Design of Perceptualization Applications in Medicine

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ABSTRACT
We are in this position paper presenting the experiences we have from three medical application projects. A user centered design methodology have been applied in order to ground the design in requirements gathered from field studies of professional medical environments. Methods used have been interviews, user observations in the work context and cooperative evaluations of prototypes. With a particular focus on haptic (touch) feedback, we are exploring how novel medical applications can benefit from feedback to more senses than vision and how needs can be revealed and transformed into effective design.

Keywords
User centered design, perceptualization, haptics, medical applications

INTRODUCTION
In this position paper we will report on the application of User Centered Design as a valuable method when developing medical applications that aim at exploiting the benefits of perceptualization techniques, i.e. visualization extended to audio and haptic feedback. We propose that grounding medical software design in user requirement data gathered from field studies and prototype-based user studies are an effective and efficient way of improving complex medical procedures of today. This will be discussed based on the following three cases:

Case 1: Oral surgery simulator
Case 2: Liver surgery planning
Case 3: Heart simulation

The radiologist and researcher Ratib [23] argues that ”It is important to convey to device manufacturers that a wider adoption of multi modality imaging techniques such as PET/CT in clinical routine will be properly enhanced only if the technology has an effect on the whole process of patient management and not just on achieving higher diagnostic accuracy” and that “an important step in the process of patient management is the collegial discussion between interpreting and referring physicians, surgeons, and oncologists who review the images together to make an appropriate decision” [23]. We suggest that applying a User Centered Design method that also addresses aspects of collaborative work is very well suited to fill these needs.

BACKGROUND
We will here give a brief description of User-centered design and how we applied it, perceptualization theory and the field of surgical simulators.

Application of UCD in the medical domain
A method is qualified as a User Centered Design method as defined by ISO 13407 if the method includes four distinct design activities that form one development iteration [11]:

1. understand and specify the context of use
2. specify the user and organizational requirements
3. produce design solutions
4. evaluate design against requirement

The iterative nature of this process leads to gradual improvements of the product, as well as allowing for early changes of the direction of application development.

To understand and specify the context of use contextual inquiry [4] is used which involves field studies with observations of the intended users workplace and on-site interviews to elicit user needs. Much emphasis is put on understanding how the future users of the system carry out their tasks today, and the field studies are rather designed to get a broad description of the workspace than of obtaining detailed requirements. In an ethnographic study of multi-disciplinary medical team meetings, Kane et al. [13] show the importance of the radiologist and pathologist being able to point to specific areas in the medical information (radiology images and pathology samples), as it is an essential part when presenting their statements to the other participants in an inter-disciplinary meeting. This kind of information is fundamental to consider in a design process in order to develop a system with good validity. In our studies annotations are made of video recordings and audio recordings of interviews. The results of the analysis of the data gathered in field studies together with concurrent technical feasibility studies informs the requirements and design recommendations. These recommendations are in turn used as a basis for implementation of lo-fi or hi-fi prototypes. The primary evaluation methods used are cooperative evaluation and observations of groups of collaborating users. Cooperative evaluation is a method where the user is given a task to solve with the prototype, and the user and the evaluator is allowed to discuss the interface during the session. The user is also encouraged to "think aloud" [20]. A rather new approach to "think aloud" is evaluating users that collaboratively solve tasks which allows the researcher to observe the complex and often more realistic use of a system [19]. The users discuss the task with each other while using the system and that result in a more natural kind of "think aloud" data that most probably does not add as much to the cognitive load of the users as traditional "think aloud". The analysis of the dialogue provides information about problems in the design of the system. This method also reveals how well the system supports social interaction.

Perceptualization

Perceptualization is an emerging research field that expands visualization to utilizing several senses such as hearing and touch. Just as the purpose of visualization is mainly insight, and not necessarily realism, the purpose of perceptual-ization is insight and to afford exploration of data in an effective and efficient way. The research presented here aims at exploring how advanced interaction devices can support medical professionals analytical work by providing feedback to more senses than vision.

One example is making it easier to analyse the images from ultrasound-based diagnostic medical imaging. Already today colours in Doppler echocardiography represent information such as the direction and velocity of blood flow. Researchers have however shown that temporally distributed events such as velocity and direction are easier to perceive kinesthetically (touch modality) than by vision and even better by hearing the information [15]. In a perceptual perspective colour coding is might not an optimal way of representing that kind of information.

The most spread use of haptic feedback systems in medical applications are simulators for training surgical procedures and robot assisted surgery [21]. Haptic sensing is defined as "The use of touch in combination with motor behaviours to identify objects" [2]. With a haptic feedback system it is possible to feel the shape, weight, texture, friction and stiffness of an object and for example collisions between objects. In collaborative virtual environments it is also possible for each user to feel the other's persons pulling and pushing forces on shared objects or the other persons cursor.

