Designing an Interactive Visualization of Ventriculostomy for General Surgeons in Austere Areas

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SUMMARY

Physicians and position extenders located in austere, rural, and other resource limited areas must be able to perform a variety of emergency procedures to limit mortality associated with the increased time between injury and higher-level treatment at a robust facility. To help reduce skill attrition, there is a need for educational resources for medical professionals who may need to perform neurosurgical techniques at a moment's notice. This study aimed to address the gap in research associated with the informed development of neurosurgical teaching applications for physicians and position extenders working in austere and rural areas.

Here, we examine how an educational resource for the ventriculostomy procedure can be designed to take into consideration the limitations of working in an austere environment, varied education of learners, and the necessity to encourage long term retention of the procedure. This investigation aimed to provide insight into the development of teaching tools for medical professionals working in austere and rural areas and add to the body of educational resources available to surgeons and practitioners for review.

INTRODUCTION

A. Overview of research problem

Medical professionals located in austere, rural, and underserved areas hold a unique role in healthcare. They must be able to perform several emergency procedures that would normally fall outside of their expectations of care with precision and confidence. When robust hospital systems and specialized physicians are far away or difficult to access, medical professionals must focus their efforts on damage control treatment, or the treatment of injuries and illness with the goal of limiting mortality and further injury, in order to combat the increased time it may take to reach more advanced health care.

In advanced hospital systems, neurosurgery is reserved for specialized surgeons with extensive and specific education in neurosurgery. In cases of emergency in austere and rural areas, however, emergency neurosurgery must often be performed by non-neurosurgeons (Atiyeh et al., 2010). Traumatic brain injuries can happen at any time, and medical professionals must know how to manage these types of injures to limit mortality and secondary brain injury.

B. Significance of the problem

Medical professionals on the front line of emergency healthcare must know an extensive number of procedures and be able to perform them quickly and effectively in a variety of situations. In reality, physicians and surgeons do not encounter every possible procedure regularly and are thus unable to routinely practice less common procedures. To help reduce skill attrition, there is a need for educational resources for general surgeons, physicians, and position extenders who may need to perform neurosurgical techniques in austere environments at a moment’s notice.

LITERATURE REVIEW

1. Austere Environments

Where resources are plentiful and geographically nearby, it is standard procedure to transport injured and critically ill patients rapidly to a hospital for definitive care, usually by means of an ambulance. According to Fang et al. (2015), “such rapid evacuation may not be feasible in the military setting for reasons to include long transport distances, ongoing combat actions, non-availability of evacuation assets, or mission goals superseding casualty movement" (p. 183). During a deployment, soldiers are often in austere areas where transportation is not only difficult but potentially unsafe (Chalela & Britell, 2019). This situation has helped to form the concept of damage control neurosurgery. As described by Rubiano et al. (2019), damage control neurosurgery is “an abbreviated urgent neurosurgical procedure [intended] to help prevent secondary brain injury, assist in stabilizing the patient, and improve patient survival and outcome”(p. 84). Military surgeons are not often intending to provide definitive care, but only to provide enough care so that soldiers can survive the potentially long and arduous transport process of getting to an upper-level treatment center (Rubiano et al., 2019).

The United States Military recognizes the “occasional need for certain non-neurosurgeons (usually general surgeons) to perform cranial procedures in the far forward setting” (Gurney et al., 2020, p. 151). Within the context of a deployment, neurosurgery is not necessarily performed by traditionally trained neurosurgeons but rather general surgeons who have been specifically trained in emergency techniques (Gurney et al., 2020).

To create a learning tool catered toward general surgeons in the harsh austere environment of military deployment, the environment and how it affects treatment protocol must be considered. Soldiers undergo direct exposure to the elements which is often unconducive to keeping fragile technology safe from water, soil, and damage. As stated by Chalela and Britell (2019), “operational constraints, the tactical environment, and resource availability dictate that tactical neurocritical care be practiced within a well-defined, mission constrained framework” (p. 254). While civilian healthcare faces problems directly associated with the care of the patient, military surgeons must face the tactile challenge of performing surgery in a harsh environment with few resources to draw upon (Gurney et al., 2020, p.185). A learning application not only must be able to survive transit and usage in less-than-optimal environments, but it must also assume that the surgeon is performing procedures with limited tools, limited access to electricity, and with operational constraints that may affect how the procedure is performed.

2. Rural Environments

Although surgeons and physicians in rural hospital systems do not have to consider battlefield conditions, providers in rural areas do find themselves similarly isolated from advanced healthcare facilities. As stated by Atiyeh et al. (2010), “rural and remote areas share common issues of dispersed and isolated populations together with communication, transport, and climatic barriers which makes delivery of health care to these areas challenging and poorly accessible”(p. 581). Not only can it be a longer process for patients to get to rural emergency departments, but surgeons and physicians located in rural hospitals can be quite far away from specialists located in the large hospital systems in metropolitan areas (Upadhyayula et al., 2018). It can be surmised that bad weather can only add to this problem of rural isolation.

In these remote situations, emergency neurosurgical care is often delegated to non-neurosurgeons to perform. As one study conducted by Luck et al. (2015) in Darwin, Australia found, “general surgeons, in conjunction with their ICU specialists, definitively managed the vast majority of emergency neurosurgical cases” (p. 613). Not only must management of brain trauma be familiar to general surgeons, but also to position extenders such as ICU specialists, physician assistants, and nurses (Atiyeh et al., 2010). Learning tools for emergency neurosurgery must consider the fact that surgeons and position extenders who are not specialized in neurosurgery need to understand and practice the skills necessary to manage emergency situations far away from specialists.

