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Development of a Computer-Assisted Cranial Nerve Simulation From the Visible Human Dataset

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Advancements in technology and personal computing have allowed for the development of novel teaching modalities such as online web-based modules. These modules are currently being incorporated into medical curricula and, in some paradigms, have been shown to be superior to classroom instruction. We believe that these modules have the potential of significantly enriching anatomy education by helping students better appreciate spatial relationships, especially in areas of the body with greater anatomical complexity. Our objective was to develop an online module designed to teach the anatomy and function of the cranial nerves. A three-dimensional model of the skull, brainstem, and thalamus were reconstructed using data from the Visible Human Project and Amira®. The paths of the cranial nerves were overlaid onto this 3D reconstruction. Videos depicting these paths were then rendered using a "roller coaster-styled" camera approach. Interactive elements adding textual information and user control were inserted into the video using Adobe Creative Suite® 4, and finally, the module was exported as an Adobe Flash movie to be viewable on Internet browsers. Fourteen Flash-based modules were created in total. The primary user interface comprises a website encoded in HTML/CSS and contains links to each of the 14 Flash modules as well as a user tutorial. Anat Sci Educ 4:92–97. © 2010 American Association of Anatomists.

Key words: anatomy education; computers in anatomical education; Internet application in anatomy; undergraduate medical education

INTRODUCTION

The technology behind personal computing is advancing at a rapid rate. Over the past two decades, the proliferation of Internet-enabled personal computers in the household and educational institutions is ubiquitous. This effect enables access to vast amounts of information from the convenience of our own homes. Not surprisingly, educators have been quick to adopt this technology to provide resources, such as lecture notes, over the Internet. As the performance of personal computers and Internet connections improves, so too the types of information that may be broadcasted. The amount of multimedia that can now be streamed over the Internet is immense, allowing even for lectures to take place in full high definition.

This technological advancement is a welcome and necessary resource especially in undergraduate medical curricula due to the ever-increasing body of knowledge expected of our future physicians. Research in education has also identified the importance of self-directed learning and its positive outcomes in comparison to traditional didactic learning (Knowles, 1975). Moreover, in Ontario, the physician shortage has led to the implementation of satellite campuses, pushing students to remote locations far removed from professors and libraries. All

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of these changes are evident at the Schulich School of Medicine and Dentistry in London, Ontario, where lecture times are decreasing and being replaced by self-directed and small group exercises, and students are being encouraged to carry out their clinical placements in rural, community areas. This is not dissimilar to the trend observed in the five other medical schools in Ontario. Ultimately, the result has been a decreased emphasis on many subjects including anatomy, and this is evidenced as well in the United States, where a survey of postgraduate residency programs identified that 57% of program directors felt incoming students required a refresher on their knowledge of anatomy and 14% felt incoming students were severely lacking in their knowledge of anatomy (Cottam, 1999). As such, computer-assisted learning (CAL) appears to be the ideal medium to overcome these paradigm shifts, by providing educational resources that are self-directed and interactive as well as accessible anywhere and thus cost effective. Several medical specialties have realized this potential and have subsequently developed CAL modules to supplement didactic lectures and other curricular exercises. Previous work by our group in the Department of Otolaryngology-Head and Neck Surgery has resulted in the construction of CAL modules demonstrating several integral topics in undergraduate medical education, including basic knowledge of anatomy and physiology, clinical case-based knowledge, and procedural knowledge/skills (Beyea et al., 2008; Glicksman et al., 2009; Hu et al., 2009; Sowerby et al., 2010). CAL offers many advantages over traditional learning supplements (namely study notes and textbooks), the most obvious being multimedia capability. CAL may particularly be useful in anatomy education due to the ability to demonstrate three-dimensional (3D) structures and anatomical relationships to the students. Continued advancements in computing has made this type of visualization a reality, as users' computers and Internet connections are able to handle higher fidelity models and the developers' computers are able to process larger amounts of data at an affordable cost.