Our sense of touch and kinaesthetics is capable of supplying large amounts of intuitive information about the location, structure, stiffness and other material properties of objects. Providing feedback to more human senses in interfaces makes it possible for humans to access more of their brain capacity [15] or more popularly stated, it increases their cognitive bandwidth. It has been shown [5] that the integration of senses in multimodal environments is done implicitly in the perceptual system by statistically optimal integration. This means that the addition of touch is of increasing importance with decreasing quality of the visual impression. While some applications may see only marginal improvement in user performance and understanding others may depend entirely on the successful integration of the haptic modality. Also, with the increasing size, detail and complexity of data presented in volume visualization environments it is of increasing interest to augment the visual impression with information obtained via other complementary sensory channels. Thus, the integration of haptics with volume visualization has potential to significantly increase the speed and accuracy of volumetric data exploration as well as improved interactivity.

It has also been shown that the design of the haptic feedback is of utmost importance. Choosing the wrong haptic representation of a feature in data may result in poor understanding or even misinterpretation of the features at hand [22]. This further stresses the importance of user centered design in the application development.

Surgical simulation

Simulation of surgical procedures is a popular and important application of perceptualization technology such as haptic feedback. The goal with a simulator is usually high realism that makes the person using it feel that it is a real patient or object she is handling. Meijden and Schijven [18] review a number of studies with VR-simulators and results indicate that haptic feedback is especially useful when it comes to achieving psychomotor skills. Haptic feedback has been implemented in applications for surgery simulation, bone drilling and virtual prototyping [3, 21].

Simulation-based training of laparascopic procedure has proved to improve the performance of novice surgeons as well as ensure they reach required skill level prior to practice in real operations [1, 17]. The conventional apprentice-based training of surgery is being challenged, since supervised practice in operating theaters are expensive and occupies teachers for long time. In 2009 United Kingdom implemented the European Working Time Directive to limit surgeons working hours to 48 per week. This have led to complaints by the president of Royal College of Surgeons who argue that trainees do not gain enough experince anymore [10].

In the field of medical simulation for training a distinction can be drawn between scenario mannequins and task trainers. The scenario mannequins often consist of a full scale human mannequin with some simulated behavior and it is often remotely controlled by a technician that can suddenly invoke a heart stop or something similar. The scenario is prepared in beforehand by the teacher and technician and the purpose is often to teach team skills in critical situations. The task trainers, on the other hand, often simulate a specific procedure or are designed to improve the student's fine motor skills. Many of the laparoscopy trainers are of this type. According to Johnson

[12] this type of simulators builds "on an understanding of medical practice as being made up of constellations of discrete skills that can be learned separately and out of context, and then put together in the examination or operating room to create a complete medical procedure". That implicit knowledge or situation-based experience is important, is also argued by Giles when he states that the simulators (task trainers) only cover a small part of the surgical curriculum, even though he acknowledge their value and fit for purpose [10].

CASE 1: ORAL SURGERY SIMULATOR

The first case in this paper concerns a surgery simulator for teaching. The purpose of this project is to allow for dental students to practice surgical extraction of wisdom teeth in a risk-free virtual environment together with a supervising teacher.

Figure 1 Oral surgery simulator

Design process

To form a mental model of what was possible to implement within reasonable time, a technical feasibility study was conducted in advance. Previous work, such as a temporal bone surgery simulator [3] shows that haptic feedback enabled virtual reality based simulations can well be used for training of bone drilling tasks. To find out what is the most important aspects of the procedure that is new to the students, a contextual inquiry method was applied that involved observations, interviews and experimentation. These studies revealed some of the tacit knowledge the surgeons depend on such as haptic perception of different tooth and bone material.

Application

The oral surgery simulator consists of a physical and visual model and provides haptic and audio feedback. The monitor is aligned in a way such that the user looks with stereoscopic shutter glasses through a mirror that makes the visual and virtual haptic model co-located and that allows the user to feel the model where she sees it (figure 1). In the image, a ray-cased based volume rendering of bone and teeth are projected within an artificial 3D face model. The purpose of the face model is to limit the view as is the case in real life. A physical head model (mannequin) is also used where the haptic device is located to limit the physical work space of the haptic device and to give the correct hand support. With the haptic feedback device, the user can feel the shape of the teeth and resistance and vibrations while drilling with differences depending on material such as bone, enamel and dentin. A segmentation map of the volume also keeps track of where the user should and should not drill, and which parts can be removed with the tools (drill and elevator). A state-machine progress the user through the procedure. These features are all designed based on data from field studies [7].

