Department of Neuroscience and Biomedical Engineering

Usability of emerging technologies

User studies with wearable, multimodal and augmented reality solutions

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Iina Aaltonen

Aalto University

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Usability of emerging technologies

User studies with wearable, multimodal and augmented reality solutions

Iina Aaltonen

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Abstract

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Abstract

Working life is undergoing a gradual change from using computers to devices that enable access to information anywhere and anytime. The devices once seen only in science fiction films are permeating our homes and workplaces. In the work context, however, the introduction of new technologies has not always been a painless process for the users despite usability improvement efforts. Nevertheless, working life is now facing an abundance of emerging technologies whose suitability for work is as yet unknown.

The six user studies of this thesis examine the usability of emerging technologies and their suitability for work in the context of navigation, maintenance, telerobotics, robotic surgery, and e-justice in courts. Additionally, aspects related to their evaluation are considered. The emerging technologies cover wearable, multimodal and augmented reality solutions. Wearable devices are bodyworn computers or interfaces. Augmented reality means that the user is presented with information that enriches what is seen or experienced in the real world. With multimodal systems, the user is presented with feedback through multiple sensory channels or the user interacts using multiple input modes or devices. A requisite for all of these technologies is well-functioning electronic information exchange. The examined technologies were mostly in the early development stages, meaning that the potential of the technologies for the users in the context of work gained more emphasis than usability evaluations in the traditional sense. The qualitative research methods included questionnaires, interviews, observations, focus groups and future workshops.

This thesis offers a collection of practical user aspects that need to be considered when designing, developing and adopting these technologies at workplaces. Most of the evaluated technologies were estimated to be useful for work tasks, although their suitability for work contexts was partially limited. Firstly, the issues of robustness and distractibility were raised especially regarding wearables, although wearables otherwise feel easy and natural to use. Secondly, the redundancy offered by multimodal solutions can benefit users with added certainty, but can also cause confusion in multiple ways. Thirdly, augmented guidance is easy to follow, but its usefulness for experienced workers is unclear. Finally, when technologies bear combinations of these characteristics, issues such as mental load, ergonomics, workflow, collaboration and information presentation need careful consideration. Suitable user evaluation approaches are suggested for these technologies, with a special emphasis on the often under-recognised multimodal interaction. The results will facilitate designing future technologies with the user's best interests in mind, benefiting the users in general, but especially future workers and employers, in addition to researchers developing and evaluating these solutions.

Keywords usability, user study, user evaluation, evaluation methods, emerging technologies, wearable, multimodal, augmented reality, work context

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Tiivistelmä

Työelämässä on meneillään asteittainen muutos perinteisistä tietokoneista laitteisiin, joiden avulla tietoon pääsee käsiksi missä ja milloin vain. Laitteet, joita ennen nähtiin vain tieteiselokuvissa, ovat lipumassa koteihin ja työpaikoille. Työpaikoilla uusien teknologioiden käyttöönotto ei kuitenkaan ole sujunut aina kitkatta, vaikka käytettävyyden parantamiseen on panostettu. Tästä huolimatta työelämään on tarjolla paljon teknologioita, joiden soveltuvuudesta työhön ei ole vielä varmuutta. Tämän väitöskirjan kuusi osatutkimusta tarkastelevat tulevaisuuden teknologioiden käytettävyyttä ja niiden soveltuvuutta työhön navigoinnin, huoltotyön, telerobotiikan, robottikirurgian ja lainkäytön sähköistämisen kontekstissa. Lisäksi käsitellään käyttäjäarviointiin liittyviä näkökohtia. Näihin teknologioihin kuuluvat puettavat, multimodaaliset ja lisätyn todellisuuden sovellukset. Puettavat laitteet ovat vartalon päälle puettavia tietokoneita tai käyttöliittymiä. Lisätty todellisuus tarkoittaa, että käyttäjälle esitetään tietoa, joka rikastaa hänen näkemäänsä tai kokemaansa reaalimaailmaa. Multimodaaliset järjestelmät antavat käyttäjälle palautetta useamman kuin yhden aistikanavan välityksellä, tai käyttäjä toimii järjestelmän kanssa useamman syöttötavan tai -laitteen avulla. Hyvin toimiva sähköinen tietojenvaihto on edellytys näiden teknologioiden käytölle. Tutkitut teknologiat olivat varhaisessa kehitysvaiheessa, minkä vuoksi tutkimuksissa keskityttiin vahvasti niiden tuomiin mahdollisuuksiin työkontekstissa ja perinteistä käytettävyysarviota painotettiin vähemmän. Laadullisiin tutkimusmenetelmiin kuuluivat kyselyt, haastattelut, havainnoinnit, fokusryhmähaastattelut ja tulevaisuustyöpajat.

