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A software system for evaluation and training of spatial reasoning and neuroanatomical knowledge in a virtual environment

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ABSTRACT

This paper describes the design and development of a software tool for the evaluation and training of surgical residents using an interactive, immersive, virtual environment. Our objective was to develop a tool to evaluate user spatial reasoning skills and knowledge in a neuroanatomical context, as well as to augment their performance through interactivity. In the visualization, manually segmented anatomical surface images of MRI scans of the brain were rendered using a stereo display to improve depth cues. A magnetically tracked wand was used as a 3D input device for localization tasks within the brain. The movement of the wand was made to correspond to movement of a spherical cursor within the rendered scene, providing a reference for localization. Users can be tested on their ability to localize structures within the 3D scene, and their ability to place anatomical features at the appropriate locations within the rendering.

1. Introduction

Neurosurgeons make use of their perceptual and spatial reasoning skills when they make judgements involving anatomical structures and their context. Often, these precepts are based on two-dimensional preoperative images, which may be impoverished in terms of visual features and spatial cues. In addition, it has been found that inexperienced surgeons rely more heavily on their innate spatial abilities, as compared with experienced surgeons; presumably their experience can overcome any shortcomings in their individual visuo-spatial skills [1]. It has also been demonstrated that surgical residents can attain competency in visual-spatial tasks through practice and feedback in order to overcome any initial difficulties [2]. In order to study these effects, it is important to develop methodologies for establishing objective metrics of performance in tasks involving the perception and spatial reasoning about anatomical structures.

The purpose of this project was to develop an application that provides stereoscopic visualization of anatomical brain structures in order to have an objective tool to test the

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residents' and medical students' knowledge of the spatial relationship of anatomical brain structures, allowing for real time rotation and translation of individual anatomical features in 3D and supporting 3-degrees-of-freedom (DOF) input for selection of points in the 3D virtual workspace. The software was designed to be part of a study on the evaluation of Anatomical Training techniques, and so was used to test users' knowledge of brain anatomy in 3D, and their ability to localize features in the context of a 3D surface rendering of the brain. We have developed an evaluative methodology in which the subjects view a neuroanatomical scene as a context, and are required to select an anatomical model of a target region, and place it within the 3D scene, specifying position and orientation using a 3D interaction device. Different structures within the 3D brain would have to be positioned and oriented by the user. In our case study, our task involves the neuroanatomical structures of the ventricular system.

Our methodology involves a visuo-spatial task which requires that subjects use an interactive 3D graphical interface to reconstruct a brain from its constituent anatomical features in the context of translucent surface renderings of these colourized components and the cortex. A separate task involves point localization, where the user specifies a location within the 3D Cartesian space using a 3 DOF input device to move a cursor within the scene, identifying the location of an anatomical feature of interest which is initially absent from the rendering. For both tasks, the users need to rely in part on effective stereoscopic visualization, in addition to using other depth cues in the displayed scene, in order to interpret and target the anatomical structures accurately. A primary design goal was to make this task as intuitive as possible in order to facilitate recognition and localization of the targets using the display and input device. As part of the evaluative methodology, various randomly initialized viewing directions are pre-set. The user must then locate and identify the position of a cued or absent anatomical feature at each rotation. The user's selection from each rotation is recorded and compared to a predetermined standard for accuracy, which depends on the feature being tested. The task time for selection is also recorded, so that we may apply a Fitts's model [3] to analyze their performance on this task.

2. Background

The need for this system is driven by the lack of standard tools that allow neurosurgical residents to be objectively evaluated on their spatial reasoning skills, and their spatial anatomical knowledge within a neuroanatomical context. While there are numerous training tools and surgical simulators that allow exploratory learning in virtual reality contexts [4,5], there is a lack of tools and methodologies for testing critical knowledge of spatial relationships as well as spatial reasoning abilities in an objective manner. Indeed, numerous studies aiming to evaluate novel anatomy training programs often rely on subjective feedback [6] or traditional written knowledge-based tests which fail to represent the inherent 3D space that anatomical features span [7]. In addition to providing the means for objective evaluation, users can also be trained through an iterative practice and feedback routine using this natural interface. It is hoped that this tool will allow for evaluation of various anatomical learning modalities ranging from traditional textbook learning to virtual reality teaching tools such as this one. Widely employed traditional anatomical learning techniques, such as printed-diagrams and cadaver dissections, present a number of limitations [8]. Two-dimensional representations, in particular, are not able to convey the complex inter-relationships of 3D structures easily. Virtual reality teaching tools aim to rectify these limitations by providing controlled, portable and relatively inexpensive environments where complex spatial relationships inherent to neuroanatomy can be easily conveyed as well as rendered for interaction. It is widely believed by medical professionals that virtual models can enhance medical education [9], but it has been seen that not all visualization and rendering models are equally effective [10] and so optimizing the design of such visualizations is an active area of research [11,12]. One common issue seen in many computer visualizations is an increase in cognitive load due to the need to reason about the interface between the user and the software [13,14]. A difficult aspect in introducing new anatomical teaching tools is in evaluating their effect on student knowledge and performance. Often, such evaluations are based partially, or sometimes completely, on subjective measurements based on user experience [15–17]. Part of the issue stems from the fact that there is no standard for testing knowledge and understanding of complex spatial anatomical relationships in this applications domain, and studies often evaluate these abilities through two-dimensional testing [17].

Our goal was to develop a tool that could objectively evaluate subjects' understanding of spatial relationships within a neuroanatomical context and provide a setting for practicing the application of such knowledge. In addition, our aim was to provide a natural and simple interface to reduce cognitive load introduced by the system, allowing users to focus entirely on the task and not the interface to it.

3. Design considerations

3.1. *Use requirements*

The primary requirement of the system was to be able to provide anatomical high-density surface renderings with maximal depth cues in real-time, while allowing the user to interact and to specify spatial locations using a 3-DOF input device. A methodology was also developed in conjunction with this system to evaluate user performance in targeting a desired location in space within the brain, or placing a neuroanatomical structure in the correct location based on additional anatomical knowledge. All points and structures were to be placed within a surface rendering of the brain's gray matter, which was rendered with appropriate transparency so as to not to occlude the view of other structures and 3D cursors, and also to be visible to the user. In addition, the system provided a mode to allow evaluators to setup experimental sessions for the user. The overall requirement of the software package was to assess user spatial skills and neuroanatomical knowledge, therefore permitting its use as a testing tool, as