Results

The work has resulted in an open architecture and open source software, as well as a particular simulation model for training of surgical extraction of wisdom teeth. Results from cooperative evaluation sessions showed important design considerations such as shading and coloring of the teeth, physical hand support and positioning of dental instruments. Shading is an important clue for seeing texture and depth in the rendering [6].

In an independent course intervention study of the oral surgery simulator conducted by Karolinska Institutet in Huddinge, 73% of the 60 course participants very much agreed on that this simulator training should be a permanent part of the course [24].

Preliminary results from the latest evaluation suggest that the best benefit from the simulator is the opportunity for the teacher and student to discuss the procedure freely while performing it repeatedly. The simulator is used as a mediating artefact that makes it easier for the teacher and the students to contextualize theory, makes instructions more concrete and makes it possible to teach tacit knowledge like what forces to apply, drilling angles and depth etc.

CASE 2: LIVER SURGERY PLANNING

Our second case is a visualization tool for supporting decision-making. In the liver surgery planning project, the objective is to explore multi modal technologies for enhancing communication in medical multidisciplinary team meetings concerning patient specific liver surgery planning.

Design process

In these multidisciplinary team meetings, a patient case is introduced by a surgeon and discussed while a radiologist presents radiological diagnosis along with the patients' medical images as shown in figure 2 [9]. The images are mostly contrast-enhanced computed tomography (CT) but also magnetic resonance imaging (MRI) and ultrasound images are displayed. Although they occasionally display pre-computed (non-interactive) 3D volume renderings, gray-scale 2D slices are the standard way of presenting.

Figure 2 Multi-disciplinary team meeting

An understanding of the context of use has been obtained by observation analysis of video recordings of real meetings. The radiologists use their standard workstation for this demonstration, but utilize scrolling and pointing with the mouse cursor to indicate regions of interest. The discussion is often related to the location and dimension of one or several tumors in relation to blood vessels and other organs. The surgical audience has to mentally reconstruct the region of interest in the 2D images to the 3D anatomy, which can be challenging. When the radiologist is absent, as when a surgeon is revisiting the case report before a surgery, the surgeon has to depend on their ability to perceptually link the verbal descriptions in the reports even though some markings in the images exist. For this reason, have our research group proposed an interactive radiology report system where verbal statements can be directly linked to image annotations [14].

Furthermore, our observations showed a need for improved visualization and for new ways for the audience to interact with the data to enhance communication between radiologists, surgeons and other specialists. In one case, a surgeon uttered "oh, is it that big?" referring to a tumor, half-way through the discussion, although the radiologist had shown images and attempt to state the size prior to the discussion. Gestures were also made in the air by the surgeons in the audience that indicates a need to point at specific parts of the patient images, to get the radiologist to show more of some specific data or zoom in on details or to show where the surgeon planned to cut in order to take out the tumor. These pointing behaviors were however very imprecise as the surgeons did not have access to any other means of interaction than gesturing with their hands.

Application

To allow for a richer visualization while leaving the radiologist with a familiar interface we developed a software solution that combined visualization of 2D slices of a Computed Tomography volume, with a stereographic visual and haptic rendering of iso-surfaces of the same volume (figure 3). With a haptic feedback device, the surgeon is able to feel the size and shape of a pre-segmented tumor, and distances to contrast-enhanced tissues. The two views are linked in such a way that the radiologist can scroll the stack of slices and point with the mouse cursor, which is shown simultaneous in the 3D view along with the position of the current slice. The position of the haptic device proxy is also displayed in the 3D view.

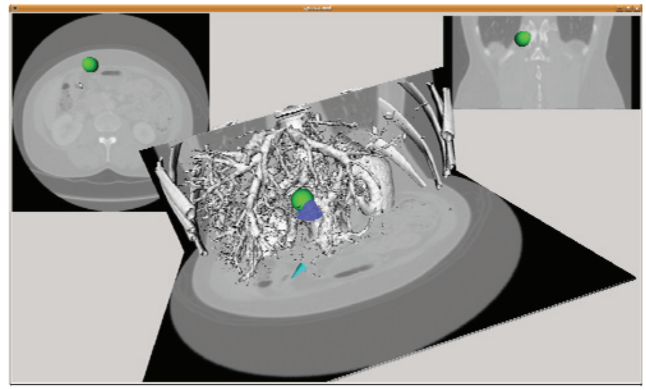

Figure 3 Collaborative surgical planning tool

The purpose of the haptic rendering in this case is not to simulate the feeling of performing surgery, but rather as an additional perceptual channel to explore the dataset. In the prototype, a binary classification based on the attenuation level in the images is used, and all voxels (after filtering) above a threshold are perceived as hard material.