The gold standard of anatomy education has historically been cadaveric dissection. It offers a level of intricacy and realism that to date has not been replicated. Moreover, the ability to physically manipulate the human body (i.e., haptic feedback) offers the student a unique appreciation for the texture, consistency, and strength of different tissues. Reproducing this unique aspect of cadaveric dissection has been described recently in the literature, but these systems have yet to be perfected and widely adopted (Kinnison et al., 2009; Sowerby et al., 2010). However, when self-directed learning is considered, while studying the human body itself may provide an excellent sense of anatomical relationships and structural integrity of the tissues, it does not provide a great degree of adjuvant information, such as physiology, function, pathophysiology, and clinical relevance of the anatomical structures being studied. This is in contrast to traditional, text-, and image-based learning supplements, which provide no tactile/haptic feedback but may be better suited to providing relevant physiological and clinical information. CAL holds promise in being able to take advantage of both the above learning modalities, by providing better visualization of structures through three-dimensional reconstructions and relevant information regarding the structures being visualized (Luursema et al., 2008). These 3D reconstructions may especially be of use when the structures in question are small and intricate, such as those in the head and neck. One group of these structures is the cranial nerves, whose tortuous courses through the craniofacial skeleton are difficult to understand. In spite of their complexity, understanding the anatomy and function of the cranial nerves holds value for many medical specialties, including Otolaryngology and Head and Neck Surgery.

This initial article describes the development of a CAL module of cranial nerve (CN) anatomy for use by undergraduate medical students. This proof of principle study aims to reconstruct filamentous structures, namely the cranial nerves, using previously described methodology (Hu et al., 2009). The predefined objectives of the module are to demonstrate: (1) the pathways of the twelve pairs of cranial nerves in relation to the craniofacial skeleton and (2) their sensory and motor function. Our module was designed based on three principles. First, as per the objectives, it was designed with the capability of visualizing the craniofacial skeleton in mind. Second, it was designed with accessibility in mind; the module can be viewed on any computer with an Internet connection and a browser with Adobe Flash® (Adobe Systems Inc., San Jose, CA) support. Finally, the user's ability to interact with the module and control his/her own pace of learning was emphasized.

METHODS

Dataset

The three-dimensional model was constructed using the data from the Visible Human Project (Ackerman, 1999). This dataset was created from two cadavers, one male and one female. To create the dataset, these cadavers were frozen in gelatinous material and thin, axial slices were shaved from the cadaver one at a time so that the presenting structures could be photographed. The female dataset was chosen because of its superior resolution (0.33 mm slices) compared with the male dataset (1 mm slices). The female dataset is approximately 40 gigabytes in size. We also made use of the accompanying axial computed tomography (CT) scans. These images are publicly available and additional details regarding their acquisition/construction were previously described in the literature (Ackerman, 1999).

Three-Dimensional Reconstruction

Three-dimensional reconstructions of the craniofacial skeleton, brainstem, thalamus, common and internal carotid artery, and the major laryngeal structures were created (the hyoid bone, the thyroid cartilage, and hyoid cartilage). This was accomplished using the Amira® version 5.0 software (Visage Imaging, Inc., San Diego, CA) platform. First, the images from the Visible Human Female were batch cropped and converted to grayscale using Adobe Fireworks CS4 (Adobe Systems Inc., San Jose, CA). This enabled them to be imported into Amira. The CT images were also imported and coregistered manually with the cadaveric images such that the structures were aligned. Because the CT scan was performed on the cadaver after it had been "frozen," only translational and scaling changes were required to coregister the two datasets. Reconstruction of the 3D structures was achieved using a process called image segmentation, whereby the structure of interest was outlined on the 2D axial image. This process was repeated for all the slices encompassing the structure, and the outlines are subsequently stacked on top of one another, resulting in a 3D volume. The craniofacial skeleton was reconstructed using the CT data through automatic threshold segmentation. The other structures were reconstructed using the cadaveric images and were done so through manual segmentation and interpolation. Amira visualizes the 3D-segmented images as a collection of voxels. To make these usable, they were converted to 3D mesh surfaces, comprised of multiple interconnected triangles. These mesh surfaces resulting from the reconstruction of the structures yield surfaces comprised of several hundred thousand triangles. This level of detail was both taxing on the computer hardware and did not provide any additional benefit with respect to ability to visualize minute details (ultimately, the detail of the images was limited by the resolution or pixel size of the original digital photographs) or the smoothness of the surfaces. Thus, an automatic simplification tool was applied to the surfaces to make them more manageable and decreased the total number of triangles to the order of the 10,000. A smoothing filter was also applied to the surfaces to remove the jagged edges caused by human error associated with manual segmentation.

