Temporal Bone Dissection Simulation

of commodity-based computing, we believe, will facilitate the adoption and early adaptation of simulation technologies (NRC–1997). Acceptance of these environments can take place only after data sets have been certified and system efficacy has been proven through controlled validation studies involving multiple institutions.

C. Preliminary Studies and Rationale

C.1 Medical Simulation, Other Surgical Trainers

The interdisciplinary team of clinicians, computer scientists, technologists, and radiologists presented within this proposal has been involved in the adoption and adaptation of emerging and enabling technologies to medical simulations and surgical training for over a decade. Our early studies correlated structural information from magnetic resonance images with functional data from electroencephalograms into integrated displays used for investigating drug and alcohol addictions, and sleep disorders (Lukas 1993, 1994). Subsequent work involved the development and evaluation of three-dimensional volumetric displays of patient specific data as compared to traditional methods in the study of brain and cranial base tumors (Wiet 1994, 1996, Bier-Laning 1996, b-Yagel 1996, Wiet 1998, Stredney 1999, 2000,Wiet 2001). Concurrent work involved simulations for training anesthesia residents in the delivery of an epidural (Stredney 1996, Hiemenz 1996,1998). The epidural simulations were our first investigations into integrating volume graphics with haptics (force reflecting technology). Using volumetric techniques, we also simulated pelvic compression neuropathies associated with birthing (McDonald 1997). Subsequently, we were part of a multi-institutional effort to develop and evaluate a Functional Endoscopic Sinus Surgery simulator that integrated visual and haptic interfaces. Our group was actively involved in two parallel developments, one that focused on surface-based representations (Edmond 1997, Weghorst 1998), the second focused on volumetric representations (Rosenberg 1996, a,c,d-Yagel 1996, Wiet 1997, Rudman 1998).These studies showed that although surface-based representations were expedient and could provide interactive rates, they lacked the complexity and realism found in volumetric displays (Stredney 1998). The ENT Surgical Trainer, as it has come to be known, has recently been identified as the first true procedural surgical simulation environment to undergo vigorous validation (Gallagher 2003).

Encouraged by emerging techniques such as texture-based rendering, we continued to focus on direct volumetric rendering techniques. Direct volume rendering eliminates the expensive pre-processing needed for indirect methods, maintains underlying complexity, and provides an avenue to exploit patient-specific data. These recent developments and our work defined below establish feasible and cost effective methods to create realistic real-time representations of temporal bone surgical technique and procedure. These advantages provide a direct pathway to eventual integration of patient specific data for use in diagnosis, pre-operative assessment, and treatment planning. However, the critical step of evaluating the simulator as compared to traditional dissection techniques remains.

C.2 Temporal Bone Dissection Simulation

Within the past three years we have developed a seamless, multimodal environment for simulating temporal bone dissection (Wiet 2000, 2001, 2002, Bryan 2001, Stredney 2002). We have pursued a direct volumetric approach to render the structural model of the temporal bone. Because of recent developments in commodity computing hardware, a more cost-effective, realistic, and robust system is emerging. This approach allows us to integrate anatomical variance more directly than surface-based approaches. Our preliminary evaluative trials demonstrate that we have reached a level of sophistication for the system to be useful in resident training as an adjuvant to traditional temporal bone dissection with cadaveric specimens. Through several presentations at national conferences (Wiet 2001, Stredney 2002), as well as direct communications, we have received expressed interest from other key institutions, national and international, in being involved in this effort (see appendix). The integration of our techniques with commodity-based graphics and computing provides a unique opportunity to pursue a cost-effective multi-institutional study to establish the efficacy of the system and to facilitate the adoption and development of more accurate and useful simulation technologies.

