute to extraneous load and impair learning. Finally, germane load refers to WM resources that are required to process the intrinsic load but which enhances the acquisition and automation of a schema.[8] For example, specific tasks like asking a learner to pause and visualize the precise position of a needle in tissue will increase total cognitive load, but can have the effect of enhancing schema formation.

The main objective of this study was to use the principles of CLT to design a curriculum that incorporates a progressive part practice approach to teaching USG IJC to novices. The curriculum includes three sessions of progressive part practice, with the goal of titrating the intrinsic cognitive load to match the evolving demands on the WM of novice learners as they become more proficient over time. A secondary objective was to compare the technical proficiency of residents trained using this curriculum with the technical proficiency of residents trained with the current local standard of a single simulation session, and to look for evidence of retention over time.

METHODS

Study population

The study population included postgraduate years 2 and 3 residents in the Departments of Family Medicine, Surgical Specialties, Internal Medicine, Obstetrics and

Gynecology, Emergency Medicine, and Anesthesiology at Queen's University in Kingston, Ontario, Canada. The study took place in 2015 and 2016 in the Faculty of Health Sciences Clinical Simulation Centre, and targeted residents who were scheduled to do an intensive care unit (ICU) clinical rotation as part of their training. Residents were excluded if they did not attend either the course described in this study or one of the introductory USG IJC training sessions offered by the ICU.

Study protocol

All residents in the experimental (E) group completed three 2-hour training sessions, with 2 weeks off between sessions. Regular assessment using hand motion analysis (HMA) and total time (TT) to procedure completion of the E group residents was used to monitor technical proficiency. All residents in the control (C) group were similarly assessed for technical proficiency at the end of their single ICU training session. Eight out of 16 E group residents also attended one of the ICU training sessions at some point (range 1-10 months) after their three sessions of training. Their results were analysed separately to look for evidence of skill retention over time. Eight of 16 E group residents were excluded from the retention group because they were not scheduled for their ICU rotation during the study period.

Curriculum

The curriculum (Figure 1) included advance preparation through online videos, online reading materials, and pre-tests. The advance preparation was intended to reduce the cognitive demands of the sessions by limiting the need for a discussion of background knowledge.

The entire sequence of USG IJC was segmented into part tasks that were learned and practiced in a progressive fashion. Each of the part tasks was intended to introduce new information the learners would need to process and practise, but was felt to represent a manageable cognitive load that would not overwhelm their WM.

Learners were introduced to basic US skills and needle guidance on a femoral model. The vessels in the femoral model are considerably deeper than those in the IJ model, and so they allow more opportunity to practise precise needle tip guidance through tissues. All practices and assessments were done using Blue Phantom™ and Simulab™ femoral and internal jugular training phantoms.

Hand motion analysis

HMA can be used to provide valid, reliable, and objective measures of technical proficiency in skill-based training programs by capturing the number of hand movements during the performance of a procedure.[9,10] It has been shown to be a feasible and valid way of measuring technical proficiency in USG IJC insertion and USG peripheral nerve blockade.[11,12]

The HMA hardware consisted of a TrakStar electromagnetic field generator and control box (Ascension, VT, USA), one reference sensor, and two hand sensors (Model 800, 7.9 mm, 6-DOF). Three-dimensional pose data from the electromagnetic sensors were acquired using the PLUS (www.PlusToolkit.org) open-source software. Perk Tutor (www.perktutor.org), an open-source image-guided interventions training platform for 3D Slicer (www.slicer.org), was used to record the poses of all sensors, analyse the recorded data, and compute the HMA metrics.[13]

Data collection

Self-reported prior experience with USG central venous catheter (CVC) insertion was collected at the beginning of session one for the E group, and prior to the training session for the C group. Data for prior experience for one of the C group residents were missing and thought to be because that individual failed to complete the form.

HMA data collection started with the resident holding the US probe and syringe ready to visualize the vessels and insert the needle, and ended when the catheter was in the vein and the guide-wire removed. The total number of hand motions for each hand was determined as the number of distinct time periods in which the hand's translational or rotational velocity exceeded 50 mm/s or 50 degrees/s, respectively.