Tämä väitöskirja tarjoaa kokoelman käytännöllisiä käyttäjänäkökohtia, jotka tulee huomioida, kun näitä teknologioita suunnitellaan, kehitetään ja otetaan käyttöön työpaikoilla. Suurin osa arvioiduista teknologioista arvioitiin hyödyllisiksi työtehtäviin, vaikka niiden soveltuvuus työhön oli osittain rajoittunutta. Puettavien teknologioiden kohdalla nousivat erityisesti esiin laitteiden kestävyys ja häiritsevyys, vaikka niiden käyttöä pidettiin muuten helppona ja luonnollisena. Multimodaalisten järjestelmien tarjoama redundanssi voi tuoda käyttäjille varmuutta, mutta aiheuttaa myös hämmennystä useilla tavoilla. Lisätyn todellisuuden teknologioilla toteutettuja ohjeita oli helppo seurata, mutta niiden hyödyllisyys kokeneille työntekijöille jäi epäselväksi. Lisäksi, jos teknologialla on piirteitä useista edellä mainituista tulevaisuuden teknologioista, tulee tarkastella huolellisesti myös käyttäjän kokemaa henkistä kuormitusta, ergonomiaa, työnkulkua, yhteistyötä ja tiedon esitysmuotoa. Väitöskirjassa esitetään näiden teknologioiden käyttäjäarviointiin soveltuvia tapoja painottaen erityisesti usein huomiotta jäävää multimodaalisuutta. Tulokset auttavat suunnittelemaan tulevaisuuden teknologioita käyttäjän näkökulma edellä hyödyttäen käyttäjiä yleisesti, sekä tulevaisuuden työntekijöitä, työnantajia ja tutkijoita, jotka kehittävät ja arvioivat ratkaisuja.

Avainsanat käytettävyys, käyttäjätutkimus, käyttäjäarviointi, arviointimenetelmä, tulevaisuuden teknologia, puettava, multimodaalinen, lisätty todellisuus, työkonteksti

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Preface

I have always liked science fiction. I recently looked up a sci-fi book that I had read as a child, and realised that the book was awful. The book did have the flying robots—now we would call them drones—that I reminisced about though. I acknowledge I may have become more critical towards the books I read, but I find my work vastly more interesting than that piece. Then again, not everybody gets to do work on so many different emerging technologies as I have.

The research of this thesis has accumulated over the past eight years while I have been working at VTT Technical Research Centre of Finland. I am grateful to VTT and the other project participants for the opportunity to do this research. It has been exciting to work on state-of-the-art technology in so many domains. The research projects were co-funded by VTT, EDA (European Defence Agency), FIMECC Oy (Finnish Metals and Engineering Competence Cluster Ltd) S-STEP programme, EU (FP7-ICT-318329 TellMe and FP7-AAT-285681 VR-Hyperspace), Academy of Finland, RYM Oy PRE (Built Environment Process Reengineering) programme, Tekes (Finnish Funding Agency for Technology and Innovation), and other research institutes, universities, countries and companies that collaborated in the research projects. I am also grateful to the companies who allowed me to use their images and the publishers for the permission to reproduce the articles. Additionally, my gratitude goes to my other financiers: Aalto University, the Finnish Education Fund, the Finnish Foundation for Technology Promotion, and the Jenny and Antti Wihuri Foundation.