C.3 Task Analysis and Description

Our initial task analysis comprised reading manuals (Nelson 1991), texts and atlases (Schuknecht 1986, Glasscock and Shambaugh 1990, Donaldson 1992, Swartz 1998), viewing CDROMS (Brodie 1997, Blevins 1998), viewing videos, attending surgeries, and performing dissections in a temporal bone lab. Because the dissection lab emulates the surgical approach, a task analysis of temporal bone dissection and surgery presents similar, if not identical, ergonomics (see Fig. 1 below). The resident/surgeon sits comfortably in an adjustable chair. The specimen, or patient, lies directly in front of the individual and is visualized indirectly through a binocular microscope. In dissection, the extricated bone specimen is placed in a specialized bone cup that firmly holds it in place. The dominant hand usually controls the drilling burr, while the contralateral hand controls a combination of irrigation/suction. A foot pedal controls the action of a variable speed drill. The basic task requires the progression from superficial to deep exposure through the iteration of *identify* and *expose*. Structures are initially *identified* through visualization and/or contact with subsequent underlying structures *exposed* by slowly and carefully removing thin layers of bone. Bone color provides a strong cue for localization to critical structures, such as the lateral canal, facial nerve, and sigmoid sinus. Often auditory cues are used to identify location; such as when approaching the sigmoid sinus, the vibration of the drill changes on the dural plate (Nelson 1991). Irrigation/suction is used to remove debris from the surgical field. As the surgeon/resident proceeds through the material, care must be taken not to contact critical nerve, sensory, and vascular structures. Some structures, such as the facial nerve, are not directly exposed but instead are "skeletonized" to assure location, decompression, and to prevent iatrogenic injury. Our extensive task analysis provides the basic concepts for our design and methods manifest in our virtual system. Through close attention to these details we have achieved strong face and content validity (Wiet 2002, Stredney 2002).

Figure 1~~1~~: Left: Surgical scenario. Right: View of temporal bone lab scenario.

C. 4 System Description

To emulate the functionality of the temporal bone lab , we have chosen the following specific interfaces**:**

??

?? **Visual** -- A Virtual Research V8™ binocular display. This display provides an unencumbered stereo view of the simulated environment at a resolution of 640x480 per eye, best approximating the operating microscope. Each eyepiece can be individually focused and inter-pupillary distances can be adjusted similar to any set of field binoculars.

?? **Haptic** -- A 6 Degree of Freedom (DOF) (3DOF force feedback) Sensable PHANToM™ provides the emulation of the variable speed drill and irrigation/suction. We use a 1.5 PHANToM™ for the drill, and a Desktop PHANToM ™ to emulate the suction/irrigation.

?? **Aural** -- Simulated sounds of the drill and suction are played through a set of stereo desk speakers.

The current simulation system (see Fig, 2 below) supports an arbitrary dissection of both a left and right virtual temporal bone, with sufficient anatomy segmented to simulate a basic mastoidectomy. We are implementing data sets that support approaches to the facial recess, epitympanum, and facial nerve decompression. The simulation includes stereo presentation with aural and haptic feedback. During bone removal, interactive visual (**stereo**) rates peak at around 20 frames per second, with an average of approximately 15 frames per second. Haptic feedback is computed on the virtual drilling burr by a spherical force-field of virtual springs which sense their distance to the volume using ray-cast techniques (Bryan 2001). Synthesized audio is generated from a combination of multi-harmonic sinusoids and white noise. These sounds are modulated based on drill speed and the haptic response. This system provides the most robust simulation of the temporal bone dissection environment available to date.