3. Non-neurosurgical Training

When a surgeon is interested in deploying with one of the United States military branches, he or she must undergo what is known as the “Emergency War Surgery” course (Military Health System, n.d.). This course ensures that all surgeons, despite specialty training, are all competent in a variety of combat injury related emergency techniques (Military Health System, n.d.). The Emergency War Surgery Course (EWSC) is intended to provide Department of Defense (DOD) trauma surgeons the necessary knowledge to treat injured soldiers in austere deployment environments, military treatment facilities, and at Level I trauma treatment facilities (Military Health System, n.d.). This training ensures that all surgeons being deployed are ready to care for common combat injuries and understand how to treat soldiers in sub-optimal environments and situations.

Rural communities often have very few, if any, neurosurgeons on staff, meaning that general surgeons, other doctors, physician assistants, and nurses must take on additional responsibilities in an emergency (Upadhyayula, 2018). According to Upadhyayula et al. (2018), “most studies in rural communities focused on general surgeons, rather than neurosurgeons, performing neurosurgical procedures” (p. 130). Few rural areas have ready access to neurosurgeons, so it is commonplace for these areas to enlist the help of general surgeons to perform emergency neurosurgery (Luck et al., 2015). In more resource-limited areas, access to surgeons in general may be so limited that emergency surgical duties fall to general practitioner physicians and position extenders (Gauchan et al., 2018). Although this responsibility shift may sound dangerous, this is not necessarily the case. Upadhyayula et al. (2018) explains that position extenders “with condensed training can safely perform a variety of common neurosurgical procedures in the rural setting and can serve as the foundation for rural neurosurgical emergencies" (p. 130). Not only are position extenders relied upon in emergency situations, but Upadhyayula et al. (2018) found that they can perform procedures safely and effectively, despite not being trained specifically as doctors. Supporting staff is necessary to help when physicians and surgeons are spread too thin.

Although the specific training of all non-neurosurgeons expected to perform surgery is broad and relatively inconsistent, one can assume that each physician has undergone some basic training in performing general surgery. While individual education and experience varies, all providers are familiar with human anatomy and fundamental surgical technique.

4. Emergency Neurosurgery for Traumatic Brain Injury

Moderate-to-severe traumatic brain injury (TBI) causes significant morbidity in both civilian and military contexts. According to Fang et al. (2015), “moderate-to-severe traumatic brain injuries sustained by members of the Department of Defense (DoD) worldwide [from 2000 to August 2014] totaled 32,996 cases” (p. 181). In civilian terms, Swanson et al. (2017) found that

"An estimated 1.7 million people in the general US population sustain mild, moderate, or severe TBIs each year: of these, approximately … 275 000 require hospitalization, and 52 000 die from their injuries" (p. 251). Truly, TBI cases are universally important to study and research.

The United States Military Emergency War Surgery course is explicit in its curriculum regarding head injuries. It teaches students how to perform burr holes, ventriculostomies, and craniotomies (Cubano & Butler, 2018). Although the expectations in rural areas are less defined, Upadhyayula et al. (2018) found that the most common procedures performed in rural areas consisted of craniotomies, burr holes, ventriculostomies, craniectomies, Spina bifida repairs, skull fracture repairs, ventriculoperitoneal shunt (VPS) placements, myelomeningocele repairs, and laminectomies. Of all the procedures that were found to be common, the ventriculostomy procedure was selected as the focus of this investigation.

5. The Ventriculostomy Procedure

The ventriculostomy is a neurosurgical procedure in which a catheter is placed within a cerebral ventricle for drainage or intracranial pressure monitoring. According to McCafferty et al. (2018), "management of severe TBI patients using information from ICP monitoring is recommended to reduce in-hospital and 2-week post-injury mortality" (p. 69). The complete ventriculostomy procedure is performed by creating a burr hole (surgically penetrating the skull, dura mater, and brain until a ventricle can be accessed), placing a catheter into a cerebral ventricle, and then connecting this catheter to a collection device located outside the cranial cavity (Cubano and Butler, 2018). For the sake of this limited study, the steps involved in placing and securing the catheter will be the focus of the investigation, as they require the most anatomical knowledge and are often difficult to visualize.

The following steps were initially derived from the “External Ventricular Drain” chapter of *Fundamentals of Operative Techniques in Neurosurgery* (Connolly et al., 2010) and amended by Dr. Rocco Armonda, Director of Neuroendovascular Surgery for MedStar Washington Hospital Center and MedStar Georgetown University Hospital, Surgical Co-Director for the Neuro Intensive Care Unit at MedStar Washington, and Associate Professor and Director of Neurosurgery at the Uniformed Services University of the Health Sciences (USUHS).

1. The sharp trochar or spinal needle is inserted into the burr hole located at Kocher’s point, a landmark that is 2.5 to 3.0 cm lateral to the midline and approximately 10.5 to 11.0 cm posterior to the nasion to gently puncture dura. Using the sharp end of the trochar, an access path out is tunneled below the galeal layer of the scalp and "popped" out at a site 5-7 cm away from your burr hole site.
2. The catheter with stylet is inserted perpendicular to the brain surface to a depth no deeper than 7 cm below the skin edge. The stylet is withdrawn to ensure CSF flow. If CSF flow is obtained prior to 7 cm, the stylet is removed and the catheter is passed the remaining distance.
    a. If no CSF flow is obtained at 7 cm, the catheter is removed without the stylet and flushed with saline. The catheter is inserted again aimed slightly more medially.
    b. Using blunt forceps, the catheter is "pinched" at the skull with the surgeon’s non-dominant hand. Using the other hand, the trochar is pulled through the tunneled pathway.
3. The catheter is cut from the end of the trochar. The included stopcock device is placed

on the end of the catheter to prevent CSF from leaking. Using 3-0 nylon sutures, a drain stitch is placed at the point where the catheter exits the scalp.

4. The incision is closed with 3 or 4 interrupted sutures.

5. Instructional Analysis

Surgeons and physicians tend to be intelligent, busy professionals balancing high levels of responsibility and expectations of knowledge. Although these individuals are often intrinsically motivated to learn and medically competent, their stress levels and odd schedules must be considered to create an effective learning tool for this audience. One cannot assume that any one time will work well for these people to learn and study, or that they will be able to devote several hours at a time to studying. Emergencies can happen unexpectedly at any time. It is important that a learning tool is developed that can be used completely on the learner's terms, at times and at a frequency that is flexible and conducive to consistent use.