I would like to thank my supervisor, Prof. Mikko Sams, for the opportunity to begin my research career back in 2003 at the Laboratory of Computational Engineering at Helsinki University of Technology (TKK), which later became part of Aalto University. I started as a research assistant on multisensory integration and brain-computer interfaces, and although my research perspective has changed since then, I feel like this thesis closes the circle. During my thesis work, my instructor Dr. Jari Laarni has been a mentor in my everyday work. It has been a pleasure working with and especially learning from him. I am grateful for his advice, encouragement, and the collaborative writing. I also want to thank my preliminary examiners, Docent Jukka Häkkinen, and Assoc. Prof. Thomas Olsson, and all my anonymous reviewers for their constructive feedback that has helped me improve my work. I am excited to have Professor Chris Baber as my opponent and I am looking forward to my defence.

My research career has been full of inspiring and supportive colleagues. Firstly, I would like to thank all my co-authors and others who contributed to the research in the case studies. Susanna Aromaa and I have done a lot of collaborative writing and our online chats have been an especially important encouragement for me. Ali Muhammad has helped me by giving me just the right push to achieve my goals and pointing out the relevant bits in our research. I also appreciate that he introduced me to the robotics research community. Mikael Wahlström and Eija Kaasinen have given me the kind of mental support that is hard to put into words; I have always known I could rely on your help. Antti Väätänen and Juhani Heinilä, it was a pleasure freezing with you in Lapland—and I usually hate being cold. Kaj Helin, Jaakko Karjalainen and Timo Kuula, working with you on AR has been fun and efficient. Special thanks for the excellent images. I also want to thank my other co-authors Karo Tammela, Joona Elo, and Ilari Parkkinen, and also those researchers whose input was essential in the research projects: Mika Häkkinen, Petri Honkamaa, and Charles Woodward from VTT and Laura Seppänen from the Finnish Institute of Occupational Health. I am also grateful for all the volunteers who participated in our research as test subjects and experts.

I also want to thank many other former and current colleagues that I have worked with; I cannot think of one instance when you would not have shared your time, knowledge and English skills. First of all, Leena Norros took me under her wing at VTT and initially taught me what human factors research is about. In addition to the colleagues already mentioned, I am also grateful to Paula Savioja, Marja Liinasuo, Hanna Koskinen, Hannu Karvonen, Maiju Aikala, Tiina Kymäläinen, Vladimir Goriachev, Göran Granholm, Juhani Viitaniemi, and Leena Salo. I have also enjoyed the company of our newer team members, and the former and current “noppa members” Janne Valkonen, Antti Pakonen, Nikolaos Papakonstantinou, and Jussi Lahtinen. Thanks to Alain Boyer and Stephen Fox for improving my English. Along this final stretch with my thesis, I have also been working with a number of other colleagues and robots. Although I cannot name all of you, I want to thank especially Marketta Niemelä, Ilari Marstio and Timo Salmi, for bearing with me and my thesis. In the future, you will have to bear with me only.

My research career at VTT has also been influenced by Jari Hämäläinen, Riikka Virkkunen, Raimo Launonen, Johannes Hyrynen, Jari Kiviaho, and Simo-Pekka Leino, and I am grateful for their support. Special thanks to our assistive staff. In addition, I am thankful to my former colleagues and instructors at TKK, especially Veikko Jousmäki, Iiro Jääskeläinen, Laura Koponen, and Harri Valpola, who have steered me during my early years of research.

I warmly thank my friends who keep me nourished in spirit and in physique. Hanna Puharinen, Kaisa Rolig, Katri Koskentalo, Maija Vanhatalo, and Virpi von Alftan, you make my Mondays special—I am looking forward to having Jaakko Kauramäki back as well. In addition, my “fuksifriends”, Emma Tullila and others, in you I found kindred spirits with whom I started my journey into life and science. I have also enjoyed filling my free moments with taido, dance, and numerous other activities, but there is no space to name all of you, my friends. Thank you.

Finally, thanks to my family and relatives for their support, and for patiently waiting for this work to be finished. Katja, special thanks for the precious talks about life, children, work and buying fabrics. Äiti, I wrote my lectio praecursoria thinking of you, hoping you could be there to listen to it. Niko, thanks for feeding me technology alerts, please keep them coming. Mika, thanks for lending me your eye. Isä and Irma, Lea and Raimo, Kati, other in-laws and children, thank you all for being there and supporting our family.