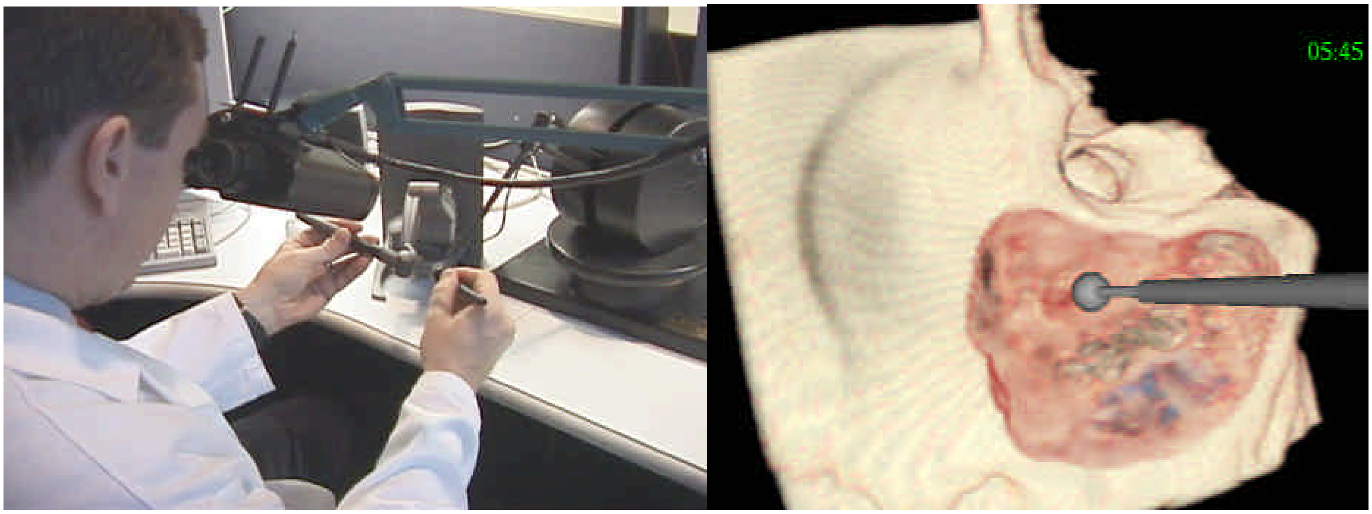

Figure ~~2~~2: Left: Current system configuration. Right: monocular view of simulated surgical field (Note: discoloration of underlying sigmoid sinus).

C.5 Data Acquisition

In any simulation, the quality of the model is the most important factor not only for realism and fidelity, but also inevitably for usability and transfer. Our initial development data was obtained using a dry skull specimen (right side only) and was acquired on a spiral CT scanner at Children's Hospital, Columbus, and resulted in a 64MB anisotropic volume with a voxel resolution of 0.35mm inplane resolution and a 1mm slice thickness. Our second data set (bilateral) was acquired with a single-detector row CT scanner (CTi; GE Medical Systems, Milwaukee, Wis.). A fresh (< 24 hours after death) cadaver was scanned in situ and reconstructed using the following parameters: section thickness of 1.0 mm using a helical acquisition with a pitch of 1.0; gantry rotation time of 1 second; x-ray tube voltage of 120 kV; x-ray tube current of 200 mA; an imaging field-of-view of 10 cm; images reconstructed every 0.5 mm (50% overlap between adjacent sections). The imaging protocol yielded 1.0 mm thick axial images of the temporal bone with a 512 x 512 image matrix. Image resolution was therefore 0.19 x 0.19 x 1.0 mm. These acquisitions provided excellent structural data for the development and initial evaluations of the system. We define more intricate and novel approaches to data acquisition in the methods section.

C.6 Segmentation

Segmentation is the delineation of structural or functional subsets of a data set used in three-dimensional reconstructions. We have integrated our semi-automatic segmenting software with the above physical interface (See C.4 above) to facilitate the segmentation process. The segmentation software allows one to interactively establish a transfer function to optimize the demarcation of structural or functional subregions within the volume rather than image by image. This is expeditious to the slice-by-slice segmentation experienced by previous authors (Sando 1989, Kuppersmith 1997, Mason 1998). The system allows the user to view the structures in stereo, and to use the haptic device to validate location of a tool to mark (3D paint) the actual structure, with a single voxel of precision if required. These masks "tag" volume elements with structural or functional information, i.e., information that is surgically relevant but is independent of structure (See Figure 3 below). In addition, the system allows for arbitrary sectioning of the data. Thus segmentation can occur not only on surface structures, but on internal structures as well. This provides an extremely intuitive environment for segmentation, allowing the user to "paint and feel" in real-time e.g. the curves of the semicircular canals. In addition, the system allows several user-imposed constraints; including the option to write over or to preclude write over of existing segments, or to select only structures within a certain threshold value. In addition, a revert function allows the user to correct any mistakes. We will make this software available to participants in the multi-institutional study to facilitate the integration of their local data sets for use locally and nationally. We will provide this software free of cost, and will train them through tutorials and courses at national meetings so that they may develop their own local data sets to be shared in federal repositories. We present our methods to validate the accuracy of our segmentation in Section D.Methods.

The following structures have been segmented and are available in the current simulation (See Figs. 3 & 4 below). These structures provide the basis of surgical navigation within the simulated regional anatomy. By having these structures segmented, we can highlight them during the simulated procedures, and evaluate with precision the proximity of the surgical tools, e.g., precision of exposure and "nicking" nervous or vascular structures. These metrics are tracked and used in the scoring and documentation of the user's performance. Additional structures will be determined by the participants in the study to provide a minimum set that can be expected when structural data sets are shared.