Another aspect that must be considered is that everyone's level of understanding coming into a learning experience can be different. Although one physician may be a bit more well-versed in the subject matter presented, another physician may have spent more time away from the material and be less comfortable. A learning apparatus intended to teach and reinforce knowledge for an emergency should cater to both levels of prior knowledge to scaffold both audiences up to the level of mastery. The learning experience developed for this research should have the ability to provide a reasonable foundation to those with less prior knowledge while reinforcing the knowledge of those with more prior knowledge, without causing frustration for either user.

The nature of surgery in and of itself must be considered when developing a learning tool for surgeons. Clark et al. (2019) explain that “whilst surgery is part a technical skill, the constant decision making…means that in reality surgery is a complex cognitive task” (p. 5). Not only do surgeons need to know what step they are on in a procedure and what comes next, they also need to be able to consider what tools they will be using now and next, manage their surgical team, and accommodate for anything unexpected that may happen during the procedure, such as an unexpected pathology or a power outage (Clark et al., 2019). For surgeons to competently manage unexpected challenges amid a procedure, it is of particular importance that surgeons are well versed and comfortable with the procedure’s technique. Considering these fundamental aspects of surgery, a learning tool that emphasizes committing the steps of a surgical procedure to long term memory is essential.

6. Multimedia Learning Theory

To make an effective learning tool, it is imperative to follow best practices previously established in the literature. Richard E. Mayer (2010) established one of the most famous concepts in learning theory and how it applies to multimedia learning. In his 2010 article in *Medical Education*, he explains the cognitive theory of multimedia learning as “an information-processing explanation of how people learn from words and pictures” (p. 544). In following this theory, the main goals of developing a multimedia learning tool are to reduce cognitive processing not relevant to learning, mange the amount of information presented during the learning process and foster processing that aids in the understanding and long-term retention of the presented material (Mayer, 2010). To do this, one must be careful and deliberate in planning how the learning material is to be presented.

To achieve the goal of long-term retention, one must first understand how memory works. Most literature regarding memory breaks it up into two main parts: working (short term) memory, and long-term memory. Schweppe and Rummer (2014) explain that “working memory as a cognitive system [is] separate from long-term memory that is responsible for briefly maintaining and manipulating information” (p. 286). Working memory and long-term memory should not be considered synonymous. In fact, for the purposes of teaching, Khalil & Elkhider (2016) suggest that one can assume that working memory is very limited while long-term memory is unlimited. Facilitating the process of transferring information from the small bank of working memory to unlimited long-term memory can be a challenge for instructional designers. Fortunately, systems and suggestions to help have been developed through research to aid in the design process. Although some concepts may be applied to all media, it is particularly helpful to start by selecting a target media for teaching material.

7. Instructional Media

Instructional materials tend to fall into one or a mix of the three general categories: illustration (static graphics), animation, and interactive visualizations. Each medium aims to achieve similar goals but are utilized and optimized in different ways for different audiences. To effectively teach busy health care professionals a surgical technique, one must consider each media separately.

Illustration (static graphics) can be used to explain processes by presenting a series of single images to help identify points of interest and clarify what would otherwise be confusing if shown dynamically. Although illustrations are extremely accessible and portable, learning through still images may promote rote memorization, a form of passive learning (Khalil &

Elkhider, 2016). Rote memorization may be helpful in contexts in which one only needs to know the information for a short duration of time, but it might not be suitable for promoting long-term retention. Stienen et al. (2017) argue that “knowledge construction requires active cognitive processing of information and is less likely to occur by passive learning” (p. 331). Although illustrations can be informative and helpful, learning from a still images may lead only to short-term retention (Khalil & Elkhider, 2016). Another problem which must be considered is that 2D images cannot dynamically show spatial information (Fan et al., 2017). For a surgeon learning to work in a compact and complicated area of the body, where understanding anatomical structures’ spatial positions is of utmost importance, this could be of significant detriment. Chen and Bowman (2009) found that interacting with a 3D representation improved task performance over traditional 2D visualizations of similar content (p. 371). For these reasons, illustration is not the most advantageous media for this research.

Animations are most used to teach when time is a driving factor for a process or system. In this case, the “successive and transient elements” that disappear before they can be retained in long term memory would create problems. Although an animation may be conveniently watched in a short duration of time, Paas et al. (2007) found that “attempts to keep such information active in working memory while simultaneously receiving new information causes high extraneous cognitive load and is therefore a major detriment to learning from animations” (p. 784). Viewing a complex animation with many steps might also cause the viewer to become overconfident. Sweller et al. (2019) found that students often use ‘ease of processing’ as a cue for understanding and that they will test well on the material. Although an animation may explain material very clearly and be easily viewed and understood by the learner, the high extraneous load inherent to animations may cause viewers to think they have retained more information than they actually have. Despite this problem of perception, Paas et al. (2007) notes that animations can still be useful “provided that they are designed with sensitivity to the processing limitations of working memory and the learner’s expertise” (p. 784). Although an animation may be quite useful to effectively explain the ventriculostomy in a visual way, it may not necessarily promote long term retention. In fact, learners may believe their performance on a test of this information would be high; when in fact, they only transiently understood what they watched (Sweller et al., 2019).

Interactive applications, found in the forms of tablet and desktop applications and virtual reality headsets, starkly contrast with the previously described media, as it prompts users to actively participate in the learning experience. Research in which surgery has been successfully taught or reinforced using this media is plentiful. Unlike looking at a static image or watching an animation, interactive learning applications allow for experiential learning, which can be of particular benefit when learning how to perform a task (Khalil & Elkhider, 2016). Interactive software tools can help structure problem solving, problematize subject matter, and otherwise provides structure that focuses attention and otherwise encourages the learner to interact with and prove their understanding of the material (Reiser, 2020). Learning surgical procedures though simulation is also cost effective and allows surgeons to practice procedures multiple times with ease (Xie et al., 2011).

