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SHAHRAM EIVAZI

EYE GAZE PATTERNS IN MICRO-NEUROSURGERY

From remote to ocular-based eye tracker

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Author's address: University of Eastern Finland
School of Computing
P.O.Box 111
FI-80101 JOENSUU
FINLAND
email: shahram.eivazi@uef.fi

Supervisors: Professor Markku Tukiainen, Ph.D.
University of Eastern Finland
School of Computing
P.O.Box 111
FI-80101 JOENSUU
FINLAND
email: markku.tukiainen@uef.fi

Adjunct professor Roman Bednarik, Ph.D.
University of Eastern Finland
School of Computing
P.O.Box 111
FI-80101 JOENSUU
FINLAND
email: roman.bednarik@uef.fi

Reviewers: Associate professor Dan Witzner Hansen, Ph.D.
IT University of Copenhagen
Eye Information Lab
Department of Software & Systems
Rued Langgaards Vej 7
DK-2300 Copenhagen S
Denmark
email: witzner@itu.dk

Bin Zheng, MD Ph.D.
University of Alberta
Department of Surgery
162 Heritage Medical Research Centre
8440-112 St NW, Edmonton, Alberta
Canada
email: bin.zheng@ualberta.ca

Opponent: Professor Jeff B. Pelz, Ph.D.
Rochester Institute of Technology
Carlson Center for Imaging Science
54 Lomb Memorial Drive
Rochester NY 14623
USA
email: pelz@cis.rit.edu

ABSTRACT

The need to understand the use of technology in image-guided surgeries has increased as it has become more prevalent in various surgical domains. For instance, there has been a long tradition of work articulating how an expert surgeon develops his/her visual attention and manual dexterity skills in laparoscopic surgery.

This perspective on image-guided surgery practices, namely the analysis of eye movement patterns, is what underpins and motivates the work that follows in this dissertation. As such, we aimed to understand an image-guided surgery practice that relate to the use of a surgical microscope in micro-neurosurgery.

In fact, the key to such a surgery's success heavily depends on the surgeon's visual attention skills and manual dexterity. However, our understanding of these practices in the surgical microscope setting is lacking. It is unknown exactly how surgeons see a stereoscopic magnified view in the context of micro-neurosurgery and what this implies for medical training.

Another limitation is that traditional eye trackers present challenges for recording eye movements in the microsurgery setting. With this in mind, through an iterative development approach, we have designed, built, and empirically evaluated a state-of-the-art eye tracker for surgical microscopes. We deployed the system in the neurosurgery departments of two large Finnish hospitals for use in the context of real procedures. Our research follows a system development methodology, as this is the first attempt to record eye movement in an ocular-based setup.

We conducted a fieldwork study to understand the nature of micro-neurosurgery work. Our discussion benefits from contextual observation approaches, as typically performed in Human Computer Interaction (HCI) and Computer-Supported Cooperative Work (CSCW) practices, as well as video analysis and interviews to understand interaction flow in the neurosurgical environment.

Furthermore, we draw on previous laparoscopic research experience to show differences in gaze patterns between experts and novices when looking at the surgical screen. First, in a preliminary study, we recorded neurosurgeons' eye movements while observing images from a tumor removal surgery. Second, using our custom-made eye tracker, we recorded neurosurgeons' gaze when cutting and suturing under a neurosurgical microscope.

Our studies uncover opportunities to record detailed eye movement data in real-time micro-neurosurgery as well as valuable opportunities where gaze input might enable new kinds of interactions during surgery. In summary, our findings showed a relation between the level of microsurgical skill and the gaze pattern, whereas more experience was associated with a high level of stability, focusing, and longer fixations on eye behavior. We use these findings to discuss further implications of gaze in microsurgical training.

National Library of Medicine Classification: QT 36, WL 368, WO 512, WW 400
Library of Congress Subject Headings: Eye-Movements; Eye tracking; Gaze; Visual perception; Medical microscopy; Operating microscopes; Microsurgery; Neurosurgeons; Eye-hand coordination; Training

Yleinen suomalainen asiasanasto: silmänliikkeet; katse; seuranta; mikroskoopit; mikrokirurgia; neurokirurgia; koulutus

Preface

This research has been supported for two years (2012, 2013) by East Finland Graduate School in Computer Science and Engineering (ECSE), and two more years (2011, 2014) by the North Karelia Regional foundation in Joensuu. Research reported here has taken place in Joensuu, Kuopio, and Helsinki where our preliminary experiments were conducted at KUH NeuroCenter of Kuopio University Hospital and later at the Neurosurgery Department of Helsinki University Central Hospital.

I would like to sincerely thank my supervisors Prof. Markku Tukiainen and Dr. Roman Bednarik for providing with the opportunity to be a part of the Interactive Research group in Joensuu. Through these long years of research (2011-2016), I was given the freedom to find my own way, and I definitely learned a lot. Moreover, I would like to thank the colleagues with whom I have worked and talked during these years, particularly, Tersia, Hoorieh, Alex, Adam, and Ville. You have been more than colleagues to me and I feel lucky to have made friends like you.

Moreover, I would also like to thank my committee members, Dr. Dan Witzner Hansen and Dr. Bin Zheng the reviewers of the thesis, for their useful feedback in the review process and Professor Jeff B. Pelz for acting as my opponent.

I would like to thank all surgeons and residents at the KUH NeuroCenter of Kuopio University Hospital and the Neurosurgery Department of Helsinki University Central Hospital. Dr. Ville Leinonen, Dr. Mikael Fraunberg, and Dr. Martin Lehecka, you have all been there to support me when I recruited surgeons and collected data for my Ph.D. thesis.

My special thank goes to Prof. Juha E Jääskeläinen. More than four years ago, he guided me to the right way which has led me to the fascinating world of Micro-neurosurgery. I am greatly indebted to Dr. Ahmad Hafez who has supervised me with his maniac style in the late stage of my dissertation.

I am thankful to my colleagues from other universities, Professor Enkelejda Kasneci, Dr. Andrea Mazzei, Dr. Basilio Noris, and Dr. Wolfgang Fuhl because throughout my PhD I knew I could rely on their cooperation and helpful feedback whenever I needed.

I also greatly appreciate my family and all of my friends, who have given me strength during these years. Words cannot express how grateful I am to my dad and mom who during all these years away from home have been in my heart. Finally, this moment would never have come if I did not have love and support of Anna. Thank you, Anna, for your supports in those moments when there was no one to answer my questions.

Finally, I want to dedicate this work to my son Daniel who brought many smiles to my face.

Joensuu November 8, 2016 *Shahram Eivazi*

LIST OF PUBLICATIONS

This thesis consists of the present review of the author's work in the field of eye tracking in neurosurgery and the following selection of the publications:

I S. Eivazi, R. Bednarik, M. Tukiainen, M. Fraunberg, V. Leinonen, and JE. Jääskeläinen, "Gaze behaviour of expert and novice microneurosurgeons differs during observations of tumor removal recordings," *In Proceedings of the Symposium on Eye Tracking Research and Applications.* 377–380 (2012).

II S. Eivazi, H. Afkari, R. Bednarik, V. Leinonen, M. Tukiainen, and JE. Jääskeläinen, "Analysis of disruptive events and precarious situations caused by interaction with neurosurgical microscope," *Acta neurochirurgica.* **157,** 1147–1154 (2015).

III S. Eivazi, R. Bednarik, V. Leinonen, M. Fraunberg, and JE. Jääskeläinen, "Embedding an Eye Tracker Into a Surgical Microscope: Requirements, Design, and Implementation," *IEEE Sensors Journal.* **16,** 2070–2078 (2016).

IV S. Eivazi, A. Hafez, W. Fuhl, H. Afkari, E. Kasneci, M. Lehecka, and R. Bednarik, "Optimal Eye Movement Strategies: A Comparison of Microsurgeons Gaze Patterns When Using Neurosurgical Microscope," *Submitted in Microsurgery.* (2016).

Throughout the overview, these papers will be referred by Roman numerals.

AUTHOR'S CONTRIBUTION

The publications selected in this dissertation are original research papers on eye tracking and neurosurgery practices. In all papers presented here, cooperation with the authors has been significant and the proposed methods are the result of teamwork with joint efforts made by all authors. The order of the names indicates their contribution in preparing the papers and the first and second authors were responsible for the first drafting of the papers.

The author of this dissertation contributed significantly to all papers reported here. In all publications, the author carried out all numerical computations and the selection of solutions and materials used in the methods.

The writing of P(I) was a joint contribution of the first two authors. In particular, Roman Bednarik contributed to the content of the paper significantly. The first author key responsibilities were designing and conducting the experiment, and analyzing the data.

In P(II), first two authors contributed equally to the papers. The author was the primary writer of P(II) and Hoorieh Afkari was responsible for the data acquisition. Moreover, both authors were equally responsible for the analysis and interpretation of the data.

In P(III) and P(IV), the author contributed substantially to the conception, design, acquisition of data, or analysis and interpretation of the data. Wolfgang Fuhl was responsible for the software development (mathematical models) of the gaze tracking techniques presented in P(IV). Moreover, the second author of P(IV), Ahmad Hafez, contributed equally to the project.

Contents

1 Introduction

This thesis explores the role of visual attention in micro-neurosurgery to understand the nature of expertise and its relation to gaze patterns in this context. With the lessons learned from the eye tracking research, an ocular-based eye tracker for neurological microscope is developed and evaluated. We investigate the spatial arrangements of clinicians, artifacts, and instrumentation during micro-neurosurgery procedures to understand potential approaches and limitations of embedding an eye tracker into modern neurosurgical microscopes. We then measure the eye movements of neurosurgeons while performing an operation under a surgical microscope to report the relation between surgical skill level and changes in eye movement behavior.

In an experienced surgeon's hands after hundreds of operations, the conduct of surgery seems elegant, simple, and clean with minimal blood loss. However, any surgery is a multifaceted procedure, with significant consequences for errors, thus requiring a complex set of mental processes such as attention, motor control, comprehension, or memory retrieval. Moreover, advances in medical technology and instrumentation have led to new forms of medical professionalism in which a surgeon must be able to attend to multiple sources of information and act upon the information presented.

A leading example here is medical imaging technology in the operating room (OR). In recent decades, we have seen the widespread adoption of imaging technologies in surgical procedures. For instance, within any modern OR, the presence of visual displays is unquestionable. Of further significance is image-guided surgeries in which the entire procedure relies on imaging applications.

To help achieve higher operating precision and enhance fine movement control, surgical image technologies offer a means of making anatomical structures easier visualize (e.g. by magnification) during surgery. For instance, in a laparoscopic surgery the surgeon makes small incisions in the body to insert instruments and cameras to represent an accurate anatomical view of the body. Another example is microsurgery in which the surgeon uses a magnified view with miniaturized instruments to operate a caliber vessel in the range of 1-2 mm in diameter under a surgical microscope.

Although these techniques themselves benefit patients -by reducing recovery time, the risk of hemorrhaging, and exposure to infections- for surgeons, the procedure of viewing an anatomical structure through a range of digital imaging technologies is constrained by indirect eye-hand coordination. Thus, surgeons have to achieve a high level of concentration and fine-motor skills to attain precision.

In response to concerns regarding medical training and enabling residents to adapt their eye-hand coordination to new imaging interaction technologies, a growing number of researchers have focused on methods for training residents or evaluating the performance of the entire procedure in the operating room. Moreover, increasing financial costs related to lifelong training have drawn increasing attention to learning techniques in such an environment.

To date, medical training programs provide instruction on how to perform a particular procedure (to a resident), and over the training period, the trainee takes on a stepwise gradation of responsibility. At the end of a specific training program, the trainee will typically undergo a subjective assessment. A mentor evaluates the trainee's performance on a specific procedure to determining whether a specified objective was met (see, for example, microsurgery training programs at [1, 2]). As such, studies reported in the medical literature on, health care and training systems, focus on measurable qualitative outcomes, such as respect for tissue, instrument handling, and quality of the results, to name a few [3].

Subjective assessment systems have been validated in various clinical settings and found to be the most effective techniques to date [3]. However, the main disadvantage of such an assessment method is that it requires an experienced senior to observe trainees directly, which makes it labor intensive. Moreover, questions regarding how precisely a trainee's knowledge and skills are developed remain unanswered.

To improve the assessment techniques for the development of better surgical training systems, other researchers, namely physiologist and cognitive researchers focus on objective analysis methods. Thus, they investigate the correlation between medical evaluation scores and surgical individual skills. Our interest is also to understand these correlations; in particular, we aim to understand the relation between eye movements patterns and expertise level in image-guided surgery.

In image-guided surgery, an important question to consider is how residents learn to view and work indirectly with a patient's body. A notable approach to answering this question has been to capture visual attention and study clinicians' eye movements and manual dexterity when manipulating instruments in the operating field. The technology matures and the size of eye trackers makes it both comfortable for users and accessible for researchers to apply eye tracking methodology in the medical domain.

To date, advances in eye tracking technologies have enabled researchers to uncover the role of visual attention in medical training as well as to apply gaze-based interaction techniques in the OR. Eye tracking has been used, as early as the 1970s, to study visual search [4] and later to understand the nature of expertise [5–8] in medical domains.

The majority of medical studies have applied eye tracking in the context of image-guided surgery [9–11]. This might be due to the nature of the work in which direct access to the operating field is not possible and the surgeon sees the field of view via a camera or microscope. Thus, image-guided surgery requires special psychomotor and visuomotor skills. Thus, gaze data analysis is suitable to understand the details of these skills in the OR.

A growing number of research groups have begun to explore eye movements within image-guided surgery, mainly focusing on laparoscopic surgery using remote or head-mounted eye trackers.

For example, since the beginning of the last decade, Atkin and colleagues have investigated the role of visual attention in laparoscopic surgery [12–18].

Law et al. [13] showed that senior surgeons tended to maintain their eye gaze on a target while manipulating instruments. However, novices tracked the movement of the instrument until it reached the target. Tien et al. [14] then noted the same pattern in which novice surgeons concentrated on the surgical display in a way in which they were hardly able to look at the patient's vital signs during a simulated laparoscopic task.

