

User interface prototyping to understand radiology thinking

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Abstract Recent technological solutions for image-guided therapies focus on replacing the cognitive processes of physicians. However, there is a lack of knowledge in the field of cognitive ergonomics regarding radiology image thinking, such as image interpretation and 3D navigation. This paper addresses the need of studying mental models in this context. The goal is to be able to design better user interfaces for advanced technological solutions which match the cognitive processes of physicians. The usefulness of employing a prototype in the early phases of development is shown through the example of oblique view interpretation. Recommendations are given how user interface prototyping can be used to study mental models.

1 Introduction

Radiotherapy and interventional radiology procedures require the physician, the physicist, or technician to read a set of 2D radiology images (e.g. Computed Tomography (CT) or Magnetic Resonance Imaging (MRI)) in order to plan, perform and evaluate a treatment. These 2D images represent the 3D anatomy of the patient, which has to be mentally reconstructed and manipulated in order to make decisions for certain steps of a treatment, such as planning the trajectory of an ablation needle or a radiation beam. 3D reconstructions may provide a general 3D understanding of the scanned body part, but these images do not provide detailed anatomical information for the planned treatment. Furthermore, interaction with 3D images is restricted to basic operations, such as rotation and zooming.

Many research and technological solutions focus on replacing the cognitive processes of the physician with computationally supported visualizations, simulations and decision making, for example, segmented tumors or vessels are shown to support spatial orientation and navigation, or images are registered to exploit the combined information coming from multiple sources (e.g. when one modality clearly visualizes the tumor and the other can be used for real-time navigation) [1].

The current research was conducted as a preparation for a larger project to develop a new interface for 3D ultrasound image guidance. Integration of registered CT or MRI was considered as possible future technology. To achieve smooth integration of new technologies in the interventional scene, technological developments are sup-

ported by designing novel user interface solutions, studying cognitive ergonomics, as well as workflow redesign.

However, there is actually little knowledge about cognitive ergonomics in this field, such as how physicians can interpret and interact with segmentation overlays on radiology images or how they can interpret and navigate based on new forms of images. The main undiscovered areas for example are mental models of anatomy, mental manipulations of anatomy, spatial orientation, and navigation using radiology images. In order to be able to develop efficient 3D navigation support, a better understanding of cognitive ergonomics related issues is necessary.

The investigation addresses the need for understanding mental models of physicians in order to develop user interfaces which fit their thinking processes. While it is a general problem regarding radiology image thinking, in this paper this need is presented through the example of interventional radiology. The form of mental models and their manipulations are hard to reveal, because they are not directly available to the outsider [2] and it is difficult for people to externalize and verbalize mental models and processes. This paper reports on experiences in using an interactive prototype to study cognitive processes of physicians in the early phases of development and for iterative improvement, as opposed to only using the prototype to test usability. The difference between these two approaches will be explained in subsequent sections. Finally, recommendations will be made on the properties of the prototype which are crucial in order to obtain the expected results.

2 Mental models and manipulations

In general, mental models are internal representations of external reality, such as objects, situations or working principles of a system [3]. In medical image usage it includes aspects such as anatomy, physiological processes (e.g., temperature changes because of blood flow), etc. In the current phase of our research, we restrict the usage of the term to represent spatial mental models of human anatomy as perceived, interpreted and mentally constructed based on 2D radiology images. As the physician scrolls through a series of radiology images and observes the anatomy from different viewpoints, (s)he constructs a 3D mental model in his mind.

Radiology images are usually taken from predefined viewpoints which are orthogonal to the human body. Anatomy drawings for training, as well as CT/MRI scans show orthogonal cross-sections of the human body. These are the reference images the physician can fully interpret, that is, (s)he is able to maintain spatial orientation, locate structures and identify structures based on their contours. They are also the images based on which a physician can construct a mental model of anatomy. Images taken in oblique orientations are generally difficult to interpret and are not trusted. Manipulation of the mental model is necessary during medical image usage [4].