Baseline HMA data were collected for all residents in the E group. Subsequent measures of HMA were made at the end of session one and the beginning and end of sessions two and three. HMA was collected at the end of the single training session for all residents in the C group and the eight E group residents who attended one of the ICU training sessions.

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Advance preparation session 1:

- Online reading and review of video
- Online pre-test

Session 1 summary:

- In class pre-test
- Basic US instruction and probe handling practice

Practice on femoral vein model:

- Advance needle tip (NT) into center of US beam while interpreting image on screen (5).
- Advance NT into US beam, slide probe ahead of NT, advance NT into beam (5).
- Using a sliding and advance technique, guide the NT into the femoral vein (5).
- Advance the NT into vein, insert guide-wire, and confirm with US (5).

Practice on internal jugular model:

- Advance the NT into vein (5).
- Advance the NT into vein, insert guide-wire,and confirm with US (5).
- Advance the NT into vein, guide-wire insertion and confirmation, vessel dilation, and catheter insertion (5).

Advance preparation session 2:

- Online reading
- Online pre-test

Sessions 2 and 3 summary:

- In class pre-test (session 2 only)

Practice on femoral vein model:

- Gown, glove, tray preparation, and sterile draping for femoral CVC insertion(1).
- Advance NT into vein, insert guide-wire, and confirm with US (10).

Practice on internal jugular vein model:

- Gown, glove, tray preparation,and sterile draping for IJ CVC (1).
- Advance the NT into vein, insert guide-wire, and confirm with US (10).
- Advance the NT into vein, guide-wire insertion and confirmation, vessel dilation, and catheter insertion (10).
- Practice suturing catheter in place on a part task trainer (5).

( ) = number of repetitions.

Figure 1. USG IJC progressive part practice curriculum.

Data analysis

All analyses were conducted using SPSS Statistic software. The Shapiro-Wilk test revealed non-normal distribution of values ($p < 0.01$), therefore the Mann-Whitney U test was used to compare the groups. The results for right hand motion (RHM) count, left hand motion (LHM) count, and procedure time for the end of session one for the E group were statistically compared to the results for the C group.

The end-of-training results for the E group were similarly compared with those of the C group. The results for the E group residents who returned for the ICU training were compared with those results of the C group to see whether there was evidence of retention. The statistical level of significance was set at $\alpha = 0.05$.

The study was approved by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board. Signed consent of voluntary enrolment was obtained from each participant.

RESULTS

Study participants

All eight postgraduate year 2 residents from the Department of Emergency Medicine, seven of eight postgraduate year 2 residents from the Department of Anesthesiology, and one postgraduate year 3 resident from our College of Family Physicians of Canada Emergency Medicine (CFPC-EM) program were enrolled in the E group during the study period. A total of 77 residents from other specialties were scheduled to do an ICU rotation during the study period. Thirty-one were excluded for not attending one of the introductory USG IJC training courses, and the remaining 46 were enrolled in the C group. Reasons for non-attendance included lack of a training session during their introduction to the ICU, and absence from the course for personal reasons. One expert, who is a co-author (NR) and was a Critical Care Fellow during the study, set the HMA and TT benchmarks.

Survey results

Self-reported prior experience (Table 1) revealed a wide range of experience with a CVC insertion in the real and simulated settings for both the E and C groups. In general, the C group appeared to have more experience than the E group. The eight E group residents who returned for the ICU training session were asked to report their experience with USG CVC (IJ and femoral) in the clinical setting since course ended. Individual residents reported performing 1, 1, 1, 3, 6, 12, 13, and 55 procedures.