In this dissertation, we also wish to understand expert and novice eye movement patterns with a focus on microsurgery. We aim to capture and understand visual information processes involved in micro-neurosurgery as a step towards modeling human information processing in this domain. The particular property that we explore here deals with understanding how an experienced neurosurgeon effectively moves his/her eyes to follow the procedure and avoid obstacles while safely moving the instrument through delicate structures.

Micro-neurosurgery differs from laparoscopic surgery in its reliance on a microscope. Neurosurgical procedures consist of complex and adjustable series of actions with micro-instruments held in the left and right hands. A successful completion of a micro-neurosurgery procedure (e.g., arterial, nervous, or venous anastomoses) intrinsically relies on the high magnification of the surgical anatomies.

The operating area is illuminated and magnified by a neurosurgical operating microscope (see Figure 1.1). The microscope can be zoomed and focused onto the operating plane where the tip of the micro-instrument is functioning with miniature hand movements. The microscope with two oculars creates an image of depth in the three dimensional (3D) operating volume.

Microsurgery is technically more demanding than, for example, general surgery [1,3]. The surgeon has to keep his/her eyes on the microscope oculars for a long period time and accurately allocate

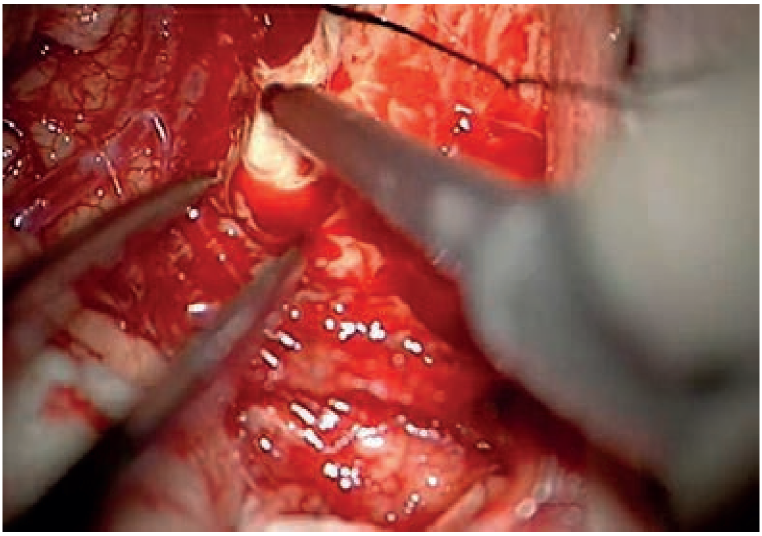

Figure 1.1: Magnified view of the operating field and micro-instruments as seen by a surgeon via a microscope.

attention to the operating field. This requires skills related to (a) the visual understanding of the magnified micro-anatomy; (b) coordination between the eyes and hands holding shafts of various micro-instruments; and (c) an efficient and suitable automatic reaction that is unnatural for the naked eyes and every-day haptics.

As such, microsurgery training programs are associated with a very steep learning curve [2,3]. Residents are required to attend a long and complex training program on indirect eye-hand coordination. For example, in Europe, neurosurgical training is six years at a minimum [19]. Moreover, a resident during his/her training must be exposed to at least four different trainers and the full spectrum of neurosurgical procedures [19].

In response to the length and complexity of neurosurgery training, there has been a growing interest in the development of microsurgical training programs [3]. The primary motivation is to reduce the training periods by improving laboratory programs as well as developing new surgical training simulators. Here, attention remains on the learning of skills in manipulating instruments and objects under the surgical microscope [3, 20].

Less, emphasis has been placed on understanding how a trainee learns to view and work with the image of depth in 3D operating volume (see an example study of using two dimensional (2D) videos during neurosurgery within the OR and at remote locations away from the OR [21]). One mechanism of understanding visual skill development is through the analysis of eye movements behavior. With this work, we aim to describe how neurosurgeons see the body through indirect vision, considering the high level of attention they engage in to conduct a surgery effectively using a microscope. To date, there has been no analysis of how eyes scan magnified anatomical structures.

1.1 RESEARCH GOALS AND QUESTIONS

The primary goal of this thesis is to understand the nature of expertise and its relation to gaze patterns in the context of micro-neurosurgery. In such a complex environment, our goal was to measure the eye movements of surgeons while performing an operation under a surgical microscope.

Eye tracking is a methodology that provides a reliable, unobtrusive, and real-time behavioral index of ongoing visual and cognitive processes. In microsurgery, including micro-neurosurgery, the measurement of eye movement patterns has not been conducted yet. This is partly due to a lack of suitable eye tracking equipment, as current eye-trackers have not been designed for use in an ocular-based setup.

During the period of this research (2011-2016), we have not seen any eye tracker built for use in a microscope. Only one paper has reported on the use of eye tracking in microsurgery [22]. Charlier et al. [22] demonstrated an eye-controlled surgical microscope; however, the paper lacks a detailed description of the system, its application, and evaluation.

Coming back to our main research question –*Do novice and expert* *neurosurgeons differ regarding their eye movement patterns while operating under a surgical microscope?*– we had to extend the application of eye tracking to micro-neurosurgery. The focus of the research reported in this PhD is divided into three sub-research questions within our collection of papers:

RQ1. P(II). What are the spatial arrangements of clinicians, artifacts, and instrumentation during micro-neurosurgery procedures? What are the challenges in terms of microscope view production and use?

An understanding of these practices can be used to inform a wide range of technological interventions. While some of these characteristics are undoubtedly unique to microsurgery, nevertheless, answering this set of questions helps to increase our knowledge on how surgeons use microscope and micro-instruments.

RQ2. P(III). What are the approaches and limitations of embedding an eye tracker into modern neurosurgical microscopes?

Recording eye movement data in the OR is challenging when equipment needs to be used by sterile team members in a complex environment. It would be impractical, however, to introduce an eye tracker for medical clinicians without considering its full environmental consequences.

With this in mind, in collaboration with expert neurosurgeons, we focused on providing a detailed description of the hardware development phases starting from the requirements analysis to design considerations, and validating the eye tracker. Our aim here was to highlight the key requirements for building such a novel eye tracker.

RQ3. P(I), P(IV). How do surgeons' eye movements differ within the microsurgical environment and do eye movement features, namely fixations and saccades, reflect expertise levels?

Various studies have consistently demonstrated gaze behavior differences among surgeons during various medical procedures. Drawing on these insights from the literature, we investigated the relation between surgical skill level and changes in eye movement behavior when surgeons use a microscope. Specifically, based on the literature and familiarity with the environment we hypothesized that the differences can be seen in longer fixation durations for experts due to the ability to focus on micro-anatomies.

1.2 RESEARCH METHODS

We used a mixed-methods approach to incorporate the strengths of both qualitative and quantitative research methods. The qualitative research method builds a complex and holistic view of the environment, and the quantitative method measures and counts the phenomena. In this study, the qualitative method was used during the earlier stage of research to understand neurosurgery practices from the OR observation experiments.

To enhance the validity of the observational findings, we then used video based fieldwork data to combine qualitative and quantitative methods. We applied a coding scheme to generate quantitative data and to explore patterns across video data [23]. As such we classified events in the OR, counted them, and reported statistical results in an attempt to explain what has been observed in the OR.

Another contribution of this dissertation is in the development of an eye tracker for the surgical microscope. Thus, system development research methodology was used here. Three key components for conducting our experiments were observation, prototyping, and data analysis. These components were used to answer specific research questions and they produced new knowledge on the visual attention strategies in micro-neurosurgery.

Table 1.1 shows a summary of the methods employed to answer the research questions mentioned in the above section and their respective publications.

Workplace study is one of the key methods used for presenting this research. We conducted the contextual observation study

RQ	Method	Paper(s)
1	Contextual observation	P(II)
2	System development	P(III)
3	Experimental and data analysis	P(I), P(IV)

Table 1.1: A summary of the methods employed to answer the research questions and their respective publications.

–P(II)– to understand the existing practices with existing artifacts in neurosurgery ORs. As such, we learned how these practical arrangements should be taken into consideration when building our prototype. We also used an activity analysis method to move from field studies to system design and development by addressing the typical events in a medical procedure, the range of time involved in its performance, and the various personal meanings that might be ascribed to it.

Next, in an iterative prototyping manner we developed our eye tracker. Our aim, in P(III), was not to determine the best technology, but rather most appropriate technique regarding the medical requirements. The evaluation method reported here was a mix of observations, semi-structured interviews, and data analysis.

Finally, the empirical evaluation of the main research question of this PhD was presented in P(I) and P(IV). We used statistical methods to conduct our data analysis in these papers. The data were gathered by both a commercial eye tracker and the custom-made surgical eye tracker. Then, the outcomes of the analysis were critically discussed and serve as a rationale for proposing the implications of gaze in micro-neurosurgery.

1.3 ORGANIZATION OF THE THESIS

This is a multiple-paper thesis that consists of an introduction and the motivation behind this work. We conduct a review of literature in Chapters 2 and 3. First, review the fundamentals of eye tracking methodologies (Chapter 2). Then, in Chapter 3, we provide a literature review on eye tracking in medicine. We also investigate the potential implications of such research.

In Chapter 4, we report our contributions in the field of eye tracking and micro-neurosurgery. Using a summary of papers in this research, we show how gaze can be used to understand experts' visual strategy in this field. The thesis concludes with a discussion on the implication of gaze and potential future work.

2 Fundamentals of Eye Tracking

In this chapter We first, review the fundamentals of eye tracking methodologies and name some of application of eye tracking then, in the next Chapter, we provide an extensive literature review on eye tracking in medicine.

It has been over 200 years since researchers first began to measure the characteristics of gaze and used this information to understand human visual attention. Earlier, researchers employed mirrors (or direct observation) to measure eye movements; however, these methods may not provide accurate information about visual attention. The mechanisms of visual attention have been studied, more accurately, since the beginning of the 20th century when new sensor technologies began to have widespread impact in developing a new type of eye trackers. To date, the most widely known impact has been the improvement of the naturalness property of eye tracking devices (usability, intuitiveness, and learnability).

Eye tracking methodologies have been applied in various domains, such as human computer interaction, reading, driving, user preference, and strategic behavior. For more detailed information on eye tracking methodologies, the reader is referred to [24]. Duchowski [24] classified eye movement methodologies into four groups, namely, electro oculography, scleral contact lens or search coil, photo oculography, and video oculography (VOG).

Among these methodologies, over the past decade, development in imaging technology have led to the growth of VOG eye tracking methodology. This technique has become the most popular method for measuring eye movements due to its comfort for users. We used the same method to develop the microscope eye tracker presented in this dissertation.

The VOG eye tracking technique is based on reflected light from the eyes recorded by a video camera. A few distinguishable features of the eyes, such as the sclera, iris, and pupil, are used to measure the eye movements captured by the camera(s). It is beyond both the scope and purposes of this work to offer more in-depth analysis of this topic. A detailed overview of the principles of the VOG eye tracking technique can be found in [24–26].

2.1 EYE MOVEMENT MEASURES

The theory of visual attention is informed by more perceptual psychological works [27–29]. Most of these studies have confirmed that tracking eye movements provides suitable information regarding to the visual and perceptual processing. In the review of literature, Henderson et al. [30] discussed the naturalness of eye movements during scene viewing. They argued that eye movement patterns maybe influenced by semantically informative scenes in terms of the image content, viewing task, and viewing time (i.e., top-down visual processing, voluntary control of eye movements) as well as by visual aspects, such as luminance, contrast, texture, and color, to name a few (bottom-up visual processing, involuntary eye movements) [30].

Here, we have no intent to discuss the theoretical traditions of visual attention, nor do we aim to select a specific theory. While we accept both top-down and bottom-up visual processing mechanisms of eye movements, as the key factors that affect the viewer's eye movements, this dissertation aims to explore the voluntary eye movements that are driven by the viewer's goal.

The particular property that we focus, deals with the expertise level as a spatial factor in the acquisition and processing of visual attention. Visual information can be obtained 'covertly' through movements of attention –mentally shifting one's focus without moving eyes– or 'overtly' through the head and eye movements [31]. In this dissertation we analysis the overt localization of visual attention and as such eye movement measures, namely fixation, saccade, and smooth pursuit, are most notable [24, 26].

Fixation is one of the most commonly used features in eye tracking. It occurs when the retina stabilizes over a stationary object of interest. When fixating on an object, we move the eyes so that the object falls on the fovea. This maximizes the high resolution of the cones in perceiving objects. Moreover, fixations are described by miniature eye movements when the visual information is available for visual and cognitive systems [27]. Thus, to understand visual attention patterns, it is important to know where fixation is located (area of interest) and how long it stays there (fixation duration).

A saccade is a fast eye movement that occurs when the eyes need to reposition the fovea to a new location. In another word, a saccade happens when the eyes quickly change direction from one place in the space to another. Often a saccade is used to gather information from the visual environment.

A smooth pursuit makes the eyes able to track the movement of objects visually. It depends on the direction of the object in the environment. As such, the eyes can matched with the velocity of the moving object. Compared with fixations and saccades, smooth pursuits are not well defined yet (this is an open research problem [26]). We thus did not include smooth pursuits in our analysis.

2.2 INTERACTIVE VS. RETROSPECTIVE ANALYSIS OF GAZE DATA

Undoubtedly, eye movement studies provide an unobtrusive, sensitive, and real-time behavioral index of ongoing visual and cognitive processes. Generally, researchers have applied eye tracking methodology either in 'interactive' applications or in 'retrospective' analysis. Interactive studies use an eye tracker as an effective input device that responds to the user's gaze [32]. For instance, gaze has been used for object selection, scrolling text, or navigating within a game interface. In this thesis, we do not discuss the methodological challenges stemming from interactive research.

In 'retrospective' studies, eye tracking provides objective and quantitative data on people's visual and attentional processes. As discussed earlier, the assumption is that eye movements during the observation of complex visual stimuli are regular and systematic [33]. Subjects' eye movement behaviors are investigated over a given stimulus to understand, for instance, visual search patterns.