My deepest gratitude in life goes to my husband Lasse and my children Valto and Viena, whom I treasure over everything. Your support in both endorsing and distracting me from my thesis has been invaluable. Lasse, thanks for the tea, and all that comes with it. I love you.

I have been anxious to begin The Real Life after this thesis—beware world, here I come!

Espoo, 20 June 2018
Iina Elisa Aaltonen

Contents

List of Abbreviations

2-D	two-dimensional
3-D	three-dimensional
AR	augmented reality
AV	audio-visual
EIE	electronic information exchange
EMU	Evaluating Multimodal Usability [method]
FOV	field of view
GPS	global positioning system
HARUS	Handheld Augmented Reality Usability Scale
HCI	human-computer interaction
HF/E	human factors and ergonomics
HMD	head-mounted display
ICT	information and communications technology
IT	information technology
IS	information system
ISO	International Organization for Standardization
MAUVE	Multi-criteria Assessment of Usability for Virtual Environments
MMQQ	MultiModal Quality Questionnaire
NASA-TLX	National Aeronautics and Space Administration Task Load Index
PROMISE	Procedure for Multimodal Interactive System Evaluation
QUIS	Questionnaire for User Interface Satisfaction
RQ	research question
SART	Situational Awareness Rating Technique
SSQ	Simulator Sickness Questionnaire

SUS	System Usability Scale
TAM	Technology Acceptance Model
USE	Usefulness, Satisfaction, Ease of Use [questionnaire]
UTAUT	Unified Theory of Acceptance and Use of Technology

List of Publications

This doctoral dissertation consists of a summary and of the following publications, which are referred to in the text by their Roman numerals and their short titles. The publications are reproduced with gracious permission from the publishers.

I Soldier navigation
Aaltonen, Iina; Laarni, Jari. 2017. Field evaluation of a wearable multimodal soldier navigation system. Elsevier Ltd. Applied Ergonomics, volume 63, pages 79–90. ISSN 00036870. DOI 10.1016/j.apergo.2017.04.005.

II Wearable maintenance
Aromaa, Susanna; Aaltonen, Iina, Kaasinen, Eija; Elo, Joona; Parkkinen, Ilari. 2016. Use of Wearable and Augmented Reality Technologies in Industrial Maintenance Work. In: Proceedings of the 20th International Academic Mindtrek Conference, Tampere, Finland, October 17–18. ACM. AcademicMindtrek ’16. Pages 235–242. ISBN 9781450343671. DOI 10.1145/2994310.2994321.

III Tablet-guided maintenance
Aaltonen, Iina; Kuula, Timo; Helin, Kaj; Karjalainen, Jaakko. 2016. Maintenance Past or Through the Tablet? Examining Tablet Use with AR Guidance System. In: Proceedings of European Association for Virtual Reality and Augmented Reality Conference, Athens, Greece, November 22–24. EuroVR Association. Pages 1–6. ISBN 978-618-80348-3-9.

IV Space telerobotics
Aaltonen, Iina; Aromaa, Susanna; Helin, Kaj. Muhammad, Ali. 2018. Multimodality Evaluation Metrics for Human-Robot Interaction Needed: A Case Study in Immersive Telerobotics. In: Chen, J. (ed) Advances in Human Factors in Robots and Unmanned Systems. AHFE 2017, Los Angeles, USA, July 17–21, 2017. Springer International Publishing. Advances in Intelligent Systems and Computing, volume 595. Pages 335–347. ISBN 978-3-319-60384-1. DOI 10.1007/978-3-319-60384-1_32.

V Robotic surgery
Aaltonen, Iina; Wahlström, Mikael. 2018. Envisioning robotic surgery: surgeons' needs and views on interacting with future technologies and interfaces. The International Journal of Medical Robotics and Computer Assisted Surgery, e1941. 12 pages. DOI 10.1002/rcs.1941.

VI E-justice
Aaltonen, Iina; Laarni, Jari; Tammela, Karo. 2015. Envisioning e-Justice for Criminal Justice Chain in Finland. Academic Conferences and Publishing International Limited. The Electronic Journal of e-Government, volume 13, issue 1, pages 55–66, available online at www.ejeg.com. ISSN 1479-439X.