Cranial Nerve Reconstruction

The cranial nerves (with the exception of the olfactory and optic nerves), although they could be seen on the Visible Human images, were not visualized with enough resolution for them to be reconstructed using image segmentation. Olfactory nerve (CN I) and optic nerve (CN II) were reconstructed using image segmentation as described above. The remaining ten cranial nerves were reconstructed using the Filament Editor tool in Amira version 5.0. Waypoints were identified along the path of each individual nerve, and software was able to connect these points through a series of polylines. The way points were placed was either via direct visualization of the nerve on the axial image or via known landmarks (such as the foramina of the skull base). The motor and sensory paths were identified in this manner. The small, autonomic branches of the cranial nerves (i.e., the tympanic nerve) were not reconstructed because of inadequate resolution of the dataset. A smooth filter was subsequently applied to improve the appearance of the nerves.

Using the camera path editor built into Amira, videos were created which mimicked a roller coaster, following the course of each cranial nerve from its origin in the brainstem to its the distal branches. A video was created for each of the twelve nerves with the following exceptions: facial nerve (CN VII) and vestibulocochlear nerve (CN VIII) were combined into one video due to their similar course, and three individual videos were created to follow the course of each of the major divisions of trigeminal nerve (CN V), namely the ophthalmic, maxillary, and mandibular nerves. These videos were exported from Amira. Fourteen videos were made in total.

A second set of schematics was drawn using Adobe Illustrator® CS4 (Adobe Systems Inc., San Jose, CA). These schematics outlined the branching pattern of each of the twelve cranial nerves as well as some of the major foramen and canals that they traveled through. These schematics were used in the final web-based module seen in Figure 2.

Web Implementation

The videos were imported and integrated into an Adobe Flash application for viewing on Internet browsers as well as the addition of interactive elements. A graphical template was first designed in Adobe Photoshop CS4. The template served as the basis for the 14 web modules that would be based on the 14 videos described above. The template, videos, and schematic diagrams were all imported into Adobe Flash CS4 and several interactive elements were added, which allows the user to move through the video at their own pace. Information regarding the associated structures as well as the functions of the terminal branches was also added. The details are described below.

Validation

Several anatomy texts were used as the basis for the content information demonstrated in the module (Wilson-Pauwels et al., 1988; Drake et al., 2005; Netter, 2006). After initial development, content validity was assessed by a board-certified otolaryngologist (K.F.) and an anatomist in the Department of Anatomy and Cell Biology (T.D.W.). The module itself was subsequently reviewed by a focus group led by the senior author (T.D.W.) consisting of a selection of graduate students in the Department of Anatomy and Cell Biology.

RESULTS

A 3D model of the craniofacial skeleton, deep nuclei of the central nervous system as well as the paths of the twelve cranial nerves were constructed and can be visualized using Amira. When viewed in Amira, this model can be fully rotated on any axis, translated, and magnified. Computers with this capability are available in the undergraduate anatomy laboratory, and 3D models can also be projected stereoscopically using two projectors and polarizing filters. A representative image of the 3D model that we reconstructed is seen in Figure 1.

We produced 14 Flash-based modules in total, one for each of the cranial nerves (one module for each of the three major branches of the trigeminal nerve was created; the facial nerve and vestibulocochlear nerve were combined into one module). Use of the Flash platform sacrificed the ability of free rotation and translation for greater accessibility. In addition, using a web format also allowed us to insert additional information such as the schematic view of nerve branching as well as text providing content information, functions not natively available in Amira. The 14 modules are aggregated on a website written using HTML/CSS and JavaScript. This webpage provides a tutorial on how best to use the module as well as learning objectives.

A representation of the final module is comprised of three main windows (Fig. 2). The primary viewing window is in the top-right corner and it provides a "roller coaster" view of the cranial nerve, following it from its origin in the brainstem to the various structures that it innervates. The roller coaster stops at various points along the way to highlight relevant associated structures (such as the foramina of the skull) and content information (such as the locations and functions of the various branches). Orange circles that overlie said structures indicate points of interest. When the user moves their mouse cursor over the circles, the information pops up. The window on the top-left is a bird's eye view, which allows the user to maintain orientation while following the course of the nerve. A red dot indicates the position of the roller coaster along the nerve. The window along the bottom of the module is an image of the schematic view, illustrating the major branching pattern of the nerve. All the points of interest are identified here by vertical, grey, dotted lines. This window also serves as a timeline, as the user can click anywhere along the schematic to take them to that point in the roller coaster. An online version of our module is accessible on the web (CRIPT, 2009).