The eye tracking analysis of users' behavior in reading and information processing was one of the first areas to be researched in this domain. Rayner [34] reviewed 20 years of research concerning the role of eye movement in the reading processes. He reported that this area of study helps to further understand eye movement features such as fixation, saccade, saccadic suppression, saccade latency, and size of one's a perceptual span.

Fundamental eye tracking practices that have been explored within linguistic studies have been used to inform a wide range of human factors research. For example, the effect of expertise on gaze behavior data has been explored extensively in driving, flight, or clinical applications (see [9–11] for a review of literature). Our focus is also on the retrospective analysis of the expert and novice eye movements in the micro-neurosurgery. Therefore, in the next chapter, we review the studies of gaze in the medical domain.

3 Studies of Visual Attention in Medical Domain

Over several decades, the eye tracking field has contributed to providing rich insights about visual attention patterns in medical practices [4, 35, 36]. Moreover, researchers have studied the implications of gaze in hands-free medical applications [37–39]. During this work, we reviewed the major themes and approaches for the development of eye tracking in the medical domain.

We found that the majority of contributions, in this area, could be categorized as data analysis studies. In contrast, only a few studies focused on designing small-scale interactive prototypes, though most do offer implications for design [37–39]. While this emphasizes a sound commitment to understanding medical users' perspectives, it also shows less engagement in applying interactive approaches in the medical domain. Perhaps, more knowledge and understanding of technology is needed and arguments for developing new interactive technologies in the OR have to be more clearly articulated within the surgical environment [40].

We have also focused on data analysis rather than building an interactive system in the operating room (OR). The remainder of the chapter is organized as follows: in Section 3.1, we review eye tracking studies in the medical image context and elaborate on the key characteristics of the gaze to study users' behavior. Section 3.2 outlines eye tracking approaches used in the OR and also gives a profile of the included papers related to the study of expertise. Section 3.3 goes on to describe the implications of gaze and its practical impact on expertise training.

3.1 EYE MOVEMENTS IN DIAGNOSTIC APPLICATIONS

In the medical domain, there has been extensive development of the imaging techniques necessary to foster effective diagnostic tools (For example, fluoroscopic X-rays, computed tomography, and magnetic resonance imaging provide the possibility for more clean and informative images). These techniques are evolving in many ways, including introducing a new representation of the patient body. Our aim, here, is to review eye tracking studies on how medical users perceive and act upon the information presented via digital representations of the patient body. In taking this focus, though, it is our assumption that eye tracking can provide an opportunity for better understanding of how one interprets and works with new tools and instruments to achieve the particular goals related to patients' safety.

Eye tracking has had a long history as a topic of interest in medical imagery studies. In the early 1970s Harold Kundel's research showed the benefit of eye tracking for understanding radiologist behavior beyond questionnaires or the think aloud data collection method [4]. Reading radiology images is where most of the image perception research has taken place. Historical accounts of visual perception in radiology images, such as chest X-rays, emphasize the visual strategies that are used by experienced radiologists [4,35,36].

Earlier Kundel et al. [4] recorded the eye movements of radiologists while viewing normal and abnormal chest radiographs. The authors found that visual search patterns of medical students are closer to a localized central search, compared to staff radiologists, which were closer to a wider circular pattern. Moreover, Kundel and colleagues investigated the relationship between eye movements and image interpretation performance. Kundel et al. [35] showed that among false-negative errors 30% occurred when searching for pulmonary nodules among a set of 24 normal and 36 abnormal (nodule-containing areas) images whereas 25% of the errors were linked to recognition and 45% to decision-making errors.

More studies of medical image use have discussed the interpretation of images in clinical and surgical works. For example, a study by the same author [41] in detecting lung nodules revealed the correlation between the fixation dwell time on the areas of interests (AOIs) and independent rating of image features. Highlighted AOIs received prolonged fixation on each image feature, and thus Kundel et al. argued that participants had an active and dynamic decision-making strategy rather than perceiving a nodule upon one decision per image.

These are important findings, because the visual detection of lung nodules is a difficult task and radiologists may miss the nodules up to 30% of the time [42]. Therefore, increasing our understanding of visual strategies may help to improve training or even contribute to medical technology innovations. For instance, Krupinski [43] suggested that gaze duration should be used as a predictor of missed lesions in mammography. He examined whether the eye movement analysis of Kundel et al.'s [35] study (the pulmonary nodule detection experiment) can be applied to lesion detection in mammographic images. For the Krupinski experiment, true-positive and false-positive decisions were associated with prolonged gaze duration, however, for false-negative decisions the gaze duration was longer than true-negatives.

More recent, technological developments provide an opportunity for researchers to further investigate eye movement metrics in the medical imaging domain. For example, to support holistic model of visual perception, leading research by Kundel [44] studied the time to the first fixation on the true lesion area of images when participants were searching for signs of cancer on mammograms. The results showed that about 57% of the cancers had a 95% chance of being fixated in the first second of viewing. The initial detection occurs before visual scanning and, therefore, must be the result of a parallel global analysis of the image resulting in an initial holistic, gestalt-like perception. In another example, Mello-Thoms et al. [45] examined the mean pupil size of four experienced mammographers. Their results showed that in the location where visual attention was focused the pupil sizes were significantly different between correctly reported lesions and unreported ones.

The interest in the eye tracking research in the medical domain was accompanied by the growth of medical vision-based systems where new techniques for visualizing and interacting with medical images, such as fluoroscopic X-rays, computed tomography (CT), and magnetic resonance imaging (MRI), provided the possibility for more clean and informative images.

CT is one technique where 3-D volumes of image data are available for radiologists and radiographers. Bertram and colleagues [6, 8] have shown that eye tracking is a potential technique to measure resident development in this domain. They found out that radiologists' strategies were to use shorter saccade amplitude, and when an enlarged lymph node was presented in the image, the number of fixations increased on the relevant area [6].

Moreover, Bertram et al. [8] concluded that experts have a greater adaptivity ability in regard to eye movement patterns. They recorded the eye movements of 15 early residents, 14 advanced residents, and 12 specialists while viewing 26 abdominal CT slides as a sequence of images at either three or five frames per second. The results highlighted differences in the experts' gaze patterns in response to the task demands and complexity. First, specialists reacted to the presence of lesions in CT images by longer fixation durations and shorter saccades. Then specialists adapted to the faster presentation speeds (five frames per second) by longer fixation durations and longer saccades (see more examples in expert visual adaptivity ability in [5, 7]).

Another significant area of research is the studies that investigated the diagnostic performance of medical practitioners while using different imaging techniques [46–48]. For example, Krupinski et al. [47] examined the observers' visual search pattern when using hard-copy versus soft-copy images. They reported a longer time to the first fixation on the trauma regions for the monitor than the film. Moreover, for true-positive and true-negative decisions, the dwell times were longer on the monitor than on the film. Thus, Krupinski et al. suggested that more time is required to detect, extract, and identify relevant information from medical images when observers use a monitor.

Following this, Cooper et al. [48] uncovered that the visual search pattern in reading multidimensional brain images is influenced by the image quality and modality of CT or MRI imagery techniques in neuroradiology. The results showed a longer fixation for experts appraising CT images than MR; however, trainees had longer fixation appraising MR than CT images. Tying this back to the prior work, we see that the image type influences the visual search and perception of medical practitioners as well. We encourage reader to refere to examples in other medical domains such as dentistry [49], cardiology [50], neck dissection [51], pediatric neurology [52], recurrent laryngeal nerve dissection [53], ophthalmology [54], and pathology [55,56].

For example, Tiersma et al. [55] studied the diagnostic decision making of pathologists. They reported two distinguished visual search patterns. One included focusing on many points within a short moment. The second strategy included a relatively long time period focused on the specific target within the lesion. In the pathology imaging technique, biopsied tissues from a glass slide are magnified by a microscope. Pathologists interpret the magnified images by either looking into the microscope or using a computer screen. More recently, Brunye et al. [56] compared the size of the pupil diameter with the image interpretation diagnostic accuracy. The results showed an increase in the pupil diameter when the task was more difficult, but only when diagnosed decisions were ultimately correct. In this domain, eye tracking studies have also shown that gaze patterns are modulated by experts ability to interpret medical images [55–57].

In sum, from this review of gaze patterns in medical image use, a clear difference between experts' visual strategy and the consequences in image interpretation are evident. The following section reviews studies that have attempted to ascertain these strategies within surgical domains.

3.2 EYE MOVEMENTS IN SURGERY

In surgery, the domain of our study, the technological advancements over the last few decades have revolutionized the way operations are conducted. As we began to introduce the next generation of intraoperative technologies in the OR, new complex challenges arise from the various ways of interpreting and working with the technology to achieve a particular goal of the surgery. The new fundamental medical practices have been extensively explored within the surgical domain. Our intent here is to highlight some of the eye tracking works that particularly help to understand what the surgeon sees while operating.

Several studies of technology use in the OR have reported using eye tracking methodologies, with a focus on the distribution of visual attention in the OR [58–60]. For example, in the anesthesia domain Schulz et al. [60] reported that 30% of visual attention was pointed to the patient's vital signs monitor during critical situations.

The tracking of visual search patterns in ORs has also been used to identify differences in nurses' gaze behaviors [61]. Marquard et al. [61] simulated a clinical setting for 20 nurses while recording eye movement. They concluded that nurses who noticed an identification error (matching of a patient to an intended treatment) tended to have predictable eye fixation sequences compared to non-error-identifying nurses who have seemingly random eye fixation sequences.

Related to expertise differences, Tomizawa et al. [62] applied eye tracking methodology to analyze the ECC operation tasks during live clinical cardiovascular surgery in the OR. Based on fixation data analysis they showed that an expert dispersed his fixations more widely than intermediate and novice perfusionists.

In another example, Schulz et al. [60] discovered that in critical incidents, experienced anesthetists –with more than two years of work experience– increased the amount of attention directed to the patient monitor from 21% to 25%, whereas the less-experienced participants' attention decreased from 20% to 14% during manual tasks in a simulated environment. See other studies of Schulz and colleagues [63, 64].

While some of these surgical domains (e.g. anesthesiology) have been well studied, little work has focused on open surgery experiments [53,65]. For instance, Tien et al. [65] reported a higher fixation frequency and dwell time for experts in a live, open inguinal hernia, surgery.

More to the point of this PhD are gaze studies on how surgeons see the patient's body. While we reviewed the major themes and approaches for the development of eye tracking in the medical domain, we found that the majority of the gaze research contributions could be categorized in the image-guided surgery domain. This might be due to the nature of the work where to conduct these surgeries, indirect eye-hand coordination is required.

It is well known that gaze control participants in the movement planning of hands to guide reaching and grasping objects in the environment. Typically, the eyes move to a target before or concurrently with the hands so that visual information is available for the sensorimotor system [66–69]. In a number of studies, Binsted et al. [67] provide evidence that the eyehand coordination is mediated by eye proprioception and not muscular afferents. Moreover, the interactions between the perception and action systems occur during the organization and control of sensorimotor system. As such, eye movements are optimized by coordinated timing and positioning of the gaze for target localization and accuracy feedback. For example, the timing of primary saccade completion can reflect a synchronization process that is determined before movement begins.

Eye-hand coordination is highly task-specific and may differ among user groups (e.g. experts and novices) based on whether the environment and target is known or not [67,70]. For example, Land et al. [71] reported much shorter eye-hand latency in the sandwich making task compare to other everyday activities (e.g. tea making). In a sight-reading musical task Furneaux et al. [72] found lager eye-hand span –the number of notes that a fixation point leads the note being performed– for more proficient musicians. Therefore, they conclude that Professionals are able to chunk several notes together and process them as a single unit of information.

In the image-guided surgery a surgeon sees the body indirectly while hands are required to manipulate the instruments that enter the body through small incisions. The performance of the surgical task significantly depends on the manual dexterity and the visual-spatial ability of surgeons [12–18, 73, 74].

Law et al. [13] conducted an experiment comparing the eye movements of five experts and five novices performing a computer-based laparoscopic surgery simulation. They reported that experts tended to maintain their eye gaze on the target while manipulating an instrument. However, novices tracked the movement of the instrument until it reached the target. In another example, Tien [14] revealed the same pattern in which novices concentrated on the surgical display so much that they were hardly able to look at the patients' vital signs during a simulated laparoscopic task.

Wilson and Vine [73,74] assessed a similar principle. They found that experts fixate on the targets more often than novices when performing an eye-hand coordination task on a virtual reality laparoscopic surgical simulator [73]. A follow-up study [74], repeated the same finding of differences between the fixation time of experts and novices on the target. Experienced participants used a longer aiming fixation (the quiet eye period) to guide precision grasping movements with fewer grasp attempts.

With the growth of the field, eye tracking studies not only concern expertise differences in their distribution of fixation on the target but in more recent years we have seen growth in a new type of eye movement analysis in the laparoscopic domain, namely mental load analysis.

For example, surgeons' pupillary response has been investigated by Atkin's research group [17, 18]. They provided evidence that higher task difficulty evokes higher peak pupil dilation as well as peak duration increases for more difficult tasks. More recently, Di et al. [75] explored a new form of gaze analysis of 18 surgical residents when performing clipping, cutting, and translocation of objects in a virtual laparoscopic simulation environment. They discovered a linear increase in gaze entropy and velocity with task complexity. As such, visual search patterns became more random when the task complexity level increased.

There are also studies that have used big data analysis method, namely clustering, pattern recognition, and machine learning, to further enable large scale applications of gaze in medicine. We next review these works as an implication for the design of gaze-aware systems in medicine.

3.3 EYE TRACKING FOR MEDICAL SKILLS ASSESSMENT AND TRAINING

Eye tracking in medicine is often seen as an objective assessment tool. Given the complexity of surgical training and longitudinal studies, the reasons for applying eye tracking methodology as a tool to measure surgical skills are obvious. For example examples, Richstone et al. [76] and Ahmidi et al. [77] introduced an automated method for assessing surgical skill using eye movement measures.