In order to achieve successful 3D navigation, the physician needs to maintain spatial orientation, that is, to be able to correctly identify anatomical locations in the human body and to understand the spatial relationships of surrounding organs or tissues [5]. The navigational goal of the physician is to guide the needle or a beam through a trajectory that is safe for the patient by avoiding vital structures, and to end in the target position, e.g. in a tumor.

3 Methods and materials

3.1 Approach

Cognitive processes of physicians were studied. This means attaining insight into the (tacit) knowledge of physicians which is built up from natural human capacities, combined with trained skills and experience in practice. Furthermore, specific understanding of cognitive strategies of manipulating 3D models of the patient's anatomy in the mind. The aim was to come up with theoretical models of 3D navigation and mental manipulations and to use in the design of matching user interface solutions.

3.2 Methods

The following methods were used for studying mental models: ethnography, explorative studies with the prototype, comparing results to vision science (in-depth literature study) and proposing a theory, and validation of theory by interviewing doctors. These methods are presented through an example in Section 4.2.

3.3 Materials

The current version of the prototype includes a number of hardware and software elements. The elements were chosen to accommodate the cognitive ergonomics investigation, and also to support following development phases, such as usability testing.

- Visual Studio 2005 was used as programming environment and the code was written in C++.
- To visualize objects from different viewpoints Coin3D was used for 3D graphics (www.coin3d.org). This was needed to attain sufficient fidelity regarding response to motor control of tools, essential for understanding mental model coupling to hand motions.
- For rapid user interface development and to design flexible user interfaces Qt (<http://qt.nokia.com/products>) was used. This is a crucial property: user feedback should lead to quick and substantial changes in user interface, i.e., doable in one evening for next round testing with significantly changed interface.
- Coin3D and Qt was integrated using the SoQt libraries.
- For handling volumetric data SIMVoleon was applied. 3D data are needed in radiology prototyping as mental models and navigation are 3D in nature.

- For easy integration of the user interface Virtual Reality Peripheral Network (VRPN) (<http://www.cs.unc.edu/Research/vrpn/>) was used.
- Motion tracking was used to provide real-time visual feedback about the tracked instrument: Ascension's Flock of Birds device (<http://www.ascension-tech.com/>).
- To create a volume out of a series of axial CT slices that is usable by SIMVoleon a Matlab (<http://www.mathworks.com/>) script was employed.

4 Results

4.1 Prototype roles

According to our experiences, using an interactive prototype is useful for:

- *Explorative studies*: Novel interactions, as they may be imagined in the final design, can be explored. Putting the user in a real clinical situation, and by providing multiple solutions at the same time, the future user can explore which solutions are the most efficient.
- *Workflow studies*: When interacting with the prototype and explaining what users are doing and thinking, it is easier for the engineer to understand the clinical workflow. Users tend to recall previous cases which can further deepen this knowledge. Difficult situations and similarities to other procedures are also explained.
- *Mental model studies*: Observations combined with thinking aloud and interviews are general methods for mental model understanding. However, observations in themselves are useless for the observer without (deep) clinical knowledge to make assumptions about physical and cognitive actions of the physician, due to the minimally invasive nature of the procedures in which difficult imaging modalities and subtle hand movements are applied. Concentrating on the treatment, physicians are only able to provide a very limited amount of information during the procedure. Deep interviews may bring up knowledge about the treatment, but this knowledge is mainly procedural. The physician recalls the procedure and explains the experienced difficulties, but being disconnected from the real situation, this method is inefficient to study psychomotor actions. Having an interactive prototype which simulates the real situation provides a relaxed way for the physicians (without harming the patient) to express themselves and for the researcher to ask specific questions. Reactions often bring up issues about learning and experience.
- *Communication*: Inefficient communication and misunderstandings are highly limiting factors in multidisciplinary projects. Discussions over an interactive prototype are useful to communicate ideas to the future end user and to correct for wrong assumptions in early phases of design. Besides, communication of other team members, such as industrial designers, computer scientists and imaging specialists becomes easier as well.
- *Experiencing interaction*: By actually experiencing the interaction (e.g. planning a needle trajectory or adjusting the needle to the planned trajectory with real-time visual feedback), the user does not need to imagine how an interaction concept

would work in reality. Furthermore, also the non-medical researcher can experience the interaction, and can have a feel of the physician's work.