Author's Contribution

Publication I: Field evaluation of a wearable multimodal soldier navigation system

Publication I presents results from a user study involving a wearable multimodal navigation system. The study was done as a collaborative effort of the research team. Aaltonen had a major role in designing the user questionnaires and performing the data and video analyses; Laarni did the statistical tests of the data. Aaltonen wrote the manuscript, which was collaboratively revised by the authors. Aaltonen is the main author of the paper.

Publication II: Use of Wearable and Augmented Reality Technologies in Industrial Maintenance Work

Publication II describes two user studies examining the use of future technologies in maintenance work. The design and the fieldwork of the study was done in collaboration with all authors. Aaltonen had an active role in preparing the interview questions, questionnaires and the observation study design. Aaltonen participated in the data collection of the study on wearable devices. Aromaa and Aaltonen analysed the data. Aromaa wrote the main content of the manuscript, and Aaltonen participated in writing and commenting on all parts of the paper. Aaltonen is the second author of the paper.

Publication III: Maintenance Past or Through the Tablet? Examining Tablet Use with AR Guidance System

Publication III describes a user study examining the practicality of using a tablet computer in a maintenance task. Conducting the laboratory studies was a collective effort of the authors. Aaltonen and Kuula designed the user questionnaires and interviews, while Helin and Karjalainen took care of the technical equipment. Aaltonen was responsible for designing and conducting the video analysis and structuring the paper. All authors participated in commenting on and revising the manuscript. Aaltonen is the main author of the paper.

Publication IV: Multimodality Evaluation Metrics for Human-Robot Interaction Needed: A Case Study in Immersive Telerobotics

Publication IV describes a user experiment where a teleoperated robot-rover system was teleoperated using a wearable, multimodal control system. Aaltonen and Aromaa participated in performing the laboratory user studies that were done as a collective effort of the research team. Aaltonen designed and conducted the video analysis. She was also responsible for the evaluation metrics described in the paper. All authors participated in commenting on and revising the manuscript. Aaltonen is the main author of the paper.

Publication V: Envisioning robotic surgery: surgeons' needs and views on interacting with future technologies and interfaces

Publication V describes a future workshop studying surgeons' views on the future of robotic surgery. Aaltonen and Wahlström did the design of the workshop together, and Aaltonen prepared the workshop materials. The workshop was carried out as a collective effort of the research team. Aaltonen analysed and reported the workshop results, and planned the initial structure and literature review of the paper. The authors collaborated on refining all parts of the paper. Aaltonen is the main author of the paper.

Publication VI: Envisioning e-Justice for Criminal Justice Chain in Finland

Publication VI describes a future workshop using the anticipation dialogue method and discusses how future technologies and electronic data exchange could aid the justice system. Aaltonen and Tammela prepared the preliminary interview questions and collaboratively performed the interviews, which were transcribed mostly by Tammela. Aaltonen and Laarni designed and conducted the future workshop. Aaltonen analysed the data and wrote the main contents of the manuscript. All authors participated in commenting on and revising the manuscript. Aaltonen is the main author of the paper.

1. Introduction

In science fiction films, technologies are depicted using visually impressive characteristics to paint a picture of smooth interaction. In that future, everything is accessible with a wave of the hand. A good example of this interaction is shown in the film *Minority Report*. In the film, there is an episode where the main character, Tom Cruise, is working on solving a potential crime. The working space is darkly lit and there is a wall-sized screen with greenish and bluish hues showing transparent images, videos, text and icons. Tom Cruise is wearing black, snugly fitted gloves, whose fingertips are glowing with small embedded blue lights. He is "orchestrating" the information flow on the screen by gesturing with his hands and arms: selecting and rotating items, zooming in on them, grabbing objects and moving them around, and playing videos. At the same time, he is talking with his coworkers and giving them orders. The interaction is fast-paced and uninterrupted, until he reaches down to shake hands with another person. That results in the display being wiped clean, but with a wave of a hand, the information is brought back up, and the work continues. In the film, working and interacting with technology is fluid, but the key issue is how these technologies should be developed to offer this experience for the real future workers.