Richstone et al. [76] applied classification methods, linear discriminant analysis (LDA) and neural network analysis (NNA), to group 21 surgeons into expert and novice classes. In a simulated surgery, the system was able to accurately distinguish novice and expert surgeons with 91.9% and 92.9% accuracy, respectively, using eye movement metrics namely, blink rate, fixation rate, pupil size, and vergence. The performance of the prediction system was 81.0% and 90.7% in the live surgery.

Ahmidi et al. [77] further corroborated the assessment idea in endoscopic sinus surgery. They recorded the eye and hand movements of a total 378 trials from seven expert and 13 novice surgeons. The experts' skill were identified correctly for 94.6% of tasks, whereas for novice surgeons the accuracy of 88.6% was achieved.

Another example includes Wilson and Vine's research on gaze training during laparoscopic technical skill acquisition [78–80]. Wilson et al. [78] divided 30 medical trainees into three groups: gaze, movement, and discovery trained participants. They showed that the gaze trained group learned more quickly as well as performed better in a multitasking transfer test. In a follow-up study, Vine et al. [79] were able to guide the gaze trained group and adopt their visual pattern to an expert-like gaze strategy. Similar results were obtained when a medical student trained for a more complex task in the laparoscopic domain [80].

Gaze training applications are not only limited to laparoscopic surgeries. For instance, Vitak et al. [81] reported that a recorded video of an expert's think aloud session augmented by their scanpath can be an effective aid for learners of visual searches in chest X-Ray image interpretation. A similar result was also reported by Jarodzka et al. [82] when diagnosing an epileptic seizure.

3.4 SUMMARY

Through the review of the literature, in the last two sections (3.1 and 3.2), we have seen visual attention studies with a particular focus on how different team members adopt their gaze pattern based on the task and technology in use within the context of medical diagnostic and surgical applications. We have also seen how the expertise level is associated with the visual search strategies and the success of medical practices.

Across these studies we see general patterns both in the eye movement metrics used in these studies and also study results. Number of fixations, fixation duration, saccade amplitude, pupil size and Area of Interest analysis (AOIs) are common measures. From the literature, it is unclear whether experts always follow the same eye movement strategy. What we learned here is that expert gaze pattern depends on the nature of the task and the presence of challenges at any given moment. However, novice gaze pattern seems to be more the same regardless of the task complexity.

There is some indication, though, that experts follow a holistic model of image perception [83]. For example, studies that have focused on medical image interpretation (e.g. projection X-ray images, dynamic X-ray exams, and multislice CT and MRI images) noted the holistic model –a global visual scan strategy to detect abnormal areas– in the medical image diagnostic tasks. With a greater degree of expertise, the abnormal areas take a greater proportion of a surgeon's focus. This reflects in the corresponding fixation location and duration on the medical images.

The holistic model of image perception describes the experts image interpretation in static stimuli however we see the information-reduction theory [84] more relevant in a dynamic stimuli. When reviewing studies of eye movements in surgery we have seen this pattern more often than holistic model. The assumption of the information-reduction theory is that experts have a selective attention allocation strategy. Thus, they optimize the amount of processed information by ignoring irrelevant information and an active focus on task-relevant information, which is accomplished through strategic considerations to allocate attentional resources [9]. For example, in Schulz et al. [60] study the experienced anesthetists increased the amount of attention directed to the patient monitor, in critical incidents, whereas the less-experienced participants' attention decreased during manual tasks in a simulated environment.

Here, we also expect that professional micro-neurosurgeons (the domain of this dissertation) are able to focus on the target rather than begin distracted by unimportant areas in the operating field. We draw on previous laparoscopic research findings [13, 73, 74] in which experts tempted to maintain their eye gaze on the target while manipulating an instrument.

However, there might be differences in surgeons' eye movement patterns when performing a laparoscopic surgery versus a micro-neurosurgery. Neurosurgeons use a magnified view with miniaturized instruments to operate a caliber vessel in the range of 1-2 mm in diameter under a surgical microscope thus a small, narrow, and deep field may cause challenges for visual information system. We go on here to reflect on the eye tracking research in micro-neurosurgery which is rapidly growing especially in light of new state-of-the-art microscopes.

4 Eye Gaze Patterns in Micro-neurosurgery: A Summary of Contributions

In the previous chapter, we presented a summary of the eye tracking research around both diagnostic and surgical applications in healthcare. Across these studies, we see considerable focus on medical image technology both used in diagnostic and OR applications. This may be interpreted as an interest in eye tracking research in a medical context where imaging technologies are used within medical procedures from diagnosis to treatment.

In image-guided surgery applications, the eye tracking studies mostly focused on the laparoscopic domain (not covering a wide range of image-guided surgery applications). This can, to some degree, be explained by the limitation of eye trackers to actually be used in the complex medical environment. We go on here to reflect on the use of eye tracking research in micro-neurosurgery, which is rapidly growing especially in light of the new state-of-the-art microscopes.

Micro-neurosurgery differs from other image-guided surgeries in its reliance on the surgical microscope. The modern high-powered microscopes provide illumination, magnification, and delineation of underlying structures. As such, the major neurosurgery operations (e.g. arterial, nervous, and venous anastomoses) are intrinsically conducted using an operating microscope. Moreover, it is recommended to use the microscope throughout the entire surgery, including when opening and closing of the skull, bone, and dura [85].

Microsurgery is technically more demanding than, for example, general surgery [1,3]. High magnification, binocular disparity, and limited field of view impacts on the surgeons' motor dexterity. Surgeons have to keep their eyes on the microscope oculars for a long period time and accurately allocate attention to the operating field.

Multi-axes adjustable arms hold the operating microscope head with oculars and handgrips so that microscope body can be installed away from the surgeon and patient; this allows surgeons and the microscope optics to move freely around the field. The ocular is often placed 20 to 30 cm away from the operating field and surgeons keep their eyes on the binocular tubes and eyepieces while performing a surgery (see Figure 4.1).

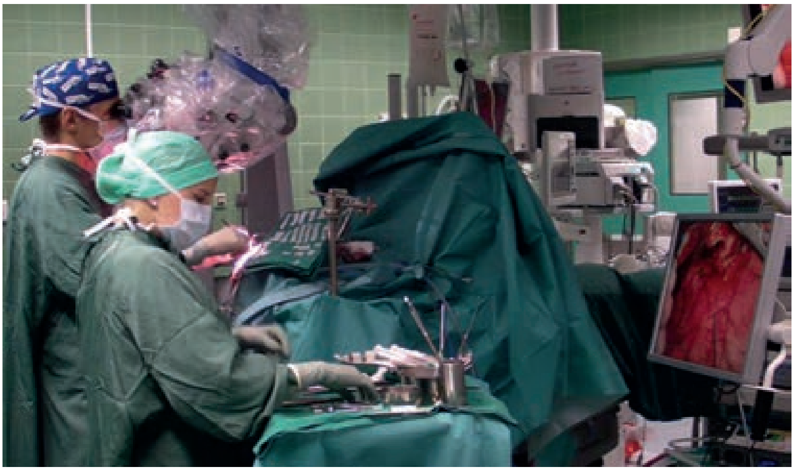

Figure 4.1: A typical view of a micro-neurosurgery operating room (OR). Multi-axes adjustable arms hold the operating microscope head with oculars and handgrips so the microscope body can be installed away from the surgeon and patient. Left: a neurosurgeon operating under a microscope. Right: a scrub nurse working continuously with the surgeon, providing the appropriate instruments in real time.

A perfect view of the operating field is a necessary condition when conducting micro-neurosurgery. Safe conduct assumes that the surgeon has a clear and unrestricted view of the field and is able to obtain the best possible angle on the operating field. As such, interaction with the microscope to obtain a perfect view is necessary during surgery.

When desired, the surgeon can use brake release controls – located on the handgrip– and move the microscope head along any axes. Zoom, focus, and light control buttons are also located on the handgrip. Modern microscopes also feature a mouth-held switch, which allows the surgeon to move the microscope head along either (x,y) or (z) axes while keeping his/her hands in the operating field.

Although the microscope provides effective assistance for neurosurgeons, it also places significant demands on visual perception and processing, namely, coordination between the eyes and hands that is unnatural for the naked eyes and every day haptics. Moreover, micro-neurosurgery requires delicate interactions between the surgeon, microscope, instrument, and the other experts in the OR.

During the period of this research (2011-2016), we have not seen any available technology to track eye movement of neurosurgeons when performing the microsurgery. In the following sections, we present the summary of the original papers of this dissertation. This includes the development of an eye tracker for the surgical microscope; The overview of our contributions in the field of eye tracking and neurosurgery is presented in four subsections (P(I)-P(IV)). For the detailed results and specific tabulated values, we refer the reader to the publications attached at the end of this thesis.

In the Section 4.3, we describe our efforts for developing a novel eye-tracker for the surgical microscope. It is highly important that such a complex, dynamic, and life-critical environment is well understood. Thus, we also provide a detailed analysis of data collected from interviews and observations of real surgical procedures during micro-neurosurgery (Section 4.2). Before these two sections, we performed a study by asking surgeons to review still images taken from neurosurgery. Initial findings on surgeons' eye gaze behaviors were highlighted in Section 4.1. Our study in Section 4.4 uncovers opportunities to record detailed eye movement data in real-time micro-neurosurgery. To our knowledge, this is first time that eye movements under microscope has been recorded.

4.1 PI: GAZE BEHAVIOUR OF EXPERT AND NOVICE MICRONEUROSURGEONS DIFFERS DURING OBSERVATIONS OF TUMOR REMOVAL RECORDINGS

In micro-neurosurgery a surgeon is required to allocate his/her attention on an operating microscope accurately for a long period. The operation necessitates concentration, and any distraction prolonging the procedure may lead to iatrogenic errors. Such a surgery has to be a well-learned routine. In Europe, for instance, to become a board certified-neurosurgeon, a trainee should have a minimum of six years of various trainings [19]. Moreover, a resident during his/her training must be exposed to at least four different trainers and the full spectrum of neurosurgical procedures [19].

The success of such surgery depends heavily on visual attention skills, eye-hand coordination, and manual dexterity [86]. Given these challenges, in the first paper of this dissertation, we planned to measure neurosurgeons' eye movements to understand the visual patterns in achieving and maintaining a high level of concentration in such a complex environment. We conducted an eye tracking study to compare expertise differences in gaze behavior.

At the time of this experiment, real time eye tracking during micro-neurosurgery was rather difficult to conduct. There were no available eye trackers to capture a user's gaze direction while using a microscope. Thus, we conducted our first experiment with a commercial eye tracker outside the OR. Drawing on the previous studies on radiology and laparoscopic surgery we hypothesized that expert surgeons would exhibit gaze behavior that could be characterized as more compact and locally defined gaze and thus they exhibit longer fixations on the area of interest.

4.1.1 Method

This study was conducted at the Kuopio University Hospital. The center for neurosurgery of this hospital (KUH Neuro Center), with more than 2200 annual operations, provides full acute (7/24) and elective neurosurgical consultation and treatment services for the

KUH catchment population in Middle and Eastern Finland. Moreover, the KUH provides neurosurgical education for the local medical students as well as foreign exchange students during a neurosurgery week with bedside, OR, and NeuroICU training in Finnish or English. Here, a graduated doctor of medicine is required to complete the six-year training program to become a specialist in neurosurgery.

The experiment was designed with two groups of participants, namely experts and novices. Their eye movements were recorded while observing a sequence of images from a tumor removal surgery. Depending on the years of expertise, the first group included four well experienced surgeons with a mean of 19 years of experience. The second group consisted of four residents with a mean of 2.5 years of experience. In summary, Table 4.1 shows the detailed description of the participants

Measures (in average)	Participants	Experts	Novices
Numbers	8	4	4
Age	40.6	49.5	31.75
Years of experience	10.75	19	2.5
Number of surgeries	1268.75	2250	287.5

Table 4.1: The detailed description of the participants

We selected four images from a neurosurgical resection of the malignant brain tumor (glioblastoma) taken under the Zeiss Pentero operating microscope. Each image was annotated by two experienced neurosurgeons. The annotations consisted of depictions of the areas that were important in each step of the surgery (Figure 4.2). There were four common areas of interest among images: AOI 1) the tip of the instrument, such as bipolar forceps, suction, and irrigation syringe; AOI 2) the bleeding areas; AOI 3) the tumor resection cavity; and AOI 4) the exterior of the tumor resection.

At the beginning of each recording we explained the experiment and the tasks for each participant individually. Subsequently, the

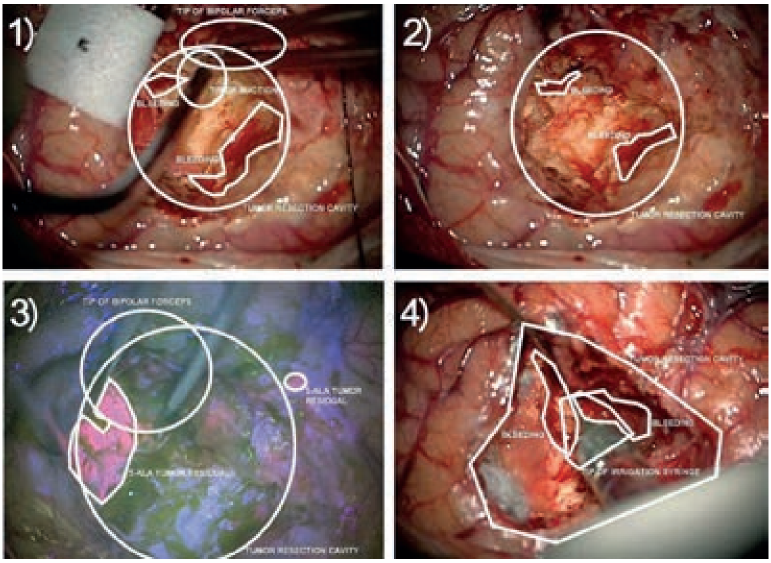

Figure 4.2: The sequence of images, each displayed for 10 seconds on the screen, employed in this study with the important areas annotated by two expert neurosurgeons. AOI 1) the tip of the instrument, such as bipolar forceps, suction, and irrigation syringe; AOI 2) the bleeding areas; AOI 3) the tumor resection cavity; and AOI 4) the exterior of the tumor resection.

participant filled the individual related information and signed a consent form. Then, the eye-tracker was calibrated by showing 9 points to the participant.