- *Co-design and idea generation*: Try-outs of the prototype naturally bring up improvement possibilities as well as new ideas.

4.2 Example: oblique slice interpretation

A prototype was designed to test some new user interaction concepts using CT datasets for two interventional radiology tasks: (1) evaluating needle trajectories and (2) following a planned trajectory. The following interactions were available:

- Traditional orthogonal views (axial, sagittal, coronal)
- Views related to the needle: slices that are orthogonal to the needle (needle-dot view: looking from the point of view of the needle), and slices which contain the entire needle line (needle-line view: rotation around the needle)
- A preoperatively planned needle trajectory in all views
- Real-time feedback about the current position of the needle (as a needle line)
- Arbitrary control of CT images while observing them from different viewpoints (selection of any oblique slice)
- A volumetric view containing the dataset (as a block form), the planned needle trajectory, as well as real-time feedback of the tracked needle and the clipping plane (which defines the oblique plane). This view was designed for spatial orientation, not for visualizing 3D organs.

Before the test, we had some *assumptions* regarding the two alternative ways of assessing critical tissues and trajectories:

- The needle-dot view is useful to check all oblique slices perpendicular to the needle in order to see where the needle intersects the body and to decide whether it is a good trajectory or not. The idea is to look from the point of view of the needle, from the skin to the tip of the needle inside the body (or the other way around), slice by slice, having a view on the needle trajectory and its close surroundings.
- The needle-line view clearly shows the route of the needle having the entire needle trajectory in view that can be inspected from different angles.

The *goal* was to know how the novel interactions are used by physicians and what kind of information they provide and add to the current situation.

The *reactions* of the physicians were ambiguous. Although the idea of having better ways to evaluate the needle trajectory was appreciated, the oblique views were not used or not trusted, because:

- It conflicts with the cognitive strategies of the radiologist: they learn to look at images which are orthogonal to the body. In general, the axial view is enough to build a 3D mental model, and other orthogonal views are used to better localize structures.
- In the oblique slices structures are distorted (as compared to orthogonal slices which are the reference images for physicians), and makes interpretation (identifying contours for organ localization, shape understanding and estimating distances) and spatial orientation difficult.

As a positive mental model related example, it can be mentioned that the use of the tracked needle was highly appreciated. It was used intuitively, and its movement was immediately understood in relation to the dataset (a foam phantom was used to represent the human body). Reportedly, this kind of navigation resembled needle navigation in the real clinical situation. It was also advised to use as a training tool to learn spatial orientation.

Interestingly, the needle-dot view was useful for adjusting the needle line to the planned trajectory. As it was said, it is similar to another procedure in which the X-ray beam is set orthogonal to the needle. This is an example when user-system interaction meets user experiences.

After the test, we wanted to know *what the reasons* are for the difficulty of interpreting oblique views.

- From physicians, we learned that they conflict with the mental model of radiologists.
- According to vision science literature [6], selecting an oblique slice is not an obvious task and cannot be imagined as a cutting operation. It is probably done through a set of mental rotations. Unfortunately, mental rotations have not been studied in this context.

Findings of vision science led to a *new assumption*: interpretation is easier when an orthogonal slice is rotated to an oblique slice. We also learned that radiologists work with spatial references (e.g. they always use previous needle insertion attempts for new trials (left, right, 1 cm further, etc.)). Another possible solution could be a well-designed spatial reference system or spatial reference links, which improve interpretation of oblique slices.