Interactive applications can utilize both illustration and animation seamlessly and optimally. For this investigation, animations may be beneficially utilized in an interactive experience. Paas et al. (2007) found that “increasing the level of interactivity of animations can be used to increase germane cognitive load …. by stimulating learners to invest more mental effort in learning" (p.785). This mechanism may be particularly helpful to scaffold for detailed interaction into more appropriate complexity levels.

8. Visual Design

When it comes to visually designing an interactive application for teaching surgical procedures, many aspects of the visualization must be considered. First, one must consider the style in which this surgical procedure should be depicted. The amount of research that recommends utilizing 3D models in learning surgical procedures is overwhelming. Chen and Bowman (2009) found that 3D models offer better spatial understanding than 2D images and that 3D models improve the user's learning experience (p. 371). In general, using a 3D display of medical subject matter to learn leads to an improved assessment of anatomical and pathological structures (Xie et al., 2011). Reiser (2020) notes that tools that provide visualizations help users by providing a conceptual representation that can be used to form "deep models of an underlying system" and "provide a vehicle for students to articulate aspects of their understanding" (p. 281). For example, studying a 3D model of a brain in which the bone, cortex, and ventricles can be seen in context with one another may make it easier for one to build a conceptual understanding of the relationships between these anatomical structures. For these reasons, the anatomical structures in this research will be created in a 3D model format.

The anatomy visualized in this project must be accurate as well as realistic to be effective learning tools. As Reiser (2020) points out, "the goal of human-computer interaction design research is to make that mapping between a tool's representation and what it represents 'transparent'" (p. 281) If the anatomy is not realistic or does not appear human, it will not be clear to the user that the anatomy represented should be used to create mental models for reference when performing the surgical procedure being taught. To make mapping as easy as possible, the models used must be anatomically accurate and accurately represent what the anatomy will look like in context to the surgery.

Another consideration that must be made to the visual design of the application is the user interface. When users do not know where they are, where they were previously, or where they are expected to go next, they experience extraneous cognitive overload and become disoriented (Park & Kim, 2000). Within the context of an instructional software, extraneous cognitive load tends to include all the interactions necessary to use the instructional material but are not beneficial for learning (Kester et al., 2005). To minimize this extraneous cognitive load, the user interface of the application designed in this study should be streamlined to ensure easy access to learning materials and a non-distracting learning environment (Kester et al., 2005). One way to ensure that an initial user interface design makes a user’s navigational experience clear is to test it for clarity before integrating design choices into the final deliverable.

9. Instructional Strategies

Instructional design is described by Khalil & Elkhider (2016) as the process of “designing instruction aimed at increasing the instructional efficiency and facilitating student learning.” (p. 147). To ensure that a user will be able to learn effectively, the instructional design must be based on evidence-based practices. Kester et al. (2009) stated that “effective and efficient instructional material avoids overloading working memory” and “attempt[s] to redirect learners’ attention to relevant learning processes.” (p. 71). Learning experiences must carefully balance what is relevant for learning and what is necessary to navigate the learning material's platform (Kester et al., 2005). To manage cognitive load, Sweller et al. (2019) suggests not only to organize learning tasks in accordance with increasing complexity, but also that learner support and guidance should decrease as complexity increases. The goal of an effective learning application should be to only provide what the students need and to not provide extraneous support that could increase cognitive load and decrease learning (Walkington & Bernacki, 2018). Fortunately, well designed instructional software provides effective scaffolding that can focus a learner on productive tasks while automating others (Reiser, 2020). When learners are limited in the parts of a task they must complete, it is easier for them to focus on what will provide the most meaningful outcome of the experience (Reiser, 2020).

Scaffolding has traditionally described the process in which a teacher assists a learner, augmenting their learning to make it possible for the leaner to accomplish what they would not be able to otherwise (Reiser, 2020). In the context of educational design, Reiser explains that scaffolding should not only support the learner in accomplishing tasks, but it should also enable the learner to gain knowledge from the experience to prepare for future tasks (Reiser, 2020).

To learn how to perform a ventriculostomy, users must be able to practice the procedure from beginning to end using a method called elaborative rehearsal (Khalil & Elkhider, 2016). Elaborative rehearsal is an active learning process which will likely be more useful for transferring the information into long-term memory (Khalil & Elkhider, 2016). Practically, scaffolding in the context of elaborative rehearsal might introduce students to the material and require very little input from the user at first. As the student becomes more proficient with the procedure, they may advance to more independent tasks (Sweller et al., 2019). This system supports what Reiser (2020) found which is that “narrowing options, preselecting data, or offloading more routine parts of the task, can help learners focus resources on the aspects of the task more productive for learning”(p. 284). By keeping the learners’ interactions limited at first and slowly introducing that aspect, learners will be able to more effectively learn the aspects which are being challenged in the experience.

To maximize student ability to transfer information learned to new problems, Kester et al. (2005) found that “learning material presented in an integrated way leads to better transfer-test results than split-source presented learning material” (p. 81). In the context of teaching neurosurgery, manipulating visualizations in a structured manner to answer questions, rather than relying on the user to connect the visualization with text, is expected to improve transfer. For this reason, users should be able to interact with the 3d models used to demonstrate the procedure. Movements of these 3D models may be introduced via short animation sequences to indicate how the 3d models are intended to be moved. By converting these meaningful parts of the process into short animations segments, the user will be able to learn what they are to do in the future without overwhelming them with interactions in earlier stages.

10. Self-Testing

Research has shown that testing can be utilized to support long-term retention of knowledge (Roediger & Karpicke, 2006). Fortunately, this can be done in a structured fashion within software.