External Acoustic Canal
Suprameatal Spine
Suprameatal Triangle
Temporal Line
Mastoid Process
Mastoid Tip
Posterior Canal Wall
Zygomatic Root
Mastoid Antrum
Koerner's Spetum
Sigmoid Sulcus

Superior Petrosal Sinus
Facial Canal
Lateral (horizontal) Canal
Superior Canal
Posterior Canal
Digastric Ridge
Posterior Fossa Dural Plate
Middle Fossa Dural Plate
Articular Tubercle
Internal Acoustic Canal
Cochlear Canaliculus

Vestibular Aqueduct
Jugular Fossa
Cochlea
Carotid Canal
Mandibular Fossa
Round Window
Tympanic Ring
Stylomastoid Foramen
Styloid Process
Ossicles

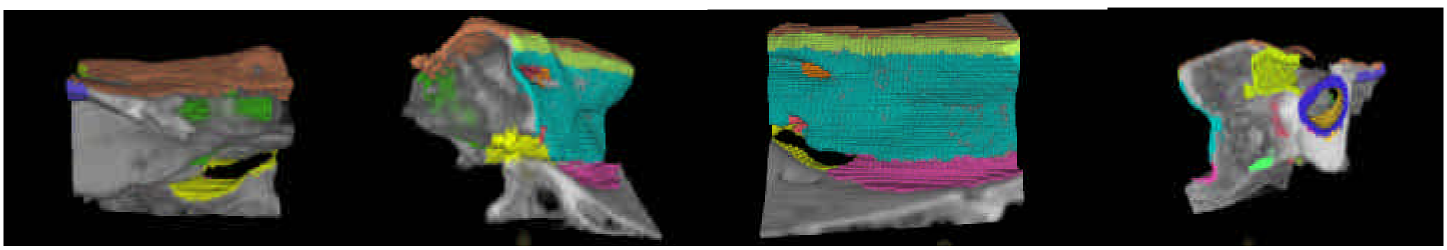

Figure 3~~3~~: Section of trimmed temporal bone reconstructed from CT. Functional segmentation appears tinted. Left to Right, anterior, medial, posterior and lateral view.

C.7 Functionality

The dexterous interfaces provide the following basic functionality during the dissection/simulation. The user peers into the binoculars to view the entry menu. The PHANToM™ provides the ability to choose and select by moving the device in space and clicking on the fingertip control. The system currently provides access to bilateral temporal bones. Once a data set is chosen, the user can change from the **surgical mode (3D)** to the **function change mode (restricted to 2D)** at any time by clicking the finger clip on the PHANToM™.

In the surgical mode, the system is completely non-deterministic, meaning a user can drill away at bone at any location with any selected type of burr. The foot pedal allows the user to vary the speed of the drill. Different sizes and types of burrs provide a unique haptic signature based upon the amount of pressure and speed of the drill, as well as the local characteristics of the bone. If the user applies too much pressure, the haptic device emulates the resistance and kickback of a natural drill.

When the function change mode has been selected, the user can select the menu (left) tool selection (center), or exit the program (see Figure 4 below). In the upper left, the state control and commands are displayed. In the upper right, a clock with 5 second increments is displayed to track time to task. At any time, the user can return to the surgical mode by simply clicking the fingertip control. These intuitive actions allow users to work easily in both 2D and 3D through the binocular display.

The tool selection menu allows the user to select the type of drill burr, either a tungsten carbide cutting or diamond burr, and the size of the burr, in 1mm increments. A spaceball™, a 6 DOF dexterous interface, is used to arbitrarily change the orientation of the virtual specimen. This is similar to reorienting the bone cup in the temporal bone lab or requesting the anesthesiologist to roll the patient in the OR. The drill can be either used to palpate the specimen or, through the use of the foot pedal, engaged to arbitrarily remove bone.

The Menu (lower left) allows the user to enter into a mode that provides access to an intelligent tutor. We believe that it is important to provide the user multiple ways to query and receive information from the system to reinforce learning and advanced knowledge acquisition, especially pertaining to complex structural relationships (Feltovich 1989). To witness an expert perform the operation, the user can select ED (for Expert Demo). At this point, the system plays a simulation of how an expert previously performed the procedure. This is not a prerecorded movie. The simulation is run from a previous expert session that was captured to file. The user is free to use the spaceball™ to arbitrarily modify the viewing parameters of the expert demonstration. In the expert demonstration mode, the simulation controls the tools.