Our findings were *validated by physicians* through interviews who confirmed the difficulty of oblique slice interpretation and also confirmed the need of oblique slices by giving clinical examples. Actually, some doctors develop their own strategies to be able to work with oblique slices, while others use their old strategies.

5 Discussion

5.1 5.1 Prototype recommendations

Development started on an experimental low-cost research platform that facilitate requirements analysis, and exploration, communication and clarification of ideas by enabling fast changes in the software. Besides this, we recommend to take care of three important properties of the prototype: interactivity, flexibility, and fidelity.

Interactivity We experienced that prototypes facilitating the design process of navigational systems of radiology images have to be interactive due to the constantly changing environment that cannot be captured in, for example, a paper prototype. Interactive prototypes enable exploring both physical and cognitive aspects of human-computer interaction while providing a realistic situation [7]. An interactive prototype is necessary because of the complexity of interaction. This way, the practitioner does not need to image how the proposed system would work, which reduces misunder-

standings and allow the researcher to focus on the studied problems. Other investigations also revealed the necessity of working prototypes in this context [8].

Flexibility Flexibility was an important factor of the experimental prototype. It was beneficial that the number, size and layout of interface elements were easily changeable to represent certain functionalities, a specific part of the treatment or specific user groups.

Fidelity To gain initial insight into the cognitive processes of physicians in early phases of research, it was crucial to provide them with a high-fidelity prototype on certain dimensions [9]. Mental model navigation in the mind is coupled to motor movements of the hand and to image guidance feedback as well. These dimensions therefore had to be high-fidelity. Considering other criteria the prototype could remain low-fidelity, e.g., in the first test a foam phantom was used; that was good enough. Also functionality was intentionally kept on a low-level of fidelity; there was no focus on overall system usability. Functionalities are gradually built into the prototype as our knowledge grows.

5.2 Mental model studies vs. usability testing

Table 1 presents the difference between using the prototype for usability testing and mental model studies in terms of goals, fidelity and expected results.

1 Mental model studies vs. usability testing

Method	Goals	Fidelity	Results
Usability testing (prototype testing in clinic or lab)	<ul style="list-style-type: none"> • Performance (e.g. time) • Accuracy (e.g. number of mistakes) • Recall (e.g. remembering after a period of time) • Satisfaction (e.g. confidence, stress, enjoyment, visual appeal) • Cognitive limits (e.g. number of menu items) 	Mixed-fidelity: fidelity requirements (as always) depend on the research target. E.g., if accuracy is measured, registration has to be perfect. In usability testing there are predefined targets defining which part should have high fidelity and which do not need it, or would even distract.	Errors and improvement possibilities; To some extent learning about user reasoning and behavior
Mental model studies (prototype explorations – combined with ethnography and vision literature study)	Understanding of cognitive processes (e.g. image interpretation)	Mixed-fidelity (for the same reasons). In the current study: <ul style="list-style-type: none"> • Low fidelity: functionality was restricted • High-fidelity: visualizations and interactions resembled the clinical situation 	Models of radiology thinking: <ul style="list-style-type: none"> • models of radiology image interpretation • models of 3D radiology navigation

6 Conclusion and future work

We have proposed to study mental models of physicians to be able to design better user interfaces for novel technological solutions. Unfortunately, there is little knowledge about modeling of radiology thinking in literature. From our prototype studies it was learned that mental models of engineers may differ from mental models of physicians, which can lead to communication problems and to ineffective user interfaces of new products. Although an example was presented from the field of interventional radiology, the problem is also valid for other fields of radiology image interpretation and navigation, such as radiotherapy. Using low-cost, interactive and flexible prototypes from the very early phases of development is a useful method for studying mental models of physicians, as well as to resolve communication and design problems. Next steps in our research will be: next iteration mental model research, requirement analysis, idea finding usability testing and clinical evaluation.

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