Situated cognition in clinical visualization: The role of transparency in GammaKnife neurosurgery planning

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Summary
Objective: The aim of this study was to investigate how the clinical use of visualization technology can be advanced by the application of a situated cognition perspective.

Methods and materials: The data were collected in the GammaKnife radiosurgery setting and analyzed using qualitative methods. Observations and in-depth interviews with neurosurgeons and physicists were performed at three clinics using the Leksell GammaKnife\textsuperscript{1}.

Result: The users’ ability to perform cognitive tasks was found to be reduced each time visualizations incongruent with the particular user’s perception of clinical reality were used. The main issue here was a lack of transparency, i.e. a black box problem where machine representations “stood between” users and the cognitive tasks they wanted to perform. For neurosurgeons, transparency meant their previous experience from traditional surgery could be applied, i.e. that they were not forced to perform additional cognitive work. From the view of the physicists, on the other hand, the concept of transparency was associated with mathematical precision and avoiding creating a cognitive distance between basic patient data and what is experienced as clinical reality. The physicists approached clinical visualization technology as though it was a laboratory apparatus—one that required continual adjustment and assessment in order to “capture” a quantitative clinical reality.

Conclusion: Designers of visualization technology need to compare the cognitive interpretations generated by the new visualization systems to conceptions generated during “traditional” clinical work. This means that the viewpoint of different clinical
user groups involved in a given clinical task would have to be taken into account as well. A way forward would be to acknowledge that visualization is a socio-cognitive function that has practice-based antecedents and consequences, and to reconsider what analytical and scientific challenges this presents us with.

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1. Introduction

Clinical visualization technology is today used in a broad spectrum of clinical settings and has attracted many categories of professional users. In clinical practice, several user groups often interact with the same visualization systems. These various user groups may have different task orientations when interacting with the same visualization system. As well, these users who are performing common tasks with the system may come from significantly different professional backgrounds. While the clinical literature does address the question of organizing physical collaboration [1], the cognitive issues that division of labor between professions raise in respect to the introduction of new visualization technology has not received the attention it should have. One area where visualization technology is used by several professional categories is surgery. Recent reviews have suggested that the operating room of the future could be an integrated environment with global reach [2]. Surgeons will use real-time three-dimensional reconstructions of patient anatomy, use miniaturized minimally invasive robotic technology, and be able to telementor, teleconsult, and even telemanipulate at a distance. When it comes to the design and development of such systems, attending to issues related to differences between user groups with regard to solving of cognitive tasks will allow us to develop more efficient technologies for the clinical workplace. Most importantly, it will help developers and end-users to address issues related to “same” and “different” that are present, but generally not acknowledged, in almost every clinical workplace. The aim of this study is therefore to investigate how the clinical use of visualization technology is influenced by situated aspects of cognition. Studies of situated cognition focus on the functional cognitive systems in which the clinical technology is involved. Here analysis focuses on the representation of the symbols, rules and images that factually are employed in practice [3–6]. Gammaknife radiosurgery is used here as an example. The technical application employed for the analyses is a radiosurgical system based on two parts: the Leksell GammaPlan (LGP) software for intervention planning, and the Leksell GammaKnife (LGK) for the surgical intervention.