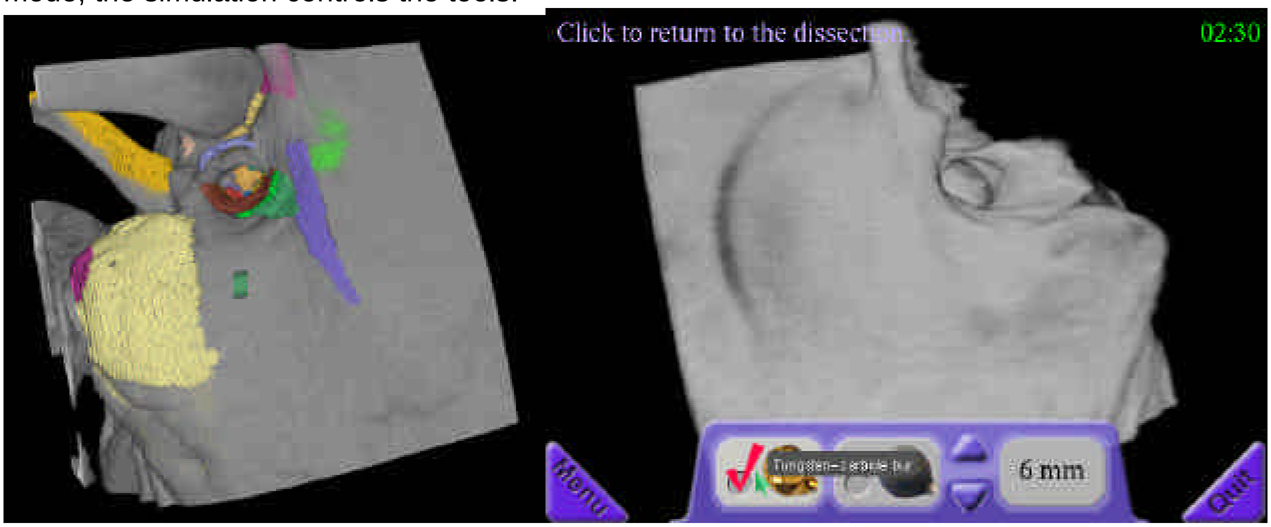

Figure 4~~4~~: Left: Colored areas of segmented regions: Right: View from simulator showing tool selection menu

For assistance in identifying structures, the user can select ID (Identify). The ID mode bifurcates into either the “ASK” mode or “TEST” mode. The TEST mode requests the user to contact a specific structure. Again, the spaceball™ can be used to arbitrarily orient the data. Upon correct selection, a new structure is requested, or the user can return to the surgical mode.

In the ASK mode, the system will fork to either “WHAT” or “WHERE”. In the “WHAT” mode, the user simply touches various structures on the temporal bone. The structure closest to the tool will be “spoken” by a precorded (AIFF) file stored in memory and played through the desktop speakers. In this way, the user can arbitrarily ask “What is this structure I am touching?” The system will respond with a recorded voice message. In the WHERE mode, the system will display a list of critical structures (see segmented list above). One or more structures can be selected. Once a selection is completed, the system displays the structures tinted, with the remaining bone semitransparent to orient the resident (see Figure 5 below).