Participants were asked to first read an instruction page on screen about the experiment: 'Your task is to carefully look at coming images. There will be four images and each image will last for 10 seconds. After each image answer aloud to questions; your voice is recorded. There is no time limit for answering the questions. If you are ready press Space key'. The questions were related to a general awareness of the surgery situation, and prompted participants to verbally describe 1) the objects just seen on the image, 2) the progress of the surgery, and 3) the expectations about the next step in the surgery. Using these questions, we confirmed that all participants had sufficient knowledge on neurosurgical resection of the malignant brain tumor (glioblastoma).

We used Tobii T120 eye tracker –at a viewing distance 60 cm, a 1024 by 768 pixel resolution, and 120Hz sampling rate– to record eye movements data. We employed a velocity-based algorithm [87] –using a custom software designed by the author– for fixation identification with a threshold of 100 deg/sec. We set a minimum of 100 ms for fixation duration and maximum distance of 30 pixel between two gaze points. The gaze behavior of the two groups was then compared (two-way ANOVA analyses) with respect to expert annotated areas of importance using common eye tracking metrics namely, the number of fixations, the time to first fixation, fixation duration, and saccade amplitude.

4.1.2 Results

We presented the findings as a series of two-way ANOVA analyses, each illustrating the key measures of the eye movement on the images or the AOIs. In overall, in all phases of the surgery (images) the experts had fewer fixations, however, only when 5-ALA fluorescent markers were applied (Image 3 in Figure 4.2)– to highlight the residual tumor areas– experts had significantly fewer fixations (on average 3.75) compared to the novice group with 8.00 fixations on average ($F(1,6) = 7.05$, $p = .038$). In summary, Table 4.2 shows the average number of fixations on AOIs.

We found that the number of fixations on the tip of instruments differed significantly between expert and novice groups. Experts had 10.9 fixations on the tip of the instruments, while novices had 15.25 fixations. However, for other AOIs, these differences were not significant. Figure 4.3 shows a heatmap of a novice surgeon fixating on the tip of the instruments.

More to the point of our hypothesis, related to the level of concentration, in micro-neurosurgery, we found that the mean fixation duration (MFD) was longer for experts. In summary, Table 4.3 shows the MDF on AOIs.The MFD on the tumor resection cavity was significantly longer for experts (308.25ms) than for

AOIs	Expert (ms)	Novice (ms)	P-value <0.05
(1) Instrument	Avg=10.9, SD=4.52	Avg=15.25, SD=4.94	Yes
(2) Bleeding	Avg=4.5, SD=4.62	Avg=4.08, SD=4.54	No
(3) Tumor resection	Avg=26.87, SD=5.03	Avg=26.08, SD=5.73	No
(4) others	Avg=2.94, SD=3.61	Avg=4.75, SD=4.52	No

Table 4.2: The Number of fixations on the AOIs. AOI (1) the tip of the instrument, such as bipolar forceps, suction, and irrigation syringe; (2) the bleeding areas; (3) the tumor resection cavity; and (4) the exterior of the tumor resection.

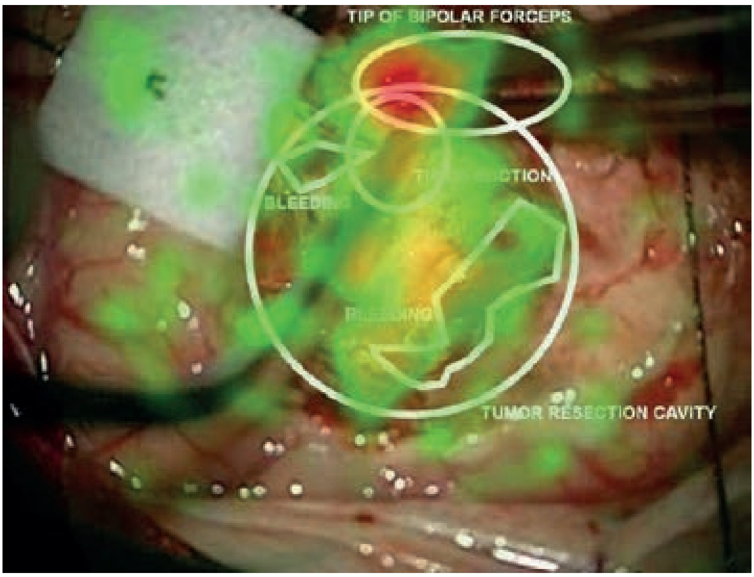

Figure 4.3: A heatmap of a novice neurosurgeon regarding the number of fixations on the tip of the instruments. Novices had more fixations on the tip of the instruments than the expert group.

novices (244.51ms). For the resection cavity on, average, the experts' MDF was 313.50, (SD=68.33) and for novices the MFD was 255.68, (SD=92.21). We reported the same pattern for the tip of the instruments (on average, the MDF for experts was 327.51 ms (SD=72.32) and for novices 253.19 ms (SD=35.50)).

AOIs	Expert (ms)	Novice (ms)	P-value <0.05
(1) Instrument	Avg=327.51, SD=72.32	Avg253.19, SD=35.50	Yes
(2) Bleeding	Avg=311.71, SD=73.57	Avg=252.97, SD=63.37	No
(3) Tumor resection	Avg=308.25, SD=51.43	Avg=244.51, SD=26.79	Yes
(4) others	Avg=313.50, SD=68.33	Avg=255.68, SD=92.21	Yes

Table 4.3: The fixation duration on the AOIs. AOI (1) the tip of the instrument, such as bipolar forceps, suction, and irrigation syringe; (2) the bleeding areas; (3) the tumor resection cavity; and (4) the exterior of the tumor resection.

Overall, the time to the first fixation for both experts and novices varied between participants. Thus, we could not claim specific differences. During this analysis, however, we noted that two novices did not have any fixation on the bleeding area, while all experts had at least one fixation on that area.

4.1.3 Discussion

In P(I) we reported a marked difference in how expert and novice neurosurgeons attend to snapshots of the surgery images. We found differences in the number of fixations directed toward the instruments and the areas highlighted by a fluorescence marker. Furthermore, the finding related to the mean fixation duration confirmed that neurosurgeons were able to focus for a prolonged time at a desired point due to the limited size of the operating area.

The overall viewing behavior of experts was characterized as more compact; typically, experts employed fewer and longer fixations as well as shorter saccades. These differences were more significant at the tip of the instrument, such as bipolar forceps, suction, and irrigation syringe, as well as for the stimuli with a fluorescence marker (Image 3 in Figure 4.2).

The results confirmed our hypothesis that differences between expert and novice can be seen in longer fixation durations for experts due to the ability to focus on micro-anatomies. While we could not find a similar study in the field of neurosurgery concerning surgeons' gaze behavior, we compared our finding with other expertise domains. As such, our results differed from some of the non-medical applications [9, 34, 88, 89] where experts were distinguished as having shorter fixations. However, a similar pattern has been reported in medical image perception tasks, laparoscopic and other the surgical domain [6, 8, 10, 50]. Compare to the laparoscopy studies –experts spent less time on tracking instruments [13]– in our task experts had longer fixation duration on the tip of the instrument. In micro-neurosurgery the field of view is narrow, and instruments are the biggest objects in the scene thus the instrument often is located on the target where surgeon should focus.

At this point in the study, neurosurgeons provided us with feedback on the processes involved in critical situations in the OR and our findings in this paper. The critique concerned the use of images in the experiment. It is not common for neurosurgeons (in contrast with radiologists) to work with images; rather, they use a microscope to conduct an operation. As such, we have to build a system that is able to record surgeons' eye movement while using a surgical microscope. We envisioned that the knowledge of visual attention patterns could be used to train future experts and assess their skills.

4.2 PII: ANALYSIS OF DISRUPTIVE EVENTS AND PRECARIOUS SITUATIONS CAUSED BY INTERACTION WITH NEUROSURGICAL MICROSCOPE

Motivated by the first paper, in this stage of work we aimed to build an eye tracker for the surgical microscope. Due to the complexity of the neurosurgical practices, to fulfill surgeons' needs and requirements, first, an in-depth exploration of the design space was essential. The previous development research in this field has focused on improving the operating precision and the freedom to smoothly operate a surgical microscope [39]. As such, current surgical microscopes provide clear magnification with powerful illumination. A sharp view of the operating field –which is the result of a controlled zoom and focus system– enables surgeons to have a natural perception of the surgical field. In addition, the option to adjust the position of the whole system allows a surgeon to select different positions as required.

At the time of this work (2014-2015), the argument for improving operating microscopes was not well articulated within the context of micro-neurosurgery routines and HCI practices [39]. Therefore, we extended [39]'s study to identify the design space opportunities and challenges (i.e. the interaction details) concerning a state-of-the-art neurosurgical microscope.

The results from this paper can be used for team dynamic and resource management analysis of neurosurgical OR, however this is not the main focus of the paper. This observational field study has been conducted to understand the requirements of building a custom-made eye tracker for neurological microscope.

In this paper, the video data from detailed observations of neurosurgeons' interaction patterns with the microscope were annotated and analyzed quantitatively. The detailed analysis was the primary step to assess appropriate circumstances to apply eye tracking interventions in the micro-neurosurgery settings.

4.2.1 Method

In the KUH Neuro Center, Kuopio University Hospital, for a course of one year inside OR we observed over 20 surgeries and video recorded nine surgeries including three aneurysms, three brain tumors, and three spinal surgeries. Surgeries were performed by six surgeons, from the Kuopio KUH Neuro Center, with an average of 17 years of experience in neurosurgery (all but one was male).

Two video cameras were placed on tripods behind the surgeons, in the left and right corners of the room, to provide a complete view of the operating area including the microscope, surgeon, scrub nurse, and OR screens. We also recorded the surgeries using the microscope's built-in camera. Figure 4.4 shows the schematic view of the OR configuration presented in P(II).

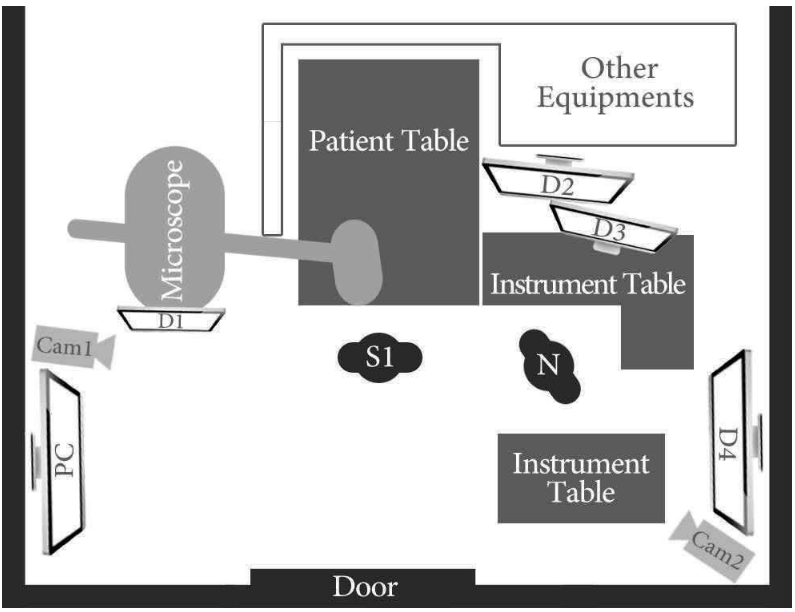

Figure 4.4: Schematic view of the operating room configuration presented in P(II). S1) the positions of the surgeon. N) scrub nurse. D1, D2, D3, and D4) OR displays. Reprinted from P (II).

In sum, 54 hours of video materials from three different cameras were processed. The ELAN annotation tool (version 4.6.2) was used to annotate the videos. Three views recorded from the cameras were available to the coder. Two layers of parallel annotations were employed to analyse the video materials.

We developed an annotation scheme to classify different interactions and to evaluate their temporal alignments and durations. The annotations were based on an emergent bottom-up approach, in which appropriate annotation categories were defined, merged, and modified as the analysis was conducted. We considered a minimum duration of 1 second to annotate each event. The coding scheme is shown in Table 4.4. A total of 2122 events involving the surgeons, surgical instruments, and microscope were annotated. The first annotation group considered all surgeons' interactions that occurred at any time during the surgery. These included:

In the second group of annotations, we used the video recorded by the microscope camera to define the non-focusing view and the area where the surgical instrument was functioning. These annotations were used to identify whether surgeons experienced any difficulties related to microscope view. We considered a minimum duration of one second to define a situation as undesirable.

In addition to the recorded video materials, our data also contained interviews with surgeons that were collected before, during, and after each surgery. All recorded surgeries were conducted by senior neurosurgeons (experts), and they were encouraged to provide us explanations about the procedure while performing surgeries.

4.2.2 Results

During our observation, we noticed that providing fast and easy access, for personnel, to the patient and equipment was one of the main concerns in the OR setup. Moreover, the OR physical arrangement was set up to maintain a clear line of sight for all OR personnel and to respect the sterile zone during surgery. The microscope arm and oculars, located close to the patient's bed in the

Name	Description
Hand-off (R/L) (R)	Interaction between the surgeon, using the right (R) or left (L) hand, and scrub nurse for exchanging an instrument
Microscope handgrip (R/L)	Interaction between the surgeon, using the right or left hand, and the microscope handgrip for repositioning the microscope, focusing, or zooming
Microscope mouth switch	Interaction between the surgeon and microscope mouth switch for repositioning the microscope
Take/place instruments (R/L)	Direct interaction between the surgeon, using the right or left hand, and instruments

Table 4.4: Annotation coding scheme based on the interactions. Note: R right hand, L Left hand.

sterile area, were covered by a sterilized wrapping in the preoperative procedure. Therefore, any device (e.g. eye tracker) attached in this area had to be placed under the wrapping.