The history and development of neurosurgery has been to a large extent technology driven. This is quite different from other related fields like neurology, where even today resistances to “abandoning” things that have worked well in the past have been reported [7]. What we find in neurosurgery is however not some technology driven form of practice. It is more of a feedback cycle where technology and practice influence together define and drive what gets constituted as “best practice”. In this context, a professional identity is built through training and experience, i.e. by the social contexts and structures within which neurosurgeons and those who collaborate with them are educated and work [8]. In this study we will focus on the role previous training and experience play when using visualization technology during radiosurgery planning. The principle underpinning radiosurgery is the use of gamma radiation to destroy tissue. In specific, the LGK is used for treating tumors as well as other non-functioning tissue of the brain. There is no need for open surgery and the patient is able to leave the hospital after a short time. The LGP runs on a desktop computer with a mouse and keyboard. To plan a neurosurgical intervention, LGP utilizes data from MRI (Magnetic Resonance Imaging) images and/or other imaging modalities to visualize the anatomy of the patient’s head and to localize the target volume(s). This anatomical data can be visualized in the form of 2D-slices and 3D-models of the patients’ head generated by using imaging information. The user defines the target by drawing contours with the mouse on the images. Radiation iso-centres (an iso-center is a focus point/volume of a large number of beams) are then placed inside the target(s) in such a way that the desired amount of energy is directed to the target cells. The amount of energy one needs to deposit inside the target is a mathematical function of the location of the target and the tissue surrounding it. During the clinical procedure, a stereotactic frame is attached to the patient’s head. Because certain parts of the frame are also visible on the MRI images, it is possible to locate the brain anatomy and target(s) in relation to the frame. The operator of the LGP uses these MRI images to perform the surgical planning. The treatment-planning step involves locating the position of the target(s) and determining where the “shots” of
radiation (size, duration, and strength) should be placed. A "shot" is the dose distribution created by irradiating a small volume of tissue by a large number of beams (201 beams in the case of LGK). When the patient is within the LGK for treatment, the stereotactic frame helps place the patient in the positions that corresponding to the plan’s representations.

The study was performed at neurosurgical clinics located at three European hospitals. At all three sites, neurosurgeons were involved with the patient management from the time of admission. They decided whether the patient was suitable for LGK radiosurgery, even if they did not perform the actual intervention planning themselves. In the clinic where the physicists did the planning, their work started when a patient was ready for the MRI. Physicists and radiographers also maintained the LGK system. This largely meant checking the precision of the LGK system so that the dose rate measured in LGK was the same as the dose rate calculated and used by LGP. There were also control units that had to be checked regarding safety issues. In both countries where the clinics were located, it was a legal requirement that a physicist had to be in the department. However, the law did not specify that a physicist had to be present at each treatment. The procedure and division of labor when handling the Gammaknife and the Gammaplan can be described in five steps.

1. Diagnosis—This is always done by a surgeon, often with the help of a radiologist who analyzed the patient images. The surgeon decides whether the patient is treatable or not by LGK.
2. Stereotactic frame placement—To hold the patient’s head in a fixed position during imaging and treatment a stereotactic frame was attached by screws to the head. This is always done by a neurosurgeon, sometimes with the help of a nurse or a medical physicist.
3. MRI—The analysis of the MRI images is often carried out with the help of a radiologist. The planners, physicists and neurosurgeons, were all present at the MRI unit to indicate which pictures of the patient they wanted to use in the planning process. Sometimes image were made with other technologies than MRI, such as CAT (Computerized Axial Tomography). One reason for this might be that a patient had a pacemaker or other metal in his/her body.
4. Planning—In two clinics (the two in Sweden) the planning was performed by neurosurgeons and in the U.K. clinic by physicists. In one Swedish clinic, a physicist assisted the neurosurgeon during the planning, while the neurosurgeon did the actual interaction with the LGP. The planning procedure makes use of anatomical images and these images (coronal, axial or sagittal) are used individually or together to make a model of the patient’s brain. In the actual planning after identifying targets in the images, a treatment planner outlines the target(s) for the intervention on the monitor screen. The planner then places isocentres inside the target so the target is irradiated to the extent required.
5. Neurosurgical intervention—There was always a physicist nearby but not always in the actual room. First the stereotactic frame’s position is checked so there are no potential collisions or interferences between the frame and the LGK treatment. The actual treatment was performed differently in all three clinics. At one, a nurse supervised the treatment. At the second, a neurosurgeon and nurse supervised the treatment. At the third, in England, a radiotherapist carried out the treatment, since in the UK the law states that only a radiotherapist can deliver radiation therapy.

2. Methods

Qualitative methods were used for the data collection and analysis. Observational studies were made at three clinics that use the LGK and the LGP.

2.1. Data collection

As a first step, field observations were conducted at three clinics. The observer (DD) spent 72 h observing at the clinics, the time being evenly distributed among the three sites. During the observations, about 15–20 patients were followed through treatment. In addition to this, planning, follow-up and discussions associated to other cases was observed. Unstructured questions were asked during day-to-day practice at all sites. The observer used naturalistic observation techniques, i.e. he was present but did not participate in the actual interventions. Also, the observer sat in at staff meetings and patient discussions and discussions between the planners. These occurred when a planner had a difficult case and wanted advice and/or a second opinion. In short, the observer participated in all five steps described above. The interviews were audio-recorded and the material transcribed at the level where every word, words or phrase repetitions, and longer breaks were noted in the transcription.