To support several haptic feedback devices, a custom network haptic device proxy has been implemented, where each haptic device is controlled by a dedicated computer sending position and receiving calculated force over a local network with a measured ~800 Hz update rate.

Evaluations of the system with expert users are currently performed and it is too early to report on results from those. Suggested future work is to evaluate the concept in the natural setting, the medical multidisciplinary team meetings concerning patient specific liver surgery planning, as well as improving the feasibility of multiple haptic devices.

CASE 3: HEART SIMULATION

In the third project the added value is investigated of including multi modal feedback in a simulation of a human heart that is based on ultra sound data with the purpose to support experts that perform physiological examinations. In this recently started project the requirements are currently gathered for the design of a future simulation-based diagnostic tool for clinical physicians.

Design process

Based on a finite element method simulation of blood pressure and velocity inside a geometrical model of left ventricle of a human heart, derived from a arbitrary patient, the goal is to be able to predict heart dysfunction of a specific patient given certain attributes as input to the simulation. Both the parameter input and the resulting simulation should be perceptualized to allow a trained physician to draw quantitative as well as qualitative conclusions regarding a patient's health .

It is too early to report on results from evaluations of the system. However, findings regarding the context of the clinical physician's workplace show conspicuous differences between dedicated machines and workstations. The ultrasound machines used (GE Vivid 7 Dimension) provides sonification of ultrasound data that might assist in detecting abnormal heart rhythms. The machine also provides an interface with physical knobs, sliders and buttons. However, for post-processing and analysis, the physicians use a conventional keyboard-mouse workstation, even if the software comes from the same vendor.

The interface differences motivate further investigation, especially regarding useful sonification and tangible interface properties. Interpretation of ultrasound data is a complex practice that involves both quantitative estimations and qualitative conclusion generation. We are currently exploring the technical feasibility of perceptualizing both visually and haptically the geometrical deformation of the simulation as well as simulated blood flow.

DISCUSSION

While all three of the presented cases in this paper are related to surgery and uses similar technology, only the oral surgery simulator is focused on training. In the heart project, the application data comes from a simulation but the application itself should not be considered a simulation since the data is pre-computed. It is important to distinguish between a data-altering simulation and a pre-computed simulation based perceptualization where the goal is to perceive the data that has been generated as a result from a simulation.

The simulator we have developed for training surgical extraction of wisdom teeth is primarily a skill trainer, but in our studies of how the teacher supervising students uses the simulator results indicate that the learning it supports depend a lot on the communication between the student and the teacher that is mediated by the simulator. This is in accordance with the theories of Johnson regarding what she calls reconstitution to "create medical practice out of simulator practice" [12]. That is, during the simulation the participants, a student and a teacher, help each other to mentally create a patient out of the simulated patient and to make a surgeon of the student including the embodied knowledge that is needed (the way the student is positioned etc). Johnson mentions a situation with a laparoscopy simulator where the teacher explains the relative position of the instruments by pointing to his own leg. The same job could be achieved by using a mannequin leg but that would be more expensive and the point is that the teacher's gestures were sufficient. Also known as suspension of disbelief, this is a requirement for users to accept the simulated artefact as real enough for the purpose, in this case learning a surgical procedure.

The transition of focus from the simulator working as a stand-alone surgical trainer to primarily being an artefact that mediates and enhances the discussion between the student and the teacher suggests the need for additional alternative design solutions. Future research will include functionality that specifically support the dialogue between the teacher and student such as non-realistic rendering of the tooth and jawbone. Future evaluations will focus on how knowledge gained from training on such simulation would transfer to skills performed in the operating room.

When the focus is on supporting communication the whole design process shifts towards designing for mediation of dialogue and then designing specific functionality for mediated communication becomes important. Making that focus shift is rather novel in the area of simulation and perceptualization but is inevitable when applying a user centered approach today as most systems are used by groups of people as well as by individuals.

CONCLUSIONS

We have demonstrated the potential of applying user centered design methods to design and engineering of medical applications that strive to exploit the benefits of perceptualization, with a particular focus on haptic feedback. By following the proposed method, engineers could arguably design innovative systems that have larger impact on real work. In a recent issue of Communications of the ACM, the future of haptic feedback is discussed with the underline "After more than 20 years of research and development, are haptic interfaces finally getting ready to enter the computing mainstream?" [25]. Several haptic scholars are interviewed and the speculation is that haptics might take the same path as touch screens, that has existed for a long time but suddenly - with the iPhone - took off as a mainstream technology. Professor Colgate states the requirements for such to happen: "The technology has to be sufficiently mature and robust, there has to be an active marketplace that creates competition and drives down costs, and it has to meet a real need." [25]. We hope this paper has contributed with examples of how a user centered design process can support system designers in finding the required real needs of the professional users in the medical domain.

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