We observed that surgeons had to apply a set of interaction commands, namely, moving, zooming, and focusing by frequent manual manipulation of the microscope, to maintain a clear view of the operating field. Table 4.5 presents the average frequency and duration of each interaction.

On average, 113 (SD=15) interactions occurred during the annotated surgeries. These consumed nine minutes (SD=2) of each surgery on average. We reported that regardless of the type of the

Interactions	Frequencies	Durations
Hand-off (R)	Once per 50 (SD=13)	3 (SD=1)
Handgrip (R)	Once per 114 (SD=32)	8 (SD=2)
Mouth switch	Once per 376 (SD=386)	3 (SD=1)
Take/place instrument (R)	Once per 1098 (SD=454)	4 (SD=2)
Ongoing surgery	Once per 50 (SD=13)	3 (SD=1)

Table 4.5: Average frequency and duration of each interaction. Note: R right hand, L Left hand. We did not observe notable interaction between the left hand and different instruments (right-handed surgeons).

surgery, such interactions occurred frequently and consumed up to 18% of the annotated surgery time (50 minutes average annotated data).

We showed that surgeons in most of the interruption events organized their interactions in a way that allowed them to avoid removing eyes from the microscope ocular, for example, by combing two interactions: changing of the instrument and adjusting the microscope setting. Moreover, during these interactions, surgeons often kept their eyes on the microscope ocular, which again showed the important role that visual attention plays here (see Figure 4.5). Only in 20% (on average) of cases, neurosurgeons did not look into the microscope during hand-off interactions.

We also saw surgeons avoided necessary interactions with the microscope to keep their eyes focused on the operating field. For instance, on average, nine times surgeons worked under a non-focused view for an average duration of 13 seconds. In another example, on average, 11 times surgeons decided to continue working at the edges of field with a mean total duration of four minutes. Such events are not risk free, for instance, working on the edge created challenges for team co-operation because the view of the microscope is larger than the view of the OR displays, and thus a scrub nurse could not follow the course of surgery.

Figure 4.5: A surgeon swapped an instrument with the scrub nurse while keeping his eyes on the microscope ocular.

4.2.3 Discussion

We looked at the nuances of microscope use in the neurosurgical OR from the perspective of interaction analysis. We found that surgeons play a leading role in interacting with the personnel and instruments to expedite the progress as well as to warrant safe surgery. Two major interactions with the microscope were with the handgrip and mouth switch, which took 8% and 2% of the annotated surgical time respectively.

Interruptions caused by the readjustment of the microscope require extra time and effort from the surgeon to regain a perfect view. Moreover, these interruptions are not risk free; for example, looking away from the microscope ocular leads to a loss of alignment and potentially a loss of awareness of the situation in the operating field [39]. As such, we showed that, regardless of the stage of surgery, surgeons minimized their interaction with the microscope and maintained a high-level of concentration by keeping their eyes on the microscope ocular, even during interactions with the microscope or personnel (see, for example, Figure 4.5).

In addition to our objective for the analysis of surgeons' visual attention, this paper makes an important contribution to the neurosurgical domain, as our detailed analysis of neurosurgical practices can be used to improve the current processes and for the design of future medical interactive technologies. The novel interaction methods may include the design of control elements, display organisations, and consequently the processes surrounding the operation of the devices.

For example, based on our results, reducing the handgrip and mouth switch interactions in micro-neurosurgery could save up to 10% of the surgery. One may apply voice command or gaze contingent techniques, as new possibilities for surgeons, to adjust the microscope settings without removing their hands from the operative field.

Based on our analysis we argue that the interactions with the microscope are frequent and the duration of each interaction is short; thus a slow voice command system may not be appropriate. We have seen more complex interactions (e.g. tilting), which are very difficult to describe in speech vocabulary terms. Moreover, we confirmed that neurosurgeons have an ability to focus on the operating field for a long period of time by keeping their eyes on the microscope oculars for 80% of the surgery time thus a gaze system might be an appropriate solution for the above mentioned problems.

4.3 PIII: EMBEDDING AN EYE TRACKER INTO A SURGICAL MICROSCOPE: REQUIREMENTS, DESIGN, AND IMPLEMENTATION

Findings from previous papers support our initial motivations for exploring the possibility of recording neurosurgeons' eye movements in the OR. At the time of writing this paper (2015), we were not able to find any example of eye tracking studies in microsurgery OR. Moreover, only a hand-full of papers have reported the development of OR eye trackers [22, 90]. However, arguments for developing eye tracking devices have not been well articulated within the surgical environment. In microsurgery, only one study has reported the use of an eye tracker with a microscope. In the early 90s Charlier et al. [22] proposed an eye-controlled surgical microscope; however, the paper lacks detail regarding the description of the system, its application, and evaluation.

The most commonly used eye tracking setups in medicine are remote display and wearable head-mounted eye trackers. In practice, remote display eye trackers have mainly been used outside of the OR because the distance factor limits surgeons' freedom of movements [13,73]. Wearable and head-mounted eye trackers, however, limited surgeons to use other ocular-based optical devices (e.g. microscope).

In this paper, we presented a video oculography (VOG) solution for eye tracking in micro-neurosurgery and embedded a binocular eye tracker into a surgical microscope. Our development attention then was not on the image processing techniques used to detect gaze positions, but rather our focus was on the design principles in this environment. In addition, we highlighted the technical challenges encountered when embedding an eye tracker into a surgical microscope.

4.3.1 Method

We used a well-known eye tracking principle, VOG, to develop the microscope eye tracker. A custom-made 3D printer was used to build the prototype. the components of the microscope eye tracker were Sony PlayStation Eye cameras, CCTV camera lenses, square 45 degree hot mirrors, Optolite Infra Red Acrylic visible filters, OP166W IR LEDs, and resistors.

After each development cycle, we conducted a series of interviews and observations to lean how neurosurgeons use our prototype and applied these findings to shape the final version of the eye tracker. To evaluate the performance of our system, we extended the Haytham eye tracking software [91–93] with an implementation for accuracy and precision validation procedure. Five participants (three surgeons and two students) were required to perform calibration and evaluation procedures outside the OR with the Carl Zeiss neurosurgical microscope (OPMI Pentero). Figure 4.6 shows the experiment setup and apparatus used in this study.

4.3.2 Results

We first identified the requirements by interviewing surgeons and then provided solutions to the problems with the design of such an eye tracker. Based on the findings from P(II) and observations in this paper, collaboratively with neurosurgeons, we derived six fundamental requirements for integrating an eye tracker into a surgical microscope. These requirements shaped the design and development of the eye tracker presented in this work:

1. The system should not require any modification to the current microscope.
2. The eye tracker should be non-intrusive, causing no disruption to the standard flow for the surgeon.
3. The required time to set up the system must be short.
4. The sterility of the surgical area should not be violated after adding the eye tracker to the microscope.
5. The surgeon's face and eyes should be protected from harm (when touching the eye tracker surface).

Figure 4.6: Experimental setup and apparatus used in this study. To our knowledge, this is first time that ones record eye movements under microscope. Through iterative cycles of design, implementation, and evaluation we embedded our eye tracker into a Zeiss neurosurgical microscope (OPMI Pentero). The current version of the prototype is fully functional and complies with the design specifications defined in this study. Reprinted from P (IV).

6. The eye safety should be considered due to the long exposure times to the infrared light (IR).

We then developed an eye tracker that follows the principles of wearable eye tracking goggles and, at the same time, is part of the optical tract of a microscope. Through five prototype cycles, we improved the size and ergonomic aspects of the eye tracker as well as the image quality from the eyes captured by the cameras. As such, the height of the eye tracker –the distance between eyes and oculars– was merely 20mm, which is the same as the microscope's ocular focal length. Figure 4.7 shows the final version of the eye tracker.

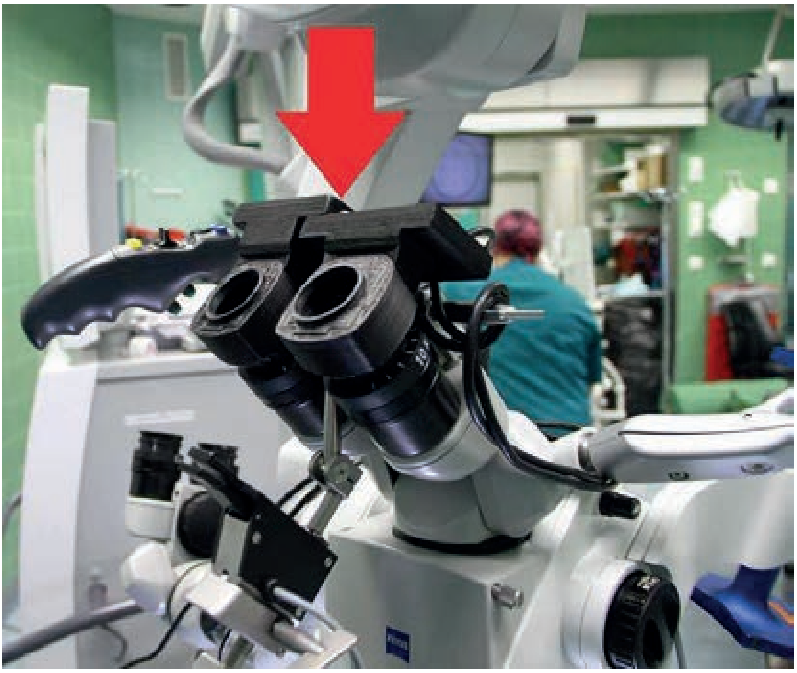

Figure 4.7: The final version of the eye tracker being installed on the OR microscope.

Finally, we tested our design and reported the accuracy of the integrated system. As a result, the final model of the eye tracker met the demands of surgeons with an acceptable degree of accuracy. In this primary test, the accuracy of the system was 1.1 degrees and precision was 0.55 (RMS). Five participants (three surgeons and two students) with median age of 42 (range=29-54) were recruited for this evaluation. Table 4.6 shows results of the validation procedure.

4.3.3 Discussion

During this project, we faced numerous requirements and limitations that shaped the development through the five prototype cycles. In this paper, we discussed problems arising in the surgical microscope after installing an eye tracker on the ocular and practical tips to solve the problems. The current version of the prototype

Eyes	Accuracy	Precision(RMS)	Precision(SD)
Left eye	1.1	0.6	0.04
Right eye	1.2	0.5	0.03
Average	1.15	0.55	0.035

Table 4.6: Accuracy and precision in degrees of the visual angle. The standard deviation (SD) is in the cm.

is fully functional and complies with the design specifications. The eye tracker is non-intrusive and allow free movement of the surgeon. Moreover, it does not violate the sterility of the surgical area.

The novelty of our approach is the way in which we designed the system. Our particular focus in this paper has been an empirical evaluation and critical assessment of the eye tracker hardware. We argue that the eye tracker proposed by Charlier et al. [22] does not fulfill the fundamental requirements identified earlier in this study. In contrast, the proposed system, has certain features (e.g. shape and size) that warrant integration of the eye tracker into surgical microscopes during operations.

Real-time ecologically valid studies can now be conducted in micro-neurosurgery practices. The captured gaze patterns can be used to improve medical education, as part of an assessment system or in a gaze-training application. We also envision the use of this eye tracker to introduce gaze based interaction in micro-neurosurgery. The applications of this eye tracker are, however, wider than neurosurgery. We envision deployment in other medical contexts, for example, ophthalmology, otolaryngology, and plastic and reconstructive surgery as well as in non-medical domains such astronomy, forensics, and chemistry.

4.4 PIV: OPTIMAL EYE MOVEMENT STRATEGIES: A COMPARISON OF NEUROSURGEONS GAZE PATTERNS WHEN USING A NEUROSURGICAL MICROSCOPE

In micro-neurosurgery, we learned that although magnification allows for a clear view of the operating field, it also reduces the overall field of view. Thus, when operating in a small, narrow, and deep field –under a high level of magnification– any tremor or unnecessary movement causes potential complications. For example, a small movement in the depth causes the field of view to become blurred. In response to these complexities, neurosurgeons undergo a long training period and have to continue practicing manipulating instruments and objects under the microscope.

For several decades now, researchers have demonstrated the potential of eye tracking to provide reliable insights into visual attention and have used them for skill assessment and training systems in professional domains [9]. While there are numerous studies of visual attention patterns in the medical contexts, these patterns have not been studied in any microsurgical context. Until now, it was not possible to record eye movements in ocular-based setups; thus, there was a lack of evidence of empirically demonstrated visual attention patterns in this domain.

To help answer questions related to the development of expertise and visual attention patterns, we presented a study of neurosurgeons performing a cutting and suturing task under a neurosurgical microscope. We have extended P(III) to record the eye movements of neurosurgeons while using a surgical microscope. The focus of our analysis was to measure the amount of attention on the scene context and understand the nature of expertise in micro-neurosurgery. Referring back to our first paper, P(I), of this PhD we hypothesize that as the year of surgical experience increase, neurosurgeon will present longer fixations on the operating field. Moreover, we expect a difference between neurosurgeons' saccade patterns regarding their years of experience too.

4.4.1 Method

The experiment was conducted in the neurosurgery department of Helsinki University Central Hospital. With the help of an expert neurosurgeon, we designed a surgical test to simulate a vessel wall suturing procedure in micro-neurosurgery. We divided our experiment into two tasks: first, participants were asked to cut precisely along a curved line drawn on the top of a latex glove sheet. For the second task, we asked them to suture an already cut latex glove.

The eye movements of nine neurosurgeons under a neurosurgical microscope while performing the cutting and suturing tasks were recorded. We provide a 7-0 needle, 20 cm thread, and suitable micro-instruments (i.e. scissor, needle holder, and forceps) for all participants. Figure 4.8 shows the experimental design. A warm-up task was designed to prepare participants. The actual recording started with the cutting task, suturing the left side, and suturing the right side of the model (having a short break in between).