In the second phase of the research, six in-depth interviews were carried out, two with physicists and four with neurosurgeons. These semi-structured, open-ended interviews lasted between 1 and 3 h.
Each started with participations describing the LGP/LKP procedure. The interviewer then discussed, in each interview, the positive aspects and possible pitfalls in each of 1–5 steps. The interviews also recorded subjects such as personal history (educational and experience at clinics), technology issues related to patient care and usability issues related to the GammaKnife system.

The experience with LGK among those interviewed ranged from 3 to 36 years. At all three sites, the observer was introduced as a person who had no ties to the system manufacturer. However, the subjects were informed that research results were to be delivered to the company as well as published in the research literature. This is because in both practitioners were similarly educated but the manufacturer had noted differences in LGP/LKP procedures. This provided an opportunity to collect data from sites that contrasted in important ways e.g., in structure and procedure from one other. This strengthened the kind of data that was possible to collect. This in turn made possible to carry out a more robust kind of data analysis than otherwise would have been possible.

2.2. Data analysis

The data analysis rested on the transcribed text and the notes taken in the field. The primary analysis process involved data categorization, building relations among data categories, relating these constructs to theory, and finally validating research conclusions against the data collected. When this process reached a saturation point, a preliminary report was presented for the study participants for comments. Their remarks led to the final version of the report. Even though the main approach was inductive, the qualitative analysis was also informed by theory. The basic theoretical grounding employed was mainly Barley’s and Wenger’s work [7,8]. Of particular use was Wenger’s discussion of how socio-cognitive processes vary in different communities of practice. In this way, the development of neurosurgery as a profession was linked to the history of neurosurgery and neurology as described by Star [9].

3. Results

3.1. Visualization in radiosurgery

All LGP sites used images of the brain. Derived largely from MRI technology, these anatomical representations are the planner’s main information source. As one physicist put it:

“Doing the planning you are blind, you just got the images” Quote 1, Physicist 1

However, there is much left for the end-user to interpret in these representations. While any picture can “tell a story”, the stories neuroradiological images tell are seldom straightforward. When it comes to LGP surgery, the story (diagnosis, opportunities for treatment, and prognosis) emerges not from the images itself but also from discussion and debate. Images, individually and collectively, are evidence that has to be interpreted in order to make clinical statements about “what is really going on here” and “what needs to be done next” [cp. also [10]]. There is significant difference, neurosurgeons believe, between open neurosurgery in which you can actually see and touch the brain and LGP interventions where this is not possible. In open surgery, it is also easier to monitor what others involved in the treatment do, since it is directly visible to the eye. In LGK surgery, in comparison, what one does alone with LGP partly substitutes for the coordination work that is so much a part of traditional neurosurgery. Further, the actions taken with LGP and LGK are only visible on computer monitors. This raises a number of issues that designers/developers have not taken into account regarding clinical validation and verification given that neurosurgeons believe that the “laying on of hands on the patients is the hallmark of ”real” clinical work. Further, visualization (reading radiological images) is not so much a process of inspection (a literal, direct reading of an image) as it is one of interpretation [see [11]]. This rests of course on the operator’s prior experience and competence in linking together, at a particular time and place, “textbook” knowledge of neuroanatomy, the patient’s history, the results of laboratory tests and whatever images a planner has at hand. LGK clinical intervention with imaging as the main visual input, not the laying on of hands, however can lead to new clinical practice routines and innovations. These include the possibility to discuss and analyze from a common knowledge base before the intervention, to back track and try alternative strategies during planning (since the representation is digitally recorded), and to get remote second opinions both before and during clinical interventions. This could help redefine how particular clinical tasks get done, and in fact alter what has been treated as stable (traditional) divisions of labor. Barley [7] suggests that innovations in technology use can provide more than just occasions for innovation or resistance in workplace. These changes can also be both an occasion and a resource for reflection that can lead to reinventions of both self and practice. Visualiza-
tion technology may not only reinforce established socio-cognitive labor and forms of clinical work. It can, like analog images did before it, lead to reflection, in and out of the clinic that over time can redefine what practitioners have seen as standard and fixed practice.