Self-testing encourages students to break their studying up into manageable parts and receive feedback on what they have mastered and what they have yet to learn (Roediger and Karpicke, 2006). Sweller et al. (2019) found that learners in general are not good at regulating their learning, so giving students the clarity to distinguish what is known and unknown is of great benefit to students. Understanding their own self-mastery allows students to focus study efforts toward learning what they do not know yet, rather than wasting time reviewing subject matter they have already learned (Roediger and Karpicke, 2006). By integrating self-testing and specification of learning in a virtual format, learners can be effectively productive with their time spent studying. In the context of this learning tool, research suggests that allowing the learner to focus on what they do not know will allow them to not only focus on directly improving weak areas, but also reduce extraneous information that would otherwise be encountered reviewing material traditionally.

By slowly increasing difficulty, learners are encouraged to add to their pre-existing knowledge (Reiser, 2020). It therefore makes sense to use selected details for questions and to build up expectations slowly. A system that progressively challenges a learner may be built by creating definitive levels of difficulty. This way, the learning application can scaffold the information presented directly for the next level. Although adding complexity may cause struggle in the short term, continuing to challenge a learner is productive for creating a meaningful learning experience (Reiser, 2020). In fact, Walkington & Bernacki (2018) found that “challenge, struggle, difficulty, and even failure are important dimensions of learning concepts for understanding” (p. 53).

11. Feedback

Although Roediger and Karpicke (2006) found that “tests enhance later retention more than additional study of the material, even when tests are given without feedback” (p.181), evidence-based research on feedback should considered when developing software in which a user will be tested on information. Feedback can be given in a variety of means but is generally used to verify one's response as either correct or incorrect and/or to present relevant information beyond verification (Valdez, 2012). Although Valdez (2012) found that computer-based feedback systems can effectively improve performance whether or not elaboration on correctness is indicated, Klejj et al. (2015) and Roediger & Karpicke (2006) found that elaboration is more effective than simply indicating whether the response was right or wrong. Although tests in and of themselves provide an opportunity to learn, Roediger & Karpicke (2006) found that elaborate and meaningful feedback regarding test performance was particularly beneficial to students. Regardless of the style of feedback, when students are presented with information regarding their response to a question, the feedback either confirms or alters the learners understanding of their own knowledge and skills (Klejj et al., 2015). Klejj et al. (2015) notes that in general, giving students feedback can help "correct errors and misconceptions, develop more effective and efficient problem-solving strategies, and improve self-regulation" (p. 477). Not giving a student an indication of what response is correct, leads to a trial-and-error procedure that is not effective for learning because it does not support or teach the learner about how to improve (Klejj et al., 2015).

Research into the timing of feedback has been met with varied results but some suggests that immediate feedback can improve learning more than feedback that is delayed (Shute, 2008). Klejj et al. (2015) found that students spend "significantly more time reading immediate feedback than delayed feedback" which could suggest that immediate feedback is considered more carefully and preferred over delayed feedback which may not feel as relevant (p. 479)

12. Research gap

There is a noticeable gap in the research regarding the development of teaching resources for practitioners located in austere environments to support their learning and review of emergency neurosurgical procedures. Although desktop and tablet-based learning tools for neurosurgical procedures in general exist, there does not appear to be sufficient research backing their design choices or instructional design.

RESEARCH SIGNIFICANCE

A. Significance of research study

This investigation aimed to provide insight into the development of teaching tools for medical professionals working in austere and rural areas. Many of the current applications previously created have been developed by neurosurgeons working with traditional artists rather than those with a biomedical visualization background, so this project speaks to the neurosurgical community interested in furthering the creation of educational materials for neurosurgeons, as well as the field of biomedical visualization. This project provides insight into how products for this audience may be developed, and it also resulted in a functional prototype which may be utilized by professionals as an example. This prototype also adds to the body of educational resources available to surgeons and practitioners for review.

B. Research question

The research question of this project is as follows:

How can an interactive visualization be designed to effectively teach the steps of the ventriculostomy procedure to general surgeons located in austere and rural areas?

METHODS

A. Research study design

First, the concept of the learning application was developed based on a thorough literature review of the intended audience, procedure, and design considerations for optimal learning. This literature review was used to directly inform the decision-making from that point on. In consideration of the nature of surgery, extensive research into the ventriculostomy procedure was conducted and a sequence of steps to teach the procedure was identified. It was then reviewed and verified by a neurosurgeon. The learning goals and objectives of the application were then decided based on the verified surgical steps, available time to create the deliverable, and what would be considered an optimal virtual learning environment according to research.

Information intending to be taught was organized into a basic site map and then visually reorganized in a low fidelity wireframe of the application. At this point, the low fidelity wireframe (paper prototype) was assessed by the research committee, who provided constructive feedback to help ensure that the proposed application was intuitive and easy to navigate. Further research was conducted to finalize the educational design and effectively design the main learning area of the application. Building on feedback from the committee members and further literature review, the low fidelity wireframe was developed into a high-fidelity wireframe. This wireframe was used to create a basic framework to be developed within the Unity game engine. At this point, asset creation officially began, starting with the most essential 2D and 3D elements needed for functionality. Additional research was conducted to determine anatomical accuracy of 3d models created and to determine the code necessary to make the prototype functional within Unity. All interactions were planned according to verified ventriculostomy surgery steps and the supporting instructional design was developed for the target audience.

As 3D elements were completed, they were painted, optimized, and imported into the Unity project. As code was written and interactions determined, the Unity project was developed accordingly. Once the prototype was completed and responsive, committee members reviewed the application and evaluated it based on whether the final application achieved not only the desired learning goals and objectives, but also appropriately utilized and adhered to established design choices.