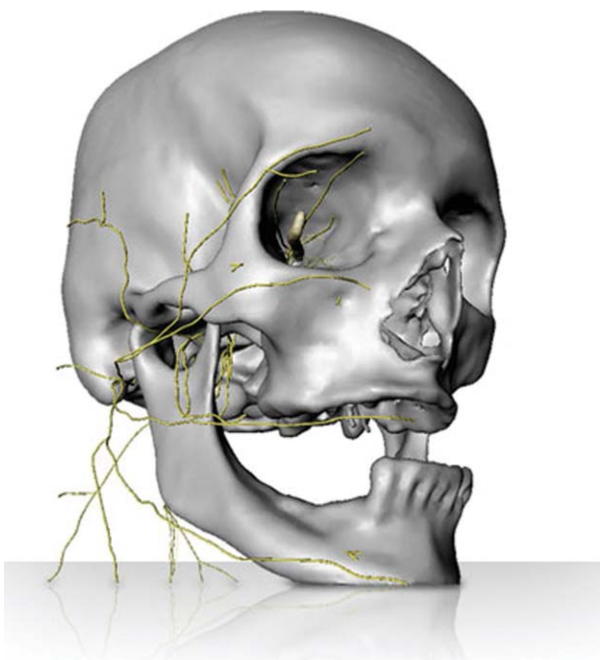

Figure 1.

The 3D reconstruction of the craniofacial skeleton with the pathways of the twelve cranial nerves overlaid. In Amira, this model can be rotated about any axis, translated, and the transparency of the individual structures can be adjusted to optimize visualization. Visible in this figure are the terminal branches of cranial nerves II, III IV, V, VII, IX, X, XI, and XII.

DISCUSSION

The purpose of this article is to describe our group's experience with the development of a Flash-based, computer-assisted learning module of cranial nerve anatomy and will be followed by a validation study. This is our group's first foray into custom Flash applications for the development of CAL modules; this method affords the developer a greater degree of customization and the end user with a greater level of interactivity and accessibility than that of previously described modules (Beyea et al., 2008; Glicksman et al., 2009; Hu et al., 2009; Nguyen and Wilson, 2009; Sergovich et al., 2010). Our module is accessible via any computer with a web browser and does not require any 3D rendering capability. Ultimately, the module described is destined to be a supplemental resource for undergraduate medical students. This paradigm, namely the use of CAL as an adjunct to conventional teaching modalities, is congruent with previous research from our group describing student perceptions on CAL (Chen et al., 2010). The module described in this article demonstrates content information (with emphasis on the sensory and motor functions) and spatial information through a novel method of visualizing the cranial nerves. This module, to our knowledge, is the first of its kind described in the literature.

Computer-assisted learning modules demonstrating 3D anatomy continue to proliferate. This has partially resulted from advances in cross-sectional imaging technology and the increased use of radiographic studies in clinical practice. It became quickly obvious that the manipulation of these datasets, such as through maximum intensity projections, volume rendering, etc., to achieve novel visualizations of the human body holds significant clinical and educational value (Tam, 2010). A review of the literature identifies several 3D models pertaining to head and neck anatomy that were previously described. The majority of these models are described in the Neurosurgery and Otolaryngology-Head and Neck Surgery literature and are designed to teach surgical skills. For instance, several authors have developed 3D models of the temporal bone to aid in temporal bone dissection (Kuppersmith et al., 1997; Mason et al., 2000; Wiet et al., 2000, 2002, 2005; Kockro and Hwang, 2009). Most recently, a model developed by Kockro and Hwang made use of the Visible Human Male and similar methods to ours to reconstruct the temporal bone and related structures, such as the facial nerve (Kockro and Hwang, 2009). Their model was visualized using Dextroscope™ (Bracco AMT, Inc., Princeton, NJ), a virtual surgery simulator. Regarding cranial nerve anatomy specifically, an elegant 3D model was developed and described by Kakizawa and colleagues who built their model based on cadaveric specimens dissected to demonstrate the cranial nerves (Kakizawa et al., 2007). Photographs of these dissections were taken from different angles and imported into Maya® (Autodesk Inc., San Rafael, CA), a 3D rendering software platform they used to reconstruct the 3D structures. The result was a highly detailed model that focuses on four areas that contain complex anatomical relationships, namely the orbit, cavernous sinus, superior/lateral surface of the temporal bone, and posterior surface of the temporal bone. The level of detail achieved by Kakizawa and colleagues is quite remarkable and cannot be replicated given the resolution of the Visible Human dataset. However, this model was again targeted toward neurosurgical residents. Moreover, the authors admit that visualization of such a model would require significant computing power. While modern personal computers have the capability to render complex 3D models, transmission of this type of data over the Internet would be difficult, and research into server-side rendering is a resource-intensive option that remains in its infancy.