3.2. The concept of transparency in clinical visualization

The Gammaplan gives users a representation of the “brain” derived from digital MRI “slices”. These images are the most important information source for surgeons and physicists have about a patient's brain and target(s), e.g. tumor(s). Of course the neurosurgeons and physicists also have the patient’s clinical history and the laboratory work that has been done on the patient. Besides the MRI images, there is also available to LGP users a 3D representation of the patient’s brain. Despite the strong claims advocates of visualization technologies have made for 3D, these operators seldom refer to or make any use of the LGP’s 3D representations.

"When you are an experienced [clinician], you have the 3D image in your head. You don’t need any software to see [the tumor]." Quote 2, Neurosurgeon 1

This raises the issue of whether we are, when it comes to some medical devices, designing and implementing what for end-users could be the “wrong” thing. It is not clear whether we know now enough about how 3D work is embedded in clinical and scientific competence. Nor is it clear whether we understand well enough how representations and operator competence provide resources or scripts for clinical action.

These end-users seemed to believe that the information provided by MRI images of the brain is more complete and accurate than any 3D representation. This has something to do with these users seeing digital slices as “closer to” the biological reality of the brain than any 3D representation could be. As one neurosurgeon put it

"You can’t plan this in 3D because you cannot see inside [the] 3D [images]. You only see the surface of a 3D volume. . . . you have to see the whole [inside] of the 3D volume and that is only possible when we slice up a 3D volume and look at it slice by slice" Quote 3, Neurosurgeon 2

With MRI “slices” only one set of machine operations is performed on the images. But to arrive at a 3D representation, other sets of operations have to be performed as well. While both the MRI brain images and the 3D reconstructions are derived from the same machine operations, to create 3D reconstructions other sets of algorithmic operations have to be performed as well. This, these users believe, further separates these images (and them) from the biological reality. This could be a historical dimension to this issue given that these users were often first trained to analyze 2D images derived from analog (X-ray) technology. However, no informant statement in this study seems to support this conclusion. But this does raise the issue of whether training on and work with analog and digital imaging technologies yields the same or similar epistemological results for clinical end-users.

In human–computer interaction design, transparency is often equated with software and hardware components that are “invisible” for the users. This means that they automatically adapt to individual users needs given a particular time and place. However, in this study, transparency meant something quite different to these end-users. Transparency refers here to the fact that 3D models can only represent the target’s surface. For this reason, a planner cannot from this kind of representation easily “build up” a picture of the tumor itself. In contrast, with slices, placed side by side, a planner can see both the tumor’s contours as well as the area of the tumor that is to be covered by an iso-dose. On the other hand, MRI images do pose for these users their own set of problems. This is particularly true when it comes to the issue of precision. MRI images, medical physicists believe, have come to represent, in respect to precision at least, the law of diminished return. Neurosurgeons are less concerned with this kind of gold standard of precision. They, like most clinicians, measure precision mainly in reference to treatment outcomes where one form of intervention is measured against another. For physicists however, transparency and precision are linked and equated with what they know and can measure. Here knowledge and measurement (and by extension precision) are seen as one and the same thing.

"This is like a chain. We know that we have a certain precision here. Then we have a certain dose that we empirically know that we have to give taking everything previously known and precision into account, and then we do it” Quote 4, Neurosurgeon 2

This statement raises two questions; How do clinicians and by what criterion define a successful treatment. A look at these issues can bring into focus the kinds of changes these neurosurgeons and physicists believe are necessary to improve the success rate of LGK surgery.

What the users of this visualization technology seemed to believe was that their professional auton-
omy, their ability to perform interpretive operations, was diminished each time there is yet one more “remove” from biological reality. To put it another way, the 3D representations provided by LGP were not seen as corresponding to nature. They were not “literal,” or “really” real. Further, end-users could not “match” their own understandings of how a 3D image should be “built up” and what it should look like against what LGP’s “black box” produces and displays as representations. Nor could the neurosurgeons and the physicists involved inspect, challenge or change the algorithms that are responsible for the form these LGP generated representations take. In brief, the considerable autonomy and authority these users derive from being able to make valid statements about brain and patient is deleted by both judgments embedded in these algorithms and the LGP representations that emerge directly from them. In other words, these representations called into question the competences these end-users have as physicians and scientists. This effect was even more obvious at the clinic where the physicists were doing all the planning.