B. Stimulus design plan

The learning application was determined to be an interactive application that integrates 2D user interface elements and 3D models relevant to the ventriculostomy surgical procedure. Due to the environmental and operational constraints of deployed soldiers discussed previously, the specific platforms chosen for this research consisted of a tablet and a desktop computer. Virtual reality headsets as of 2021 are relatively fragile and would thus not be suitable for deployment. Tablets, such as the Apple iPad or the Galaxy Tab, would be ideal as they are conveniently sized for travel, and ,with a suitably strong case, durable even under extreme weather and situations. Laptop personal computers are common technology which would be reasonably useable in both rural and austere environments. Both tablets and personal computers are generally accessible in rural hospital systems and within US army brigades.

To give the application context, the premise of this application was to be a learning space for a user to practice the top three emergency neurosurgical procedures that non-neurosurgeons must know how to perform. For the sake of this research project, only the Ventriculostomy learning area was developed for evaluation. The interactive basis of this project was built within the Unity game engine while assets were developed in Adobe Illustrator, Adobe Photoshop, Pixologic ZBrush, and Autodesk 3ds Max. Surgical procedures that involve the brain are most optimally viewed in a three-dimensional fashion; so for each step, 3D models were created and utilized to visualize the relevant anatomy for each step.

The learning area of this application was based on the premise of self-testing in accordance with supported literature. Four levels of difficulty were created to scaffold the learner to deeper understanding over time. The first level introduces the user to each step of the procedure by providing not only text explanations of the procedure but also a look at 3D models (to be interactively utilized in later levels), which demonstrate the procedure accordingly. Once the user is familiar with the procedure in general, the user can move on to the second level, which introduces self-testing. For this level, the user is prompted to answer fill-in-the-black questions with predetermined answers, so the user must use recognition to determine the answer. Feedback is offered following each step to indicate whether the user got the answer(s) correct or incorrect and provide a structed explanation for what the correct answer should have been and why. In accordance with what was determined from the literature review, this feedback will be immediate, indicate correctness, and provide elaboration. The program is coded to recall what questions the user answered correct and incorrect; so when the user finishes the procedure, the user will repeat the same level until all answers are filled in correctly. To reduce cognitive load and focus learning, each question that was answered correctly no longer prompts a response. This way, the user must only input answers for the questions they answered incorrectly. This cycle repeats until the user has inputted every answer correctly. At this point the user is prompted to begin the next level, which introduces manipulation of the 3d models presented. Questions prompt the user to respond using the models present, positioning them in the correct position for the procedure. As before, the user is prompted to repeat the level until each answer is provided correctly. In the final fourth level, users are not prompted with the written steps but must recall what step they need to perform and how to perform it. In this stage the user must manipulate the 3D models as before but without prompting. This stage works as before, so the user must perform each step correctly to move on. Otherwise, they will be required to repeat the level and repeat the steps they missed.

Slowly taking away support and testing the user facilitates independent knowledge of the procedure from start to finish through repetition and guided recall of material.

C. Evaluation plan

Project research committee members determined whether learning goals and objectives were met by answering qualitative questions developed based on literature review, learning theory, and principles of design.

Questions:

1. Did the design of the application effectively take into consideration the environmental and situational confines in which it intends to be utilized?
2. Was the interactive experience in general easy to navigate?
3. Did the interactive take into consideration the pre-existing knowledge of a general physician or position extender? (Was the information presented too complex? Did it assume more prior knowledge than what a physician assistant or nurse practitioner would know?)

4. Was each step of the ventriculostomy procedure visualized in a manner that is easy to follow and appreciate?
5. Is the relevant anatomy presented correctly?
6. Was the procedure correctly visualized?
7. Was the learning tool developed in a way that easily allows learners to leave and return at any time to accommodate lifestyle/professional demands?
8. Are the 3D models utilized in this interactive modeled and textured in a way that clarifies rather than confuses the user?

RESULTS

Due to limitations caused by the Covid-19 pandemic, the scale of this project was reduced from the entire ventriculostomy procedure to focusing on the second half, during which time a catheter is passed into a lateral ventricle of the brain. The C# code necessary to create the optimal learning environment guided by previous research was lengthy and difficult to successfully complete in the required timeframe. Research committee members concluded that completing this limited portion of the application could sufficiently answer the research question without addressing the preliminary burr hole creation.

Research committee members accessed the interactive experience developed in support of this research at https://nhamps2.people.uic.edu/ProjectResearch/. They evaluated this study in a meeting with the investigator on July 5, 2021. Overall, the committee was satisfied with the visualization developed to support this research. Most feedback involved small, easily changed details aimed at enhancing the visualization's user experience, such as instituting a note explaining at which point in the ventriculostomy procedure the simulation begins. During this meeting, the following questions were asked and answered by all committee members:

1. Did the design of the application effectively take into consideration the environmental and situational confines in which it intends to be utilized?

    Committee members found that the visualization did effectively take into consideration the intended environmental and situational confines. The target platform of a tablet was chosen appropriately, and committee members agreed that not only was the user interface suitable for a tablet, but the 3D models created were optimized for fast loading in areas with unreliable internet.

2. Was the interactive experience in general easy to navigate?

 The committee found the interactive experience in general easy to navigate and follow from one step to the next. Committee members agreed that they never felt lost or unsure of where to go next.

3. Did the interactive take into consideration the pre-existing knowledge of a general physician or position extender? (Was the information presented too complex? Did it assume more prior knowledge than what a physician assistant or nurse practitioner would know?)

 Committee members are all professionally trained medical illustrators. Although they could not speak from personal experience on whether the interactive took into consideration the pre-existing knowledge of a general physician or position extender, they were confident that it did not assume too much prior knowledge for a physician assistant or nurse practitioner. They did not believe the information was too complex and that the information and models presented were clear and easy to understand.

4. Was each step of the ventriculostomy procedure visualized in a manner that is easy to follow and appreciate?

 Although all committee members agreed that the procedure was clear and easy to follow, one committee member suggested adding a user interface callout to promote interaction at a critical step best visualized in an interactive format. During this step in which the catheter is placed, the committee member reasonably pointed out that learners should be encouraged to “turn off” the skin, meninges, and brain so that the learner can see the path the catheter takes as it enters the ventricle. Encouraging the learner to view this step in this way would help them fully appreciate the anatomical details of this procedure.