HMA results

After a single 2-hour session, there was no significant difference between the E and the C groups for median number of RHM (50.0; [30.0-164.0] v. 61.0 [31.0-197.0], respectively; $p = 0.11$), for median number of LHM (49.0 [30.0-91.0] v. 50.5 [23.0-107.0], respectively; $p = 0.75$), or for median TT (187.1 s [96.7-546.1] v. 217.0 s [94.7-660.2], respectively; $p = 0.35$). At the end of the third session, the results of the E group for RHM (34.5 [27.0-49.0]), LHM (35.5 [20.0-45.0]), and TT (117.0 s; [82.7-140.0]) were all tightly clustered around the expert benchmark and were significantly better than the results for the C group ($p < 0.01$). The results for the E group after their ICU training session were consistent with skill retention; RHM (45.0 [32.0-58.0]), LHM (33.5 [20.0-63.0]), and TT (150.0 s [103.0-399.6]), as they remained clustered around the expert benchmark and were significantly better than the C group ($p = 0.01$, $p < 0.01$, and $p = 0.02$, respectively).

To illustrate progression of technical proficiency over time, and to compare data between groups, Figure 2 plots the total of RHM and LHM for individuals in E group training sessions, the C group training sessions, and the E group residents who returned for an ICU training session.

DISCUSSION

The central premise guiding the design of this curriculum is that novices faced with the entire sequence of tasks for USG IJC will likely experience a total cognitive load that will exceed their WM capacity, in which case learning will be impaired. With this in mind, the procedure was segmented into part tasks to manage the intrinsic cognitive load experienced at key points in the

Table 1. Prior experience with CVC insertion

CVC insertions	Experimental (N = 16)	Control (N = 45)
Male/female	8/8	26/19
Observed, simulated or real, mean (range)	8 (2-16)	14 (0-50)
Performed, simulated or real, mean (range)	6 (0-21)	15 (0-90)
Total CVC insertion experience, mean (range)	14 (2-35)	29 (0-140)

CVC = central venous catheter

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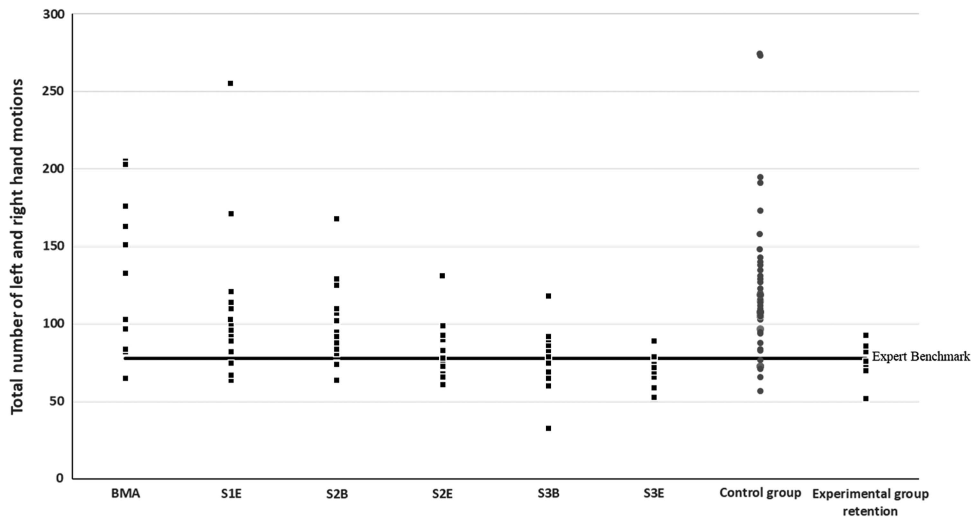

Figure 2. Total number of left and right hand motions. BMA = baseline motion analysis at the beginning of session one; S1E = end of session one; S2B = beginning of session 2; S2E = end of session two; S3B = beginning of session three; S3E = end of session three.

procedure. With practice, we expected individual part tasks to be encoded as part of a schema in LTM and become increasingly automatic, which would have the effect of reducing the intrinsic cognitive load experienced by learners for that part of the procedure. This would then open up WM for the progressive addition of new elements of the procedure until the learner eventually incorporates all of the skills of the procedure into a single schema.