3.3. Clinical impact of transparency

Even if the practitioners did not mention the actual word ‘transparency’ or ‘black box’ problems, they understood that algorithmic (machine) operations and representations “stood between” or “in the way of” the task(s) they wanted to perform. This was especially the case when the task was how to interpret MRI images so that the costs and benefits involved in LGK surgery would tip in the patient’s favor. What mattered the most here is that LGP produced a transparency that end-users did not want. This transparency paradoxically hid the data and information that was central to neurosurgical decision-making. The result was that neurosurgeons had to perform additional labor or cognitive work. This could be because LGP provided a different representation and intervention than what surgeon is trained for, and has much competence and experience with. For example, the feedback from traditional surgery is immediate and direct. Here action and representations as well as reaction times is quite different compared to LGP interventions where you first plan and then execute. With LGP, the feedback cycle is more linear, less direct. The physicists unlike the neurosurgeons did not focus as much on understanding the anatomical structure of the tumor. They were more concerned about how each step in the LGP intervention might cause loss of mathematical precision. This was particularly true of how LGP portrayed tumor boundaries and these representations, physicists believed would not, unless adjusted, lead to optimal clinical results. Because of how LGP reconstructed 3D brain images, the physicists were also unable to “open up the black box” to check what measures of precision had been employed. Nor was it clear how these measures and these representations had been validated. In brief, staff could not “get to” (inspect) the algorithms that governed how the LGP representations were “put together” given the evidence (one patient’s MRI slices) at hand. Note that this does not necessarily imply that the practitioners either wanted to challenge or change these rules. What they wanted was an opportunity to inspect the rules, to know what assumptions have informed them, and to see how this evidence and resulting LGP representations related to their previous knowledge, either in traditional surgery or with the mathematical methods physicists habitually use and value. In a word, they wanted to compare how the new LGP representations were constructed with how they build up and make sense of these images themselves. This was not a problem with the MRI images themselves. This is because what they “meant” was not only largely self-evident for the practitioners, these images represented something close to biological reality itself. It is worth noting that while the LGP’s 3D modeler was seldom used in planning, it was often used with good results in patient education when patients and their families wanted to be involved in the treatment process. This suggests that “transparency”, what it means and what it should represent is very much a function of audience and use.

4. Discussion

As we move towards the operating room of the future where surgeons will perform surgery using real-time three-dimensional reconstructions of patient anatomy, this study raises some cognitive issues that have not been systematically addressed in the literature. The aim was to investigate how the clinical use of visualization technology is influenced by the situated aspects of cognition. While transparency was a central cognitive issue for the clinical users of visualization technology, surgeons and physicists, we found, had different responses to how it was “built into” LGP. For neurosurgeons, transparency should mean that their previous experience from traditional surgery could be applied, i.e. that they were not forced to perform additional cognitive work. From the view of the physicists, on the other hand, the concept of transparency was associated with the mathematical precision and its con-
trol. This avoided creating an epistemological distance between the patient data and other clinical realities and representations. This all suggests that to design more intelligent visualization technologies, user aspects other than physical (ergonomic) work tasks have to be identified. By taking into account what different clinical users “bring with them” to the workplace, for example, what professional training teaches different practitioners to value, designers can avoid building design functionality that is not perceived as important or functional to end-users. The LGP 3D model in its current design exemplifies this, because it did not take into account well how the end-users integrate images, knowledge and clinical findings to make a statement about what needs to be done next for an individual patient.