CAL modules based on 3D anatomical reconstructions hold significant potential in providing innovative learning experiences for students and research into the efficacy of these types of modules is emerging, although evaluation of specific modules related to head and neck and cranial nerve anatomy are scarce. Generally speaking, the results of studies investigating anatomy have been varied, when undergraduate medical students were targeted (Tam et al., 2009). Earlier studies on carpal bone anatomy were unable to identify any benefit of CAL over traditional learning supplements (Garg et al., 1999, 2001, 2002). The module described by Garg and co-workers was limited at the time by the degree of interaction with the 3D model itself. Moreover, the authors suggested that as the carpal bones are anatomically oriented in two planes, visualization in 3D space may not have provided a significant advantage over traditional methods of visualization. Another study by Hallgren and colleagues investigated the ability of a CAL module to confer anatomical landmarks of the abdomen and found an advantage compared with a control group, although participants were not randomized (Hallgren et al., 2002). Nicholson and colleagues conducted a randomized trial that demonstrated the superiority of their CAL module, when assessing spatial knowledge (Nicholson et al., 2006). Their module again demonstrated anatomy related to the temporal bone, specifically that of the middle and inner ear structures. It was developed using image segmentation and allowed for free rotation of the reconstructed structures in 3D space; this however required computers with the virtual reality modeling language (VRML)