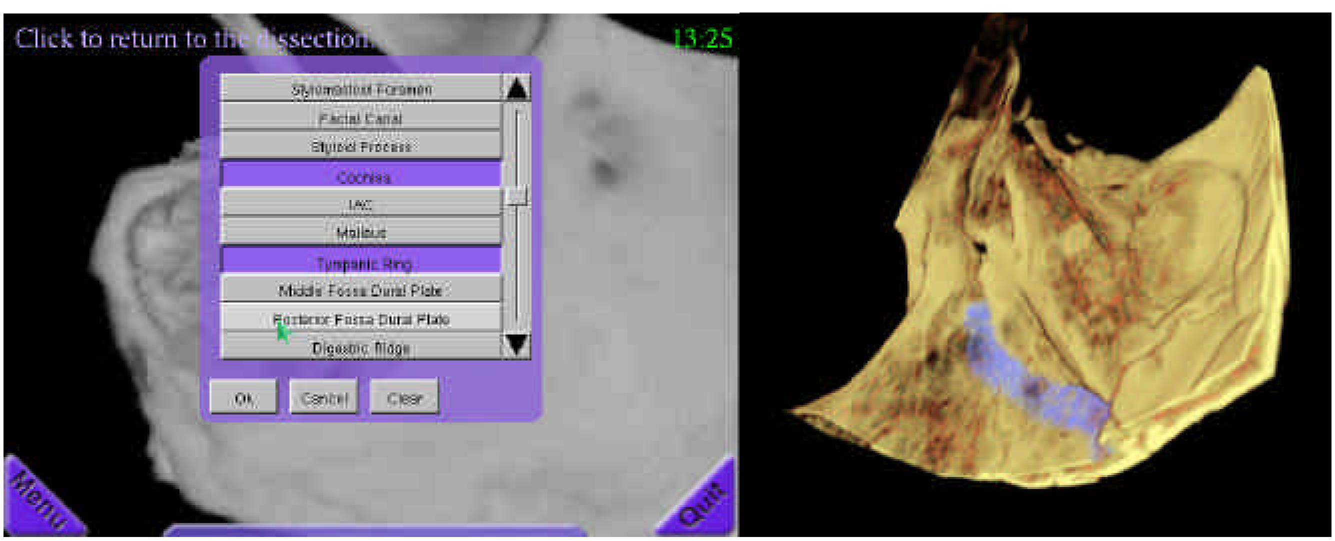

Figure 5~~5~~: Left: Menu of Structures in the "WHERE" mode. RIGHT: selected structure (sigmoid sulcus) tinted and displayed for viewing.

C.8 Initial Testing

We held several formative evaluations at OSC with the local expert faculty to establish face validity. There also reported on content validity, **including the accuracy of the data and segmented structures**, the sequencing of the system, and the type of performance metrics that are collected to file.

We subsequently presented the simulator at the American Academy of Otolaryngology-Head and Neck Surgery Foundation (AAO-HNSF)annual meeting in Denver, September 9-12, 2001. In addition, we conducted evaluation sessions at the Department of Otolaryngology at The Ohio State University Medical Center, during the week of October 1-5, 2001 (see Figure 6 below). Under an IRB approved protocol for testing interface technology (see Section E), 53 subjects evaluated the system for aspects: usefulness of the visual representation; comfort of the interface; fidelity of sensations; and ease of overall use. Last, the subjects rated the system compared to other methods of learning temporal bone dissection (See Fig. 7 for summary). Overall, our results from this study suggest that the system is acceptable to a varied population of otologic surgeons. The only significant differences within the study populations were that: 1. Expert and older surgeons tended to give lower scores on comparison to other forms of learning, and 2. People who were more comfortable with computers tended to give higher scores for comfort of the interface and fidelity of sensations. Respondents gave high marks for the overall utility of the system (Wiet 2001, 2002). As expected, user feedback indicates that both visual quality and haptic fidelity require further improvement. The results from our studies indicate that the simulator has immediate potential for improving anatomical training in an otololgy curriculum.

Figure 6~~6~~: Left: Simulation at AAO-HNSF conference. Right: System under evaluation in Dept. of Otolaryngology, The Ohio State University