5. Is the relevant anatomy presented correctly?

   Committee members agreed that all anatomy and instruments visualized were correct and appropriate.

6. Was the procedure correctly visualized?

   Committee members agreed that to their knowledge the ventriculostomy procedure was visualized not only correctly, but in a manner that is easy to follow and appreciate.

7. Was the learning tool developed in a way that easily allows learners to leave and return at any time to accommodate lifestyle/professional demands?

   Although committee members found that the design of the interactive experience did easily allow learners to leave and return at any time, a portion of code at the end of the review section that would make the second level available was placed a bit late. Rather than requiring the user to continue their learning from the first to the second level to "open" the second level, the second level should become available for entrance automatically upon completion of the final step in the first level. This way, users can exit the application immediately following their first review and immediately enter level 2 upon their return.

8. Are the 3D models utilized in this interactive modeled and textured in a way that clarifies rather than confuses the user?

   Committee members found that the overall treatment of the 3D models created for this interactive experience was appropriate. By simplifying textures, the anatomy form and placement was more clearly highlighted. Committee members agreed that the anatomy depicted was clear and easy to visually understand.

DISCUSSION

Medical professionals in austere and rural areas must know how to perform emergency neurosurgical procedures to limit mortality and secondary injury in patients (Rubiano et al., 2019). Professionals in these positions may not encounter instances in which they are able to practice the decision-making associated with neurosurgical techniques, which presents a need for educational materials that will allow for regular review. This project aimed to help address the gap in research associated with the informed development of neurosurgical teaching applications for physicians and position extenders working in austere and rural areas.

This investigation argues not only that an interactive visualization could be created for the purpose of teaching the ventriculostomy procedure but also that this visualization could be designed specifically for an austere and rural surgical audience. Extensive literature review defined the needs and desires of the intended audience, validated the use of an interactive platform to teach neurosurgery, and informed the design of such an application. The prototype created through this research supports the thesis that an interactive visualization can be designed to effectively teach or review the steps of the ventriculostomy procedure for general surgeons in austere and rural areas.

This study focused primarily on two main audience groups, related by their similar situations and working environments. A limitation of this study is that its results cannot be directly applied to research regarding other audiences with different environmental specifications. This application was not tested on subjects, which also limits the reach of this research. This project focused specifically on the informed design and development of a learning tool rather than its effect on learners. Time was also limited. The Covid-19 pandemic caused this time limitation to be particularly impactful to the results of this project, as it extended the time necessary to problem solve difficulties encountered by the investigator.

This analysis aims to impact the neurosurgical community as well as biomedical visualizers who are creating learning applications for surgeons who work in unconventional environments. It is hoped that more research is conducted to learn more about the design of interactive medical visualizations intended to teach surgeons. Although other austere environments are not specifically addressed in this study, this investigation aims to inspire investigation into the creation of visual teaching modalities for practitioners in these various environments. Although this application is a prototype, it will hopefully provide support for the creation of future applications for medical personal in rural and military settings. In the future, it is hoped that this application will be developed further and become a practical tool for those needing to review the skills necessary to perform surgical procedures in austere environments.

CITED LITERATURE

Armando, R. (2020, November 12). Personal communication [Email].

Atiyeh, B. S., Gunn, S. W. A., & Hayek, S. N. (2010). Provision of essential surgery in remote and rural areas of developed as well as low- and middle-income countries. *International Journal of Surgery*, *8*(8), 581–585. https://doi.org/10.1016/j.ijsu.2010.07.291

Chalela, J. A., & Britell, P. E. (2019). Tactical Neurocritical Care. *Neurocritical Care*, *30*(2), 253–260. https://doi.org/10.1007/s12028-018-0524-x

Chen, J., & Bowman, D. A. (2009). Domain-Specific Design of 3D Interaction Techniques: An Approach for Designing Useful Virtual Environment Applications. *Presence: Teleoperators and Virtual Environments*, *18*(5), 370–386. https://doi.org/10.1162/pres.18.5.370

Clark, M. P. A., Westerberg, B. D., Nakku, D., & Carling, P. (2019). Education in ear and hearing care in remote or resource-constrained environments. *The Journal of Laryngology & Otology*, *133*(1), 3–10. https://doi.org/10.1017/S002221511800110X

Connolly, E. S., Sciubba, D., McKhann, G. M., Huang, J., Choudhri, T. F., Komotar, R. J., & Mocco, J. (2010). External Ventricular Drain. In *Fundamentals of operative techniques in neurosurgery* (2nd ed., pp. 370–375). essay, Thieme.

Cubano, M. A., & Butler, F. K. (2018). Head Injuries. In *Emergency war surgery* (5th ed., pp. 213–234). essay, Borden Institute, US Army Medical Department Center and School, Health Readiness Center of Excellence, Fort Sam Houston, Texas, Office of The Surgeon General, United States Army.

Fan, Z., Weng, Y., Chen, G., & Liao, H. (2017). 3D interactive surgical visualization system using mobile spatial information acquisition and autostereoscopic display. *Journal of Biomedical Informatics*, 154–164.