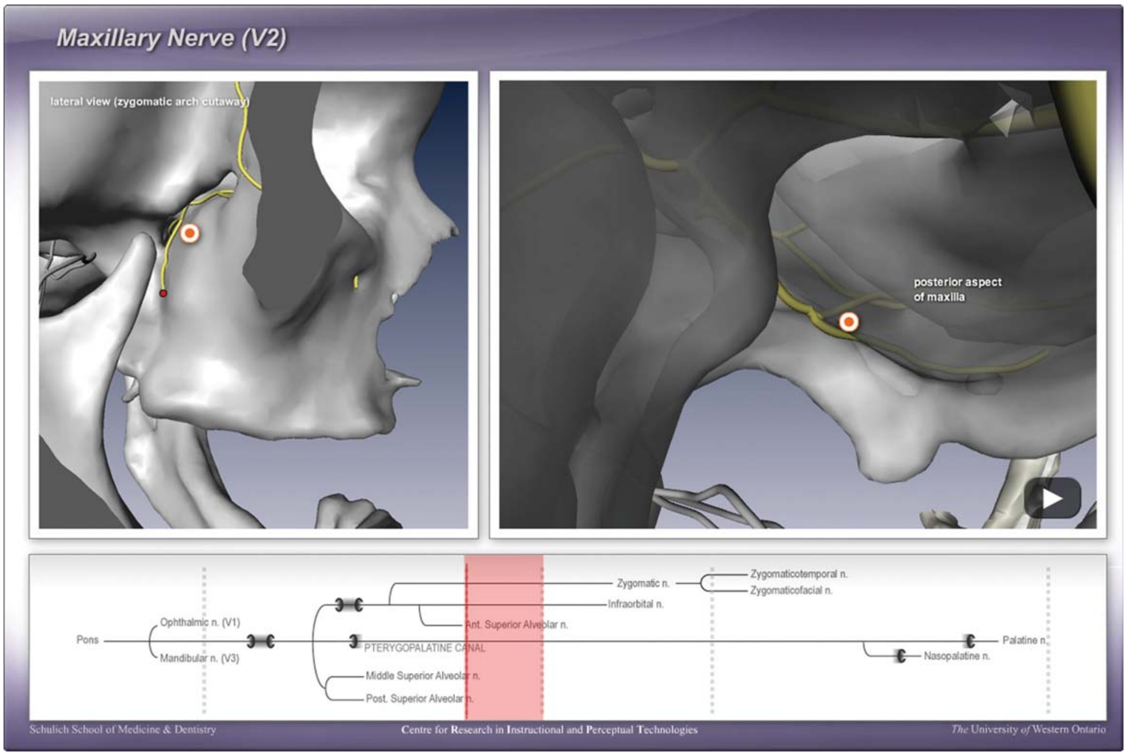

Figure 2.

A representative screenshot of the maxillary division of the trigeminal nerve (CN V_2). The window on the top right is the primary window, allowing the user to follow the course of the nerve like a roller coaster. The window on the top left is a bird's eye view and demonstrates the location of the roller coaster via a red dot on the nerve. The window at the bottom is the schematic view, and demonstrates the branching pattern of the nerve.

plug-in installed. Most recently, our group was unable to demonstrate a difference between a 3D CAL module of the larynx, neither with respect to content nor spatial knowledge (Hu et al., 2010). This module was tutorial based and allowed students to learn at their own pace, but did not offer a significant degree of interaction with respect to manipulation of the 3D structures themselves. However, it was built on the Flash® platform and is widely accessible over the Internet.

Certainly, the ability to freely rotate and zoom-in on the 3D model provides unparalleled visualization. While our module does not allow for free rotation, the authors would argue our module design offers several benefits. First, as discussed above, our module can be visualized on any computer with an Internet browser and Flash capability. It does not require any specialized 3D-rendering software or plug-ins. This significantly improves the means by which the module can be deployed. Second, as the aim of this module was to demonstrate filamentous structures as opposed to polygonal structures, we believed that this design would lend itself better to the visualization of these types of structures. Finally, the modules have a specified beginning and end. This sequential format allowed us to integrate relevant adjuvant information and also provides structure for the student.

Through rigorous development and validation phase, a module using a novel approach in demonstrating cranial nerve anatomy was built. However, the authors acknowledge several limitations in our module that warrant discussion. First, our module primarily focuses on the sensory and motor functions of the cranial nerves. While the autonomic functions are also discussed, the autonomic pathways themselves were not reconstructed because of limitations in the resolution of the dataset. The detailed pathways of these nerve branches are out of the scope of this module and beyond the level of understanding expected of our target audience. Secondly, the style of visualization used by our module may be overwhelming for some users, especially those who have relatively little experience with head and neck anatomy. This was evidenced subjectively during the focus group held during the validation phase, as the senior students (Ph.D. candidates) expressed a greater level of comfort using the module, although an objective advantage or disadvantage remains to be determined. This was a point of particular interest, as understanding complex spatial relationships between the cranial nerves and craniofacial skeleton is not generally expected of undergraduate medical students. Despite this, the module described in this article and others like it may still hold significant educational value in this population (one with little previous knowledge of anatomy), as one of the premises behind our module is an attempt to infer functional information from spatial information. In other words, one's knowledge of where a nerve travels may help one to understand what the nerve innervates, and vice versa. Further, CAL modules help to peak students' interest in anatomy due to their novel, unconventional methods of visualizing anatomic structures (Hu et al., 2009; Chen et al., 2010). Both these factors address psychological theories behind modern anatomy education, which were described by Terrell (2006). Ultimately, we aim to determine whether or not these theories, used in the manner described in this article, translate into objective differences in student performance.

In summary, a simple, interactive computer-assisted learning module was successfully developed based on a three-dimensional model of the cranial nerves. This is the first known description of the development of such a pedagogical advancement in undergraduate medical education. As with all educational tools, this module will continue on to undergo empiric evaluation to determine its role and its effectiveness as a supplemental resource for anatomy education. A prospective study is currently underway, investigating objective outcomes of student knowledge as well as individual subjective feedback on the module. Specifically, this ongoing study aims to determine the effect of novel visualizations of the cranial nerves on students' factual and spatial knowledge acquisition at the undergraduate level.

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