However, the functional specifications for transparency need not be synonymous with a toolkit end-users can use to reach into and change the black box that defines the computer-generated 3D image. It may be enough, this research suggests, for users to be able to inspect (and understand) why representations of information that the visualization technologies they work with take the form they do. What each group of users wants to know is to what extent do the representations they count on to get their clinical work done are congruent with those their own experience, training, and competence tells them are useful and valuable. It is issues of this kind that need to be addressed in any discussion of what these representations “should look like” and the place they should have in supporting clinical decisions. Further, if system designers took these issues into account, not only would the visual technology be more useful for users, their understanding of (and confidence in) the tool would increase as well. Transparency does not necessarily have to be defined as one-to-one correspondence between the physical and its virtual representation. In fact attempts to provide just such correspondences with visualization technologies often represent a misplaced faith in a kind of common sense of mimetic literalism or naturalism. What representations should do instead is to make visible tasks and functions that end-users, not designers, find problematic. For example, in radiosurgery, a visualization technology that could support a seamless switching, as tasks shift, between 2D- and 3D-representations would be useful. This feature already exists in educational models of the brain [12]. Here users can switch from brain anatomy to a function module. In addition, the user can generate and visualize cross-sectional images corresponding to the MRI datasets for training purposes.

The role that technology has in creating debate and discussion has only begun to attract action in medical informatics. Technology is not just an artifact. It can be a resource that both supports and enables reflection about what actors often take to be standard practice. What may result are qualitative changes for example in work practice and such changes are the ones often difficult to get an analytical grasp on. In the case of LGK and MRI, these technologies and associated practices created alternatives in practice, discussion and debate compared to traditional neurosurgery. The impact may be similar to the change on clinical comprehension and discourse some believe will occur as traditional narrative paper-based patient records are replaced by structured electronic medical records [13]. But given that practitioners can reference a variety of different interpretations in whatever kind of neurosurgery they carry out, it is possible that these interpretative work practices “may bleed” into each other and lead to changes in both kinds of surgery. Experience with both kinds of surgery can certainly lead to revisions of what these practitioners mean by model, representation and evidence [14]. As these elements change over time, this can lead to change and innovation in surgical practice itself.

It is not clear whether a single set of representations, however robust, can support all the work that occurs in a heterogeneous workplace. The physicist’s clinical training helped them to redefine the role they would play in the workplace. Medical physicists also often acted as problem solvers in relation to the GammaKnife technology. In fact, at each site studied, physicists tended to form a strong community of problem solvers. This reflects their long engagement and training with experimental apparatus, machines that are seldom reliable and often have to be "nursed" along. The roles they take in GammaKnife surgery also reflects how they were trained to think about science. For physicists, "improvements" of laboratory machines and apparatus leads quite naturally to more reliable, more scientific knowledge. In short, improvement meant something quite different for them than it does for the neurosurgeons we studied. For the neurosurgeons, of course machine and technological "improvements" should lead to stronger clinical and scientific results. However, the issue of what is "better" (more precise, more accurate) as physicists understand the term does not concern them as much. For surgeons, improvement is not something to be measured experimentally as much as by success, patient-by-patient, case-by-case [15]. The technological endpoint surgeons tend to value is a pragmatic, clinical one. No matter how "elegant" or "good" a technical innovation or solution is, a surgeon will almost inevitably ask ‘what will this do for my patients?’
All the informants in this study were senior clinicians with long experience in radiosurgery. Therefore, the results reported here cannot be immediately applied to other settings where visualization technology is clinically used. More research is needed to validate these findings and to see whether they apply to other GammaKnife sites, and other clinical visualization technology applications. However, by choosing countries with educational similarities, we have tried to minimize the bias that might arise from differences in how neurosurgeons are trained. Differences among the clinics, especially in their work routines were also taken into account in this research so organizational differences might not bias the results.

5. Conclusion

What led to the deployment of visualization technology in neurosurgery, we believe, was a kind of category confusion—one that equates a certain style of visualization with improved toolbox services. What may hinder the development of more effective visualization systems is misunderstanding how the different clinical professionals use visualization and imagery in their clinical practice. Visualization technology designers need to validate the visual models they generate against the one actual clinical user groups traditionally employ. In fact, this research shows that the resources intended to support visualization in clinical practice tended to increased task and cognitive complexity for surgeons and physicists involved in GammaKnife neurosurgery. Ironically, given that we are dealing with visual representations, the problems end-users had were most acute with 3D and 2D representations (the black box problem). One way forward may be to acknowledge that clinical visualization in every specialist community is a complex socio-cognitive function informed by the discipline's or domain's own history and validated by everyday practice [16]. As such, we need to consider how best to respond to the technical and scientific challenges clinical visualization presents us with.

Competing interests

All authors declare that they have no competing interests.

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