Fang, R., Markandaya, M., DuBose, J. J., Cancio, L. C., Shackelford, S., & Blackbourne, L. H. (2015). Early in-theater management of combat-related traumatic brain injury: A prospective, observational study to identify opportunities for performance improvement. *Journal of Trauma and Acute Care Surgery*, *79*, S181–S187. https://doi.org/10.1097/TA.0000000000000769

Gauchan, B., Mehanni, S., Agrawal, P., Pathak, M., & Dhungana, S. (2018). Role of the general practitioner in improving rural healthcare access: A case from Nepal. *Human Resources for Health*, *16*(1), 23. https://doi.org/10.1186/s12960-018-0287-7

Gurney, J. M., Loos, P. E., Prins, M., Van Wyck, D. W., McCafferty, R. R., & Marion, D. W. (2020). The Prehospital Evaluation and Care of Moderate/Severe TBI in the Austere Environment. *Military Medicine*, *185*(Supplement_1), 148–153. https://doi.org/10.1093/milmed/usz361

Kester, L., Kirschner, P. A., & van Merriënboer, J. J. G. (2005). The management of cognitive load during complex cognitive skill acquisition by means of computer-simulated problem solving. *British Journal of Educational Psychology*, *75*(1), 71–85. https://doi.org/10.1348/000709904X19254

Khalil, M. K., & Elkhider, I. A. (2016). Applying learning theories and instructional design models for effective instruction. *Advances in Physiology Education, 40*(2), 147–156. https://doi.org/10.1152/advan.00138.2015

Klejj, F., Feskens, R., & Eggen, T. (2015). Effects of Feedback in a Computer-Based Learning Environment on Students' Learning Outcomes. *Review of Educational Research*, *85*(4), 475–511. https://doi.org/10.3102/0034654314564881

Luck, T., Treacy, P. J., Mathieson, M., Sandilands, J., Weidlich, S., & Read, D. (2015). Emergency neurosurgery in Darwin: Still the generalist surgeons' responsibility. *ANZ Journal of Surgery*, *85*(9), 610–614. https://doi.org/10.1111/ans.13138

Mayer, R. E. (2010). Applying the science of learning to medical education. *Medical Education*, *44*(6), 543–549. https://doi.org/10.1111/j.1365-2923.2010.03624.x

McCafferty, R. R., Neal, C. J., Marshall, S. A., Pamplin, J. C., Rivet, D., Hood, B. J., Cooper, P. B., & Stockinger, Z. (2018). Neurosurgery and Medical Management of Severe Head Injury. *Military Medicine*, *183*, 67–72. https://doi.org/10.1093/milmed/usy071

Military Health System (n.d.) *Emergency War Surgery Course*. Health.mil. https://www.health.mil/Training-Center/Defense-Medical-Readiness-Training-Institute/Emergency-War-Surgery-Course.

Paas, F., Van Gerven, P. W. M., & Wouters, P. (2007). Instructional efficiency of animation: Effects of interactivity through mental reconstruction of static key frames. *Applied Cognitive Psychology*, *21*(6), 783–793. https://doi.org/10.1002/acp.1349

Park, J., & Kim, J. (2000). Contextual Navigation Aids for Two World Wide Web Systems. *International Journal of Human-Computer Interaction*, *12*(2), 193–217. https://doi.org/10.1207/S15327590IJHC1202_3

Reiser, B. J. (2020). Scaffolding Complex Learning: The Mechanisms of Structuring and Problematizing Student Work. *The Journal of the Learning Sciences*, *13*(3), 273–304.

Roediger, H. L., & Karpicke, J. D. (2006). The Power of Testing Memory: Basic Research and Implications for Educational Practice. *Perspectives on Psychological Science*, *1*(3), 181–210. https://doi.org/10.1111/j.1745-6916.2006.00012.x

Rubiano, A. M., Maldonado, M., Montenegro, J., Restrepo, C. M., Khan, A. A., Monteiro, R., Faleiro, R. M., Carreño, J. N., Amorim, R., Paiva, W., Muñoz, E., Paranhos, J., Soto, A., Armonda, R., & Rosenfeld, J. V. (2019). The Evolving Concept of Damage Control in Neurotrauma: Application of Military Protocols in Civilian Settings with Limited Resources. *World Neurosurgery*, *125*, e82–e93. https://doi.org/10.1016/j.wneu.2019.01.005

Schweppe, J., & Rummer, R. (2014). Attention, Working Memory, and Long-Term Memory in Multimedia Learning: An Integrated Perspective Based on Process Models of Working Memory. *Educational Psychology Review*, *26*(2), 285–306. https://doi.org/10.1007/s10648-013-9242-2

Shute, V. J. (2008). Focus on Formative Feedback. *Review of Educational Research*, *78*(1), 153–189. https://doi.org/10.3102/0034654307313795

Stienen, M. N., Schaller, K., Cock, H., Lisnic, V., Regli, L., & Thomson, S. (2017). ELearning resources to supplement postgraduate neurosurgery training. *Acta Neurochirurgica*, *159*(2), 325–337. https://doi.org/10.1007/s00701-016-3042-7

Swanson, T. M., Isaacson, B. M., Cyborski, C. M., French, L. M., Tsao, J. W., & Pasquina, P. F. (2017). Traumatic Brain Injury Incidence, Clinical Overview, and Policies in the US Military Health System Since 2000. *Public Health Reports*, *132*(2), 251–259. https://doi.org/10.1177/0033354916687748

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive Architecture and Instructional Design: 20 Years Later. *Educational Psychology Review, 31*(2), 261–292. https://doi.org/10.1007/s10648-019-09465-5

Upadhyayula, P. S., Yue, J. K., Yang, J., Birk, H. S., & Ciacci, J. D. (2018). The Current State of Rural Neurosurgical Practice: An International Perspective. *Journal of Neurosciences in Rural Practice*, *9*(1), 123–131. https://doi.org/10.4103/jnrp.jnrp_273_17

Valdez, A. (2012). Computer-based feedback and goal intervention: Learning effects. *Educational Technology Research and Development*, *60*(5), 769–784. https://doi.org/10.1007/s11423-012-9252-7

Walkington, C., & Bernacki, M. L. (2018). Personalization of Instruction: Design Dimensions and Implications for Cognition. *The Journal of Experimental Education, 86*(1), 50–68. https://doi.org/10.1080/00220973.2017.1380590

Xie, K., Yang, S., & Zhu, Y. M. (2011). 3D Visualization and Simulation in Surgical Planning System of Orbital Hypertelorism. *Journal of Medical Systems*, *35*(4), 617–623. https://doi.org/10.1007/s10916-009-9399-x