Minority Report was released in the year 2002—15 years before the writing of this thesis. Today, the technologies illustrated in the film are getting closer to reality; in fact, science fiction can help in creating future visions (Bell et al., 2013) and in understanding the consequences of future technologies across disciplines (Kymäläinen, 2016). Technologies such as wearable interfaces (Billinghurst and Starner, 1999; Knight et al., 2006), gesture control (Mitra and Acharya, 2007; Liu and Wang, 2016), and virtual and augmented reality technologies (Milgram and Kishino, 1994; Azuma, 1997; van Krevelen and Poelman, 2010) are emerging and being adopted into use. For example, BCC Research has forecast a compound annual growth rate of 67 % for the global market for virtual and augmented reality from 2015 through 2020—revenues in 2015 were 8.1 billion dollars—and although the price and complexity of the technologies hinder their adoption, advancements are being made to make these technologies accessible to a larger audience (Sinha, 2016). Similar forecasts by BCC Research for wearable technologies estimated a compound annual growth rate of 50 % from 2016 through 2021, while the market in 2015 was 19.1 billion dollars (McWilliams, 2016). The listed key challenges for wearable technologies included user interface and usability (McWilliams, 2016).

Many of these emerging technologies are already in use in the gaming industry (e.g., virtual reality headsets, Microsoft Kinect for Xbox), and also in monitoring personal health (e.g., activity bracelets), and companies in other domains are interested in benefiting from the technology development in their businesses. These domains include medicine and health, defence, maintenance, marketing, and knowledge work. With the adoption of these emerging technologies, workers of the future are going to experience changes in the way they do their work. It is interesting and important to consider what kind of changes can be expected and how the technologies can support future work.

This thesis is about humans, technology and work in the future, and the interaction that happens in between. More specifically, this is about practical user research examining emerging technologies in the work context with the aim of ensuring that future workers have useful and easy-to-use tools that are appropriate for the context of work.

The rest of this section first introduces the basic principles and evaluation methods of usability and human-centred design and explains why they are needed. Then follows an outline of the interaction with emerging technologies. The section concludes by describing the research gap and stating the research questions.

Emerging technologies in this thesis
The emerging technologies examined in this thesis work include wearable devices, augmented reality technologies, and interaction solutions using multiple devices and sensory channels. Additionally, the electronic information exchange underlying these technologies is examined. In this thesis, the term *technology* refers to these technologies and interactions solutions unless otherwise stated. To give a reference point in the technology development, most of the case studies of this thesis were done around the year 2015.

1.1 Usability and human-centred design

In order to ensure that users can have a positive experience interacting with technology, it is essential to focus on the users and their needs throughout the development of the technology. Human-centred design is an approach that aims at developing systems so that they are easy to use and useful from the users' perspective (International Organization for Standardization, ISO, 2010). In addition to the user benefits, systems developed using this approach can increase productivity and reduce costs related to training and support because the users' time is not wasted struggling with burdensome systems. There are many (partially overlapping) terms that describe user interaction aspects and methods related to their design and evaluation. This section clarifies the terminology and human-centred methods used in this thesis.

1.1.1 Terminology

The key terms related to human-centric design in this thesis are described below.

- *User* denotes a person who interacts with a product (ISO, 2010).
- *Usability* is defined as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (ISO, 2010).
- *User experience* is defined as the “person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service” (ISO, 2010). The term *user experience* is broader than *usability* as it includes aspects such as emotions, preferences, and physical and psychophysical responses. Many aspects of user experience can be evaluated using usability criteria, but the user experience literature emphasises the positive, experiential and emotional aspects that go beyond the functional (Hassenzahl and Tractinsky, 2006).