To capture neurosurgeons' eye movements we used our custom made surgical microscope eye tracker. We learned from the previous paper, P(III), that head movements have a negative effect on the accuracy of our eye tracker. Thus we extended our system by adding two glints to be used for gaze estimation. For the purpose of this experiment, Enkelejda Kasneci and Wolfgang Fuhl helped us to build custom-made software for surgical eye tracker microscopes. See the related paper by Fuhl et al. [94, 95] for more details.

In summary First, for the detection of the Region of Interest (ROI), our algorithm downscales the image and then calculates the mean gray value. The decision whether an image pixel belongs to the ROI is taken based on the mean value of the surrounding pixels.

After a ROI is found, the algorithm searches for the image area that represents the pupil. For automated pupil detection, we employ the Fuhl et al. [94, 95] algorithm with a validity threshold of 50. The algorithm operates on Canny-edge filtered eye images. The pupil center is found in a decision based approach. Based on the edge-filtered image, edge connections that could impair the sur-

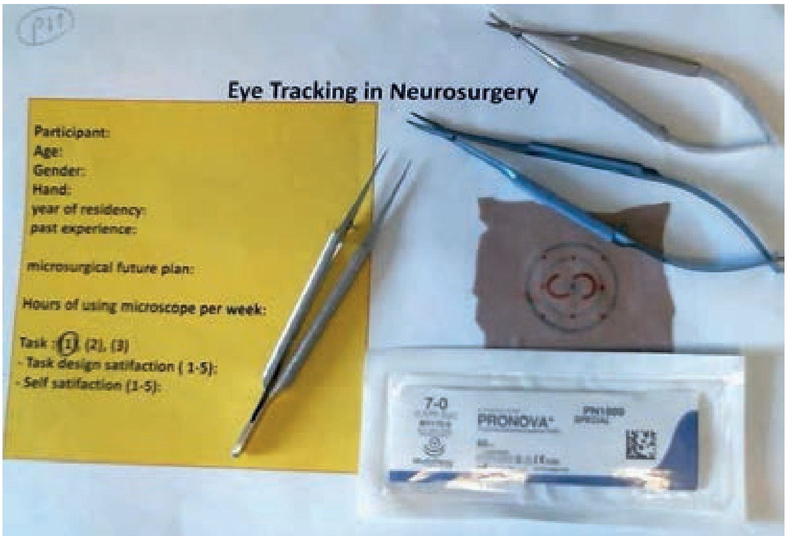

Figure 4.8: The experimental design with micro-instruments (i.e. scissor, needle holder, and forceps). Reprinted from P (IV). In addition to participant information, we asked them to rate our model from 0–5, considering five as the maximum. The average task design satisfaction score was 4.4 (SD. 0.5).

rounding edge of the pupil are removed by means of morphologic operators.

Then, connected edges are collected and evaluated based on straightness, inner intensity value, elliptic properties, the possibility to fit an ellipse to it, and a pupil plausibility check. If a valid ellipse describing the pupil is found, it is returned as the result.

Using the same algorithm, we detect glint points to correct the head movements. Since glints are represented by bright points, a circular shape, in the pupil area we used second step of Fuhl et al. [94,95] algorithm related to blob detection.

Finally, for calibration and gaze mapping, a nine point calibration pattern is employed. During the calibration procedure, we calculate the vector between the pupil center and the center of both glints. Afterward, a least squares polynomial fit is calculated where the vectors are input variables and the calibration point positions are the polynomial result. After calibration, the new pupil glint vectors and the polynomials are used for gaze position estimation.

Drawing on the eye tracking literature [26], we computed the average fixation duration, fixation rate (the number of fixations divided by the total duration of fixations), saccade duration, saccade rate (the number of saccades divided by the total duration of saccades), and saccade amplitude (distance). We used mixed model ANOVA analysis to show how eye movement patterns differ among novice and expert surgeons. We compared the mean differences between groups that have been split based on two factors, where expertise level is a between-subject factor and the experiment session is a within-subjects factor.

4.4.2 Results

In this experiment, we reported findings around the key assumptions of our hypothesis. We compared the effect of expertise on eye movements of neurosurgeons. In the cutting task, we found significant differences in the average fixation duration between expert and novice groups ($F(1, 15) = 6.29$, $p = .03$, $\eta^2=.26$). Surgeons who had a longer period of training and practice (experts) had longer fixation durations, with a correlation coefficient of 0.3. We also found the same effect of expertise in the fixation rate; however, this effect was not significant ($F(1, 15) = 3.88$, $p = .08$, $\eta^2=.22$). Table 4.7 shows comparison between eye movement features and level of training when surgeons participated in the cutting task.

Moreover, surgeons' fixation durations differed for the left and right sides of our model. On average fixation durations were 500ms for the expert group (382ms for the novice) on the right side and 848ms for the experts (402ms for the novice) on the left side. We assumed that the left side is more difficult because all surgeons but one were right handed. For the left handed participant, the longer fixation duration (35ms more) was related to the right side of the model in which he also spent more time (about two times as long) to complete the task. In contrast, it took more time for the right-

Metrics in average (SD)	Right side		Left side	
	Experts	Novices	Experts	Novices
Fixation duration (ms)	500 (188)	382 (197)	848 (377)	402 (185)
Fixation rate	0.0022 (0.0008)	0.0030 (0.001)	0.0013 (0.0006)	0.0030 (0.001)
Saccade duration (ms)	32 (12)	36 (14)	26 (6)	39 (15)
Saccade rate	0.033 (0.01)	0.031 (0.01)	0.039 (0.009)	0.029 (0.008)
Saccade amplitude (degree)	0.7 (0.4)	0.6 (0.2)	0.5 (0.2)	0.6 (0.1)

Table 4.7: Comparison between eye movement features and level of training when surgeons participated in the cutting task.

handed participants to complete the left side task compared to the right side (the t-test did not reject the null hypothesis).

The average fixation duration for the suturing task showed a similar trend –a longer fixation duration for experts– as the cutting task; however, these differences were not statistically significant. On the other hand, there was a strong significant difference in the saccade measures concerning expertise level. We noted changes in the experts' visual strategy based on the left or right side of the model; however, novices followed the same pattern regardless of the task position in stimuli. Table 4.8 shows comparison between eye movement features and level of training when surgeons participated in the suturing task.

When suturing the right side, we found significant differences for the expertise level in the saccade duration ($F(1, 52) = 9.43$, $p =$

Metrics in average (SD)	Right side		Left side	
	Experts	Novices	Experts	Novices
Fixation duration (ms)	318 (SD.83)	305 (SD.132)	332 (SD.117)	296 (SD.110)
Fixation rate	0.0033 (SD.0.0008)	0.0037 (SD.0.001)	0.0034 (SD.0.001)	0.0038 (SD.0.001)
Saccade duration (ms)	31 (SD.4)	36 (SD.5)	37 (SD.6)	34 (SD.6)
Saccade rate	0.033 (SD.0.005)	0.028 (SD.0.004)	0.029 (SD.0.005)	0.031 (SD.0.005)
Saccade amplitude (degree)	0.6 (SD.0.1)	0.7 (SD.0.1)	0.8 (SD.0.1)	0.7 (SD.0.1)

Table 4.8: Comparison between eye movement features and level of training when surgeons participated in the suturing task.

.004, η^2=.16), saccade rate (F(1, 52) = 10.22, p = .003, η^2=.17), and saccade amplitude (F(1, 52) = 4.78, p = .03, η^2=.09). In the left side of the model, however, the expertise effect was only strong in the saccade amplitude (F(1, 52) = 5.33, p = .03, η^2=.10).

4.4.3 Discussion

In this study, eye movement measures, fixations and saccades were used to precisely show neurosurgeons' visual attention patterns while using micro-instruments under a surgical microscope. It is clear from the results that the expertise level affects eye movement patterns and expert neurosurgeons developed a range of visual attention strategies to perform a simple, fast, and safe surgery.

The first strategy here concerns the long fixation duration and high level of focus that experts were able to maintain. In particular, in the left-side task (right-handed participants) when there were no distractions, well-trained surgeons increased their fixation duration on the operating field twice as much as novices.

Another important observed strategy was when surgeons performed a task with more distractions and challenges (e.g. swapping instruments). In the suturing task, though, experts tried to keep their attention focused with a longer fixation duration (compared to the novices), but they still were distracted and as a result, they had a shorter fixation duration compared to the cutting task.

To overcome the problem with distractions and reduced concentration level in our experiment, experts adopted a different strategy. First, they started to apply shorter and more frequent saccades. Second, when suturing the left side of the model (right-handed participants), experts applied long-distance saccades.

Overall, in the suturing task compared to the cutting task, we found greater variety across subjects and more complex manipulation with the center of gaze. In the cutting task, however, the attention (center of gaze) of all neurosurgeons was inevitably drawn to the area in the field where the tip of scissor meets the angle-gape of the cutting. Therefore, the important spot in the cutting field may act as a low-level visual cue (see Figure 4.9).

From our observation of the gaze reply videos, we see that expert neurosurgeons have more predictive skill in surgeries. For experienced neurosurgeons, the center of gaze proceeded their instruments' movements, meaning they anticipated the next step. There is a need for a further work to track the hand and instrument movements to obtain more in-depth information about the development of eye-hand coordination skills in micro-neurosurgery.

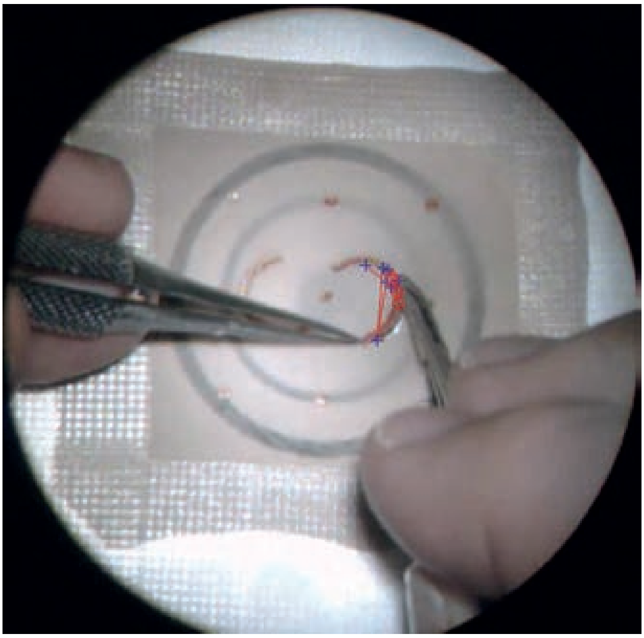

Figure 4.9: An example of a two-second scanpath of the fixations (red circles) and saccades (blue cross). The attention (fixation) of the neurosurgeon is attracted to the area in the field where the tip of scissor meets the angle gape of the cutting. Reprinted from P (IV).

5 Discussion

In this dissertation, we presented studies of neurosurgeons' visual attention and applied fieldwork and experimentation methods. Applying eye tracking in micro-neurosurgery has been a driving motivation behind this work. Typically, neurosurgery is performed under an operating microscope; thus, it requires a high level of concentration, fine-motor skills, and coordination of eye-hand movements to maneuver micro-instruments and to attain precision.

Eye tracking enables researchers to further understand neurosurgical practices without the need to distract surgeons from their routine tasks. The central contributions of this dissertation include, first, workplace studies in mapping the complexities of micro-neurosurgery practices to facilitate the development of any new technologies in the operating room (OR). Second, we integrated an eye tracker for a surgical microscope that met the OR requirements within current neurosurgical routines. Third, we discovered neurosurgeons' gaze patterns with respect to their expertise level. In light of the publications presented in this dissertation, we can now provide answers to the three research questions that have guided our work.

RQ1. What are the spatial arrangements of clinicians, artifacts, and instrumentation during micro-neurosurgery procedures? What are the challenges in terms of microscope view production and use?

The answer to this question was presented in P(II). In this phase of the work, we learned that a neurosurgeon has to have a clear, unrestricted, and magnified view of the operating field to perceive the details of the anatomical structures. Thus, a surgical microscope plays the key role in micro-neurosurgery. We observed that a surgeon's overt attention is directed exclusively toward the microscope throughout the entire surgery. On average, the microscope was used for approximately 80%

of the surgery time. We concluded that nature of the work and dependency of the procedure on the microscope causes the surgeon to be completely immersed with the ongoing surgical procedure.

Moreover, the ways in which surgeons interact with instruments and the rest of the team were impacted by the considerable time surgeons spend looking through the microscope. In our experiment, often these interactions, namely re-adjusting the microscope or swapping an instrument, were done while the surgeon's eyes were kept on the microscope oculars (up to 80% of time). Therefore, any change to the surgical microscope must take into account not only the surgeon, but also the entire OR team and environment. As such, the integrated eye tracker must respect the sterile zone (be placed under the wrapping) and be non-intrusive and allow the surgeon to move freely.

The analysis in P(II) also revealed interruptions caused by manual adjustment of the microscope settings (changing the field of view, zooming, and focusing). When operating a skull-based surgery, we observed that every time the surgeon removed his/her hands from the operative field –to adjust the microscope– compression caused by spatulas and the elasticity characteristic of brain tissue lead to the tissue collapsing back together. These interruptions require extra time and effort from the surgeon to restore the previous position and regain a perfect view. Moreover, looking away from the microscope ocular leads to loss of alignment and potentially a loss of awareness of the situation in the operative field. Thus, operating under a microscope requires advanced expertise and good situation awareness, as the precise timing of the actions has to be accurately predicted and well managed [39,96].

RQ2. What are the approaches and limitations of embedding an eye tracker into modern neurosurgical microscopes?

With the guidelines presented in P(II), we further answered this question in P(III). We first identified the requirements and then provided solutions to the problems with the design of the microscope eye tracker. The main challenge of building an eye tracker for a microscope was the design of an adapter that mounts the eye tracker components on the top of the ocular. We placed all eye tracker components on the side of a 45-degree hot mirror, so they were not visible to the surgeon's eye. To reduce the setup time, we designed the tracker to be attached to the microscope's eye-guard place.