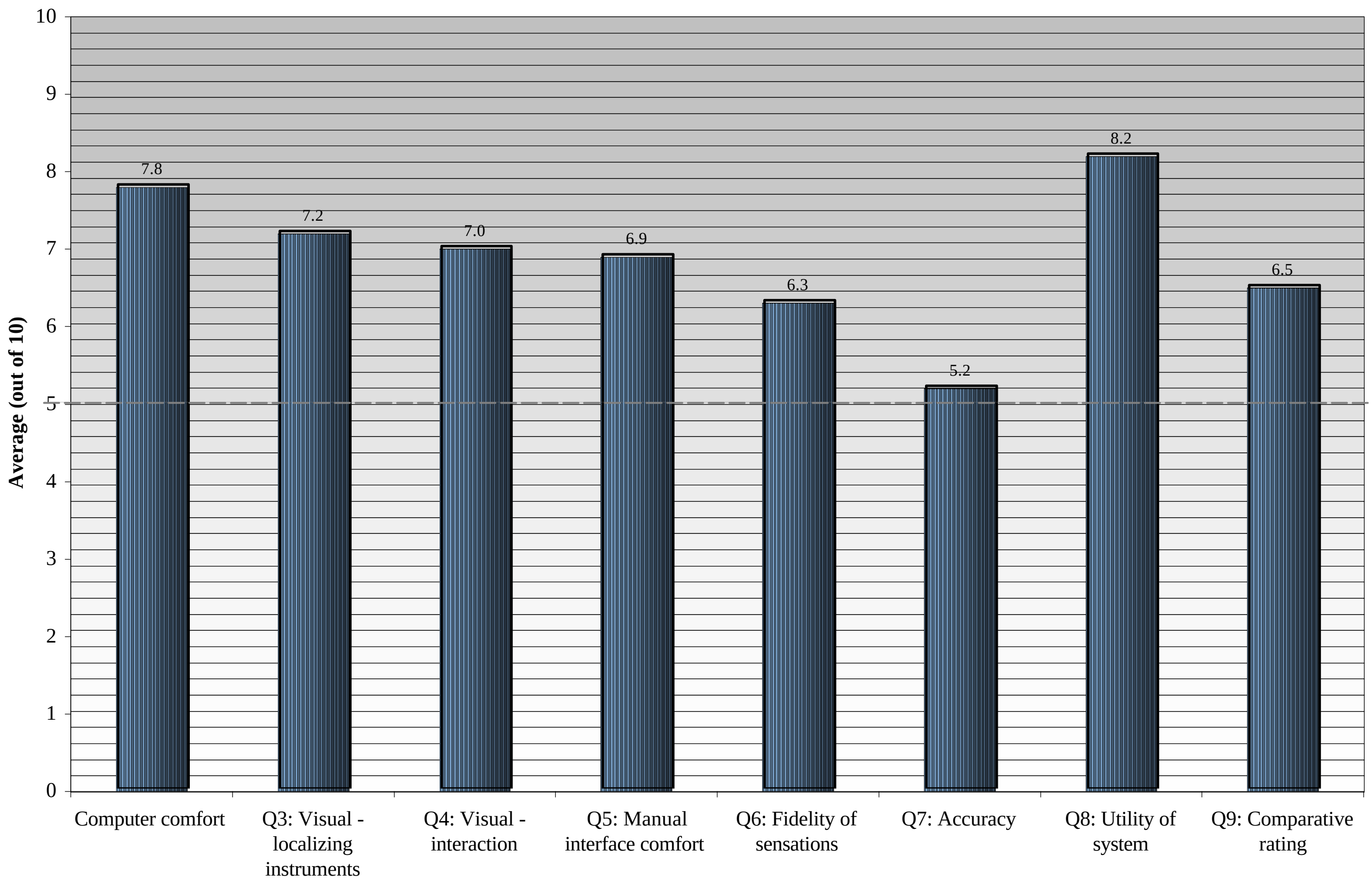

Figure 7. Average score over all respondents to the survey questions

C.9 The following publications are specifically relevant.

Wiet GJ, Bryan J, Dodson E, Sessanna D, **Stredney D**, Schmalbrock P and B Welling, "Virtual Temporal Bone Dissection" Proc. MMVR8, Westwood et. al., (Eds). IOS Press Amsterdam;2000:378-384

Wiet, GJ, Stredney D, Sessanna and J Bryan. "Volume-based Temporal Bone Dissection Simulator," AAO-HNSF/ARO Research Forum, Annual Meeting of the American Academy of Otolaryngology-Head and Neck Surgery Foundation, Denver, Colorado, September 9-12, 2001

Bryan J**, Stredney D,** Sessanna D**, Wiet GJ**, "Virtual Temporal Bone Dissection: A Case Study", Proc. of IEEE Visualization 2001, San Diego, CA, 2001:497-500.

Stredney D, **Wiet GJ**, Bryan J, Sessanna D, Murakami J, Schmalbrock P, Powell K, and DB Welling, "Temporal Bone Dissection Simulation – An Update", Proc. MMVR10, JD Westwood et al, (Eds.) IOS Press, Amsterdam, 2002:507-513.

Wiet GJ, **Stredney D**, "Update on surgical simulation: The Ohio State experience" Accepted for publication in Otolaryngologic Clinics of North America. June (2002).

Wiet GJ, **Stredney D**, Sessanna D, Bryan J, Welling DB and P Schmalbrock. "Virtual temporal bone dissection: An interactive surgical simulator", Otolaryngology-Head and Neck Surgery, July (2002) 79-83.

Wiet GJ, Stredney D, Sessanna D, Bryan J, Welling DB and P Schmalbrock. "Virtual temporal bone dissection: An interactive surgical simulator", Otolaryngology-H&NS, July (2002) 79-83.