- *User acceptance* refers to the willingness of users to take technology into use. Technology acceptance models developed for information systems suggest that the user acceptance and usage behaviour are influenced by several factors, such as perceived usefulness and perceived ease of use (Davis, 1989), or performance expectancy, effort expectancy, social influence, and facilitating conditions (Venkatesh et al., 2003).
- *Work* can be defined as the "professional responsibilities and activities" of workers, who participate and act in a socio-technical system which contains various layers: technical systems, workers, organization and environment (Vicente, 1999). The activity can be viewed to comprise of different components such as tools, rules, community, division of labour, and the object at which the activity is directed, resulting in an outcome (Engeström, 1990).
- *Human factors* (HF) *and ergonomics* (or HF/E) is defined as the "scientific discipline concerned with the understanding of interactions among human and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance" (ISO, 2010).

  The terms "*human factors*" and "*ergonomics*" are often used interchangeably, or in conjunction with each other (e.g., HF&E, HF/E). The International Ergonomics Association distinguishes three specialised domains for ergonomics: physical, cognitive, and organisational ergonomics (International Ergonomics Association, 2017). Physical ergonomics is what is typically understood by the term *ergonomics* in colloquial speech (at least in the Finnish language), and it concerns the human anatomical and other characteristics related to physical activity, such as working postures. Cognitive ergonomics covers humans' mental processes and includes aspects such as memory, mental workload, and training. Organizational ergonomics considers the optimisation of sociotechnical systems, and includes, for example, work design, teamwork and communication. Additionally, a special area of ergonomics research relevant to visual displays is visual ergonomics, which studies human visual processes and interactions including visual environment, visual function, comfort and safety (International Ergonomics Association, 2017).
- *Human-computer interaction* (HCI) studies human interaction with computers (Sharp et al., 2007), and is therefore a narrower term than human factors, but is a relevant topic especially in cognitive ergonomics (International Ergonomics Association, 2017).

In this thesis, the focus of user research is on the practical aspects related to users or workers interacting with technologies. In contrast to achieving positive emotional outcomes (e.g., joy, fun and pride) brought up in recent user experience literature (Hassenzahl and Tractinsky, 2006), the ability to accomplish a task with ease is essential in work contexts. Therefore, the term *usability* is chosen over *user experience* to emphasize the functional aspects of interaction. Additionally, although the term *usability* is often interpreted as referring only to the system's ease-of-use, the standard states that also the users' personal goals and job satisfaction can be included under the same concept (ISO, 2010). The research disciplines labelled under the terms *human factors*, *ergonomics*, and *human-computer interaction* have all contributed to this research.

Usability in this thesis

In this thesis, the term *usability* is used to examine the user's interaction with technology with a focus on the technology's ease-of-use, usefulness and suitability for the work context. The term *user* denotes a person who uses and interacts with technology. As this thesis considers the work context, the users are typically workers using technology as tools to support their work.

1.1.2 Phases of human-centred development

In human-centred design, the users are involved throughout the design and development. The process is iterative in nature, meaning that the system under development is progressively evaluated and refined (ISO, 2010). Figure 1 shows how the design begins with acquiring an understanding of the user and the use context, after which the design solutions are produced and evaluated. The iterative cycle is repeated as long as an appropriate solution is achieved.

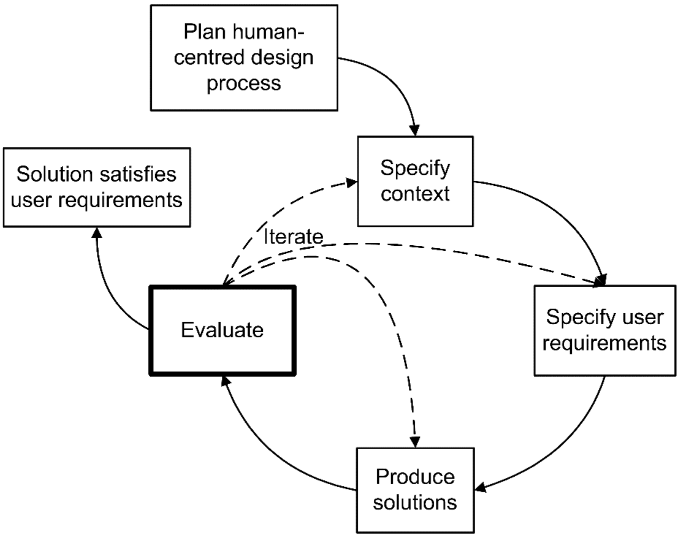


Figure 1