To overcome ergonomic and safety challenges, we made the outer casing of the tracker model more cylindrical, while the inner layout structure remained square (we used a square hot mirror). Moreover, to warrant the IR eye safety, we carefully selected an LED that meets the requirement related to the maximum permissible exposure (MPE) standard [97].

Another important challenge related to the design of the eye tracker was the size (height) of the model. A typical distance between the eye and ocular (eye relief) of the surgical microscope is about 20mm. This distance should not be exceeded, otherwise both the magnification and field of view will be reduced significantly (there is an inverse relation between the eye relief distance and the field of view). To achieve this size, through an iterative design, implementation, and evaluation, we adjusted the angle of the camera and hot mirror to 20 and 25 degrees, respectively.

The final model of the eye tracker met the demands of surgeons with an acceptable degree of accuracy [98–102] for custom-made eye tracker solutions. On average, we achieved 1.1 degrees of accuracy and 0.55 (RMS) degrees of precision.

RQ3. How do surgeons' eye movements differ within the microsurgical environment and do the eye movement features, namely fixations and saccades, reflect expertise levels?

The basis for the answer to this question was part of P(I), but was explored more thoroughly in the P(IV). The results from

P(I) and P(II) are used to support our hypothesis that there are differences between neurosurgeons' gaze patterns depending on their years of experience and to compare the results to other medical practices that do not use a microscope. We have shown that expert neurosurgeons developed a range of visual attention strategies to perform a simple, fast, and safe surgery. For the following sections, we organized our discussion around the key results from our gaze analysis studies. Later, in Chapter 6 (conclusion) we explain in more detail the implications of our findings.

5.1 LONG FIXATION DURATION REFLECTS EXPERTISE LEVEL

The main gaze strategy in P(I) and P(II) concerns the long fixation duration that neurosurgeons were able to maintain. Moreover, we showed that the ability to maintain attention at a target for a prolonged periods of time (up to 848ms of fixation duration on average) is a defining characteristics of an expert neurosurgeon. One assumption is that prolonged fixation indicates the intensive processing of visual data [26]. In reading tasks, for example, words that are not common nor known to a reader require longer fixation durations [34]. Moreover, experts encode and retrieve information more rapidly, and thus they should apply shorter fixations than novices (see [9] for a review of the literature).

This was not the same for the skilled neurosurgeons (experts) in our studies who had much longer fixation durations than the novices. Previous works [6, 8, 50, 103] in the medical domain have reported longer (and fewer) fixations for the experts as well. For example, Tien et al. [104] reported a longer fixation duration as well as a lower fixation rate for experts when analyzing eye-hand coordination in a simulated laparoscopic task.

Holmquist et al. [26] discussed that in a complex domain longer fixations are not equal to deeper processing, rather, experts extract more information around the point of fixation which makes eye movements overall more efficient. In a meta-analytic review of the sport literature, Mann et al. [105] interpreted that the longer the eyes remain fixated on a given target, the more information is extracted from the stimuli; thus, experts apply more detailed information processing techniques than novices (our results confirmed this).

The longer fixation duration for experts in micro-neurosurgery can be explained with the information-reduction hypothesis [84, 106]. This theory proposes that experts learn, with practice, to effectively distinguish between task-relevant and redundant information and to limit their processing to relevant information. We believe that professional neurosurgeons are able to chunk several notes together and process them as a single unit of information and over many years of experience they learned the selectivity of visual information processing.

As such, experts in our studies were able to optimize the amount of visual information they focus on by having fixations of longer duration on task-relevant areas. A similar argument has been addressed in other eye tracking studies [106, 107]. Later in Chapter 6. (Implication section) we discuss how this finding can be used in skill acquisition for the selective use of information in microsurgery.

5.2 VISUAL SCANNING OF IMAGES VERSUS MANIPULATING MICRO-INSTRUMENTS UNDER A MICROSCOPE

In this dissertation, eye tracking studies were divided into two categories: (a) viewing tasks of tumor removal images P(I); and (b) cutting and suturing tasks P(IV). This allows for the comparison of gaze measures between image reading tasks and manipulating instruments under a surgical microscope. In terms of the fixation duration, neurosurgeons spent less time fixating on the images (on the monitor) than during the cutting task under a surgical microscope.

For example, in P(I) – the visual scanning of images– the average fixation duration on the tumor resection cavity area was 308ms for experts and 224ms for novices and on the tip of the instruments, it was 327ms for experts and 253ms for novices. However, in P(IV), in the cutting task, experts had fixations lasting 500ms (novice: 382ms) for the right side task and 848ms (novice: 402ms) for the left side. These differences were not notable for the suturing task compare to the reading images task.

Tying these findings back to the prior studies on visual attention as well as eye tracking in surgery [9–11, 26], we see some of these strategies are undoubtedly unique to micro-neurosurgery. For example, in the cutting task, well-trained surgeons (experts) increased their fixation durations on the operating field twice as much as the novices (expert: 848ms, novice: 402). To the authors' knowledge such long fixation durations (848ms) for experts is not common within eye tracking studies in medical domains. This could have been due to either the complexity of the task, which requires a high-level of concentration, or the distance between objects in stimuli that are very small.

It also is well known that saccade measures are adapted to task demands, workload, and the stimuli characteristics. In the literature, shorter saccade durations and amplitudes are sometimes connected to a difficult search task and increases in mental and cognitive loads [26]. In both of our studies, P(I) and P(IV), experts' saccadic measures varied between tasks and stimuli types. This indicates that experts were able to adopt their gaze strategies to the task demands (similar results are reported in [5,7,8]). Moreover, we found that experts usually had more compact and locally defined gaze. Experts do not change the direction of gaze as often as novices do, and thus they exhibit longer fixations with shorter saccade amplitudes (for example, in the image with the 5-ALA indicator or the left side of the suturing task).

Moreover, changes in the saccade measures may show the increase of interactions between the perception and action systems. During eye-hand coordination the visual information system optimizes saccades for target localization and accuracy feedback of sensimotor system. In micro-neurosurgery the small and narrow fields of view elevate the difficulty of information processing. We believed the special direction between eyes and hands and the small size of target –as it has been discussed in [67]– affect eye movements and thus experts apply various saccade patterns to overcome these challenges. For example, changes in saccade amplitude could occur when the target was covered by hands or instruments (which is common when operating under a microscope) [67]. Further analysis of eye-hand tracking is required to understand the coordination of eye-hand movements when an expert maneuvers micro-instruments and attain precision in microsurgery.

5.3 OUTCOMES OF DISTRACTIONS ON GAZE METRICS

In P(II), we reported that microsurgical tasks include distractions, such as swapping instruments or adjusting the microscope settings (up to 18% of surgery time). In our gaze experiment, P(IV), the distractions during surgical procedures have been linked to changes in the surgeons' visual patterns. The effect of distractions on the experts' gaze patterns, however, was more noticeable. For example, experts had up to 40% longer fixation durations for the right side cutting task (a less demanding task without distractions) compared to the right-side suturing task (a more challenging task with distractions such as swapping instruments).

Similar arguments can be seen in driving [108,109]. In a less demanding task (simulated rural road), experienced drivers increased their fixation durations, whereas when driving a car on a dual carriageway (a complex task with visual distractions), they apply shorter lasting fixations. Thus, we also argue that shorter fixation duration is a result of a more complex task with distractions. This may be interpreted as an expert's strategy to sample more information from the stimuli and react quickly in precarious situations.

6 Conclusion

Our aim has been to understand the visual attention strategies in micro-neurosurgery in terms of surgical microscope use. We built a video oculography (VOG) eye tracker to measure the point of gaze and its changes during surgical microscope procedures. The eye tracker presented in this work provides valuable opportunities to record detailed eye movement data in real-time micro-neurosurgery.

We can now start to paint a picture of the varied ways in which eye tracking technologies might help researchers and clinicians to understand how visual skills are gained in the context of a micro-surgical procedure. Our findings in P(I,II) have contributed to further improve our understanding on visual information processing system in image-guided surgery.

We provided evidence that in microsurgery an expert follows information-reduction strategy [84,106] to optimize visual scanning of the operating field while concentrating on tiny objects in the operating field. As such, they learn to maintain attention on task-relevant areas to follow the procedure and avoid redundant information as safely moving the instrument through delicate structures. Following Binsted et al. [67] analysis of eye-hand coordination we also showed rapid changes in saccade pattern, especially for experts when facing challenges in the suturing task. We suggest to use hand and instrument tracking methods for exact mapping between eyes and hands in microsurgery.

The main conclusion from this work is that distractions caused by instruments for neurosurgeons in the operating room (OR) should be optimized when designing new OR technologies. In addition, residents may benefit from gaze training to apply various visual strategies during distractions, particularly during more challenging surgical tasks. We discovered that senior neurosurgeons developed an ability to maintain a long fixation as well as to scan over the surgical field using various strategies over different trials.

6.1 IMPLICATIONS

Eye tracking in medicine is often seen as an objective assessment tool for improving medical trainings. Given the complexity of micro-neurosurgery and longitudinal training, the reason for applying eye tracking methodology as a tool to measure the visual skills is obvious immediately. In modern-day medical interventions, the surgical skill assessment of trainees is central [11]. To date, the analysis of eye tracking data has been proposed as a suitable objective metric for the assessment of one's level of expertise in medical domains [11, 76, 77]. Thus with the help of the surgical microscope eye tracker, it is now possible to apply gaze for the assessment of residents in micro-neurosurgery.

The broad implication, is to apply our findings to the eye-hand training of neurosurgeons, for example, by guiding residents to properly ignore visual distractions and fixate on the main targets. We have seen similar examples in Wilson and Vine's works on gaze training during laparoscopic technical skill acquisition [78–80]. For example, in laparoscopic surgery to shorten the training time Vine et al. [79] asked trainees to focus and follow critical fixation points extracted from experts' eye movements data. In a ball pick-and-drop task the gaze-trained group performed the task with a translucent mask on the field of view, ensuring that only the next relevant target is highlighted (based on the experts gaze strategy): either the next ball to be picked up or the cup in which the grasped ball is dropped. As such the adopting expert gaze strategies led to an improvement in performance for the gaze-training group.

Therefore, we suggest in complex tasks such as suturing in micro-neurosurgery, eye-hand coordination must play an important role in skill acquisition. As such, microsurgical training programs may reinforce the efficient eye movement, for example, by designing a goal directed aiming task for residents and then track eye, hand, and instrument movements to evaluate the trainee's performance to determining whether a specified eye movement pattern was met. Such gaze training tasks would be beneficial for two main reasons.

First, residents may learn where and what to focus on. In P(I) we demonstrated that experts fixate longer on areas with high information value (information-reduction theory [84,106]), so replaying the gaze behavior of experts may help novices detect the importance of these areas. Second, trainees may learn about which pattern to focus on. Analysis of P(IV) indicated that experts had various strategies when operating on the left or right side, so modeling the patterns of visual search may be uased as perceptual cues on how to navigate in such environment.

Another implication of our eye tracker is the potential development of a hands-free surgical microscope. Our eye tracker offers opportunities for gaze contingent control [110–112]. Paper P(II) provided evidence that adjusting the microscope settings manually by hands caused interruption during micro-neurosurgery. Gaze input offers a potential for the development of a hands-free surgical microscope [22]. Such a system would prevent the need for adjusting surgical microscopes manually – by taking one's hands away from the operating field – and therefore, reduce the interruptions and the operation time in micro-neurosurgery.

While our contributions emphasize a sound commitment to understanding neurosurgeons' behavior (PII, PIII), this also limited the time to further engage in larger-scale and more detailed analysis of gaze. As such, our results in the gaze-related papers –P(I) and P(IV)– are relatively task dependent. Our aim, however, has been to take the first step to capture eye movements during microneurosurgical procedures.

Our data samples were small and limited to two Finnish university hospitals. Different hospitals might have a different level of training and expertise. For example, Helsinki hospital is famous for using a microscope throughout the entire surgical procedure [85,113], and neurosurgical lab training is limited in Finland.

The environment and participant characteristics should be taken into account in generalizing our results. Moreover, the surgical tasks designed in this work were a narrow practice comparing to neurosurgery as a whole. We hope these findings can be used more broadly to consider recording eye movements in other neurosurgical practices. This dissertation represents the first step toward improving our understanding of expertise differences in the field of micro-neurosurgery. Our future aim is to expand our data samples by conducting our experiment in various neurosurgical lab and surgical practices. Moreover, we will investigate eye and hand movement data with more advanced scanpath analysis.

The technical limitations of the eye tracking methodology are well known. Image noise from the cameras, pupil and glint detection errors, gaze mapping, and calibration errors are often cause changes in the accuracy and precision of any tracking system. To ensure reliable extraction of the features of interests, namely pupil and glint, it is important that these features can be differentiated from any other noisy features at the eye images.

In our case, participants' eyes were located close to the camera (about 2cm) thus we did not have other noise from environment. As such detecting pupil from the image was very accurate for our design. The challenge for us was related to the light reflected from the hot mirror and a single LED. In P(III) –a single LED– glint tracking was limited to a small range of eye movements. The glint could not be detected reliably in the eye image when the glint either inevitably merged with the sclera region at large angles of eye rotation, or was blocked by eyelashes or eyelids. In p(IV), however, we used two LEDs in which the detection algorithm was significantly improved. We identify calibration procedure as other limitation of our system. This increases the set up time and thus to improve usability of the system we should save the calibration profiles for each surgeon or apply possible free calibration techniques [25].

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SHAHRAM EIVAZI

The key to microsurgery's success heavily depends on the surgeon's visual attention skills and manual dexterity. However, our understanding of surgeons' visual infromation processes in the surgical microscope setting is lacking. This work reports on a first-ever investigation of the eye movement patterns in micro-neurosurgery using a state-of-the-art eye tracker. Our study lends itself to a suggestion for the direction for new eye-hand skill training in microsurgery.

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