The first part task (see Figure 1) in the curriculum was designed for the learners to become proficient with US image acquisition and interpretation. For a novice learner, there is actually a number of components to this fundamental US skill that is new information that has to be processed in WM for learning to occur. The probe must be held with correct right-to-left orientation and aligned over the centre of the vessel while learners simultaneously interpret what they are seeing on the screen. In our experience, the cognitive load associated with image acquisition and interpretation is high for novices, and so this skill is practised in isolation to the point of proficiency before adding additional elements.

The second part task (see Figure 1) of advancing a needle into the plane of the ultrasound beam introduces a number of novel elements to the procedure. As well, an important determinant of intrinsic load that needs to be considered at this point is element interactivity, and this is particularly relevant for USG procedures.[5] The intrinsic load of simultaneously operating the probe and the needle, while interpreting the US image, is amplified by the interaction between the three skills. For example, if the operator is confident that correct probe position was maintained throughout needle advancement, and the needle tip appears in the wrong place on the screen, cognitive resources can be focused exclusively on adjusting needle orientation. If, however, the error could have been a result of probe position and/or needle orientation, the number of options to consider for the source of the error increases dramatically and can easily overwhelm the WM of a novice learner. It is for this reason that we have residents spend considerable time practising probe position and manipulation in isolation throughout the curriculum.

Figure 2 illustrates the proficiency of the E group over time in terms of the total number of RHM and LHM. Over the three sessions, there are three key observations: firstly, the initial data show a wide range of proficiency; secondly, the learning curve flattens out by the third session, suggesting that gains from further practice will be limited; and, finally, by the end of the third session, all of the residents are tightly clustered around the expert benchmark. The three sessions of progressive part practice enabled all residents, regardless of previous experience or technical aptitude, to achieve a level of technical proficiency that approached or exceeded the expert benchmark.

The results for the C group are shown to the right in Figure 2, as well as the results for the E group residents

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who returned for the ICU training. The results for the returning E group residents remain tightly clustered around the expert benchmark, showing retention of skill, and the median score of this group is significantly better than that of the C group. The C group exhibits a wide range of scores, with several extreme outliers.

While we have not shown in this study that the E group residents are actually better prepared than the C group for performing USG IJC in the clinical setting, the HMA and TT results clearly show that, as a group, they are more proficient with the fundamental skills of the procedure. With the transition to the clinical setting, residents from both groups are expected to experience an increase in total cognitive load while performing this procedure as a result of variables like patient movement and concern for the overall clinical status of the patient. We believe that a resident with a well established and automated schema for USG procedures is more likely to have the WM capacity to manage the increased cognitive load of the clinical environment. A resident who is still experiencing a large cognitive load in association with the basic skills of USG procedures is less likely to have the WM capacity to manage the realities of the clinical environment, in which case we would expect the resident's learning and performance to be impaired.

In keeping with the goals of competency-based medical education, the three 2-hour sessions of progressive part practice enabled all residents, even ones who were markedly weak at the beginning of training, to achieve a high level of proficiency by the end. If we accept the level of proficiency demonstrated by the E group residents as evidence that they are better prepared to safely make the transition to patients, we can then argue that multiple sessions of progressive part practice serve as an effective approach to teaching this important critical care skill to novices.

Limitations

In this study, the E group has a small sample size and includes residents from only specialties that have a strong procedural bias. It is therefore not clear that these results would generalize across a larger group of residents, or residents from other specialties. Based on our survey, participants entered the study with a wide range of previous exposure to central line training but were not asked about the specifics of prior training. This limits our understanding of baseline characteristics of both groups, which limits our ability to generalize these results to other groups of trainees. As well, we acknowledge that we did not follow the C group's performance beyond the single training session, and it is possible that with continued practice they could have achieved the same level of proficiency.

CONCLUSION

Using a CLT framework, we have designed an effective simulation-based curriculum for teaching the skills of USG IJC to novices. All residents trained with this curriculum demonstrated a high level of technical proficiency, and there was evidence of retention over time. These results support multiple sessions of progressive part practice in a simulation lab as an effective competency-based approach to teaching USG IJC in preparation for the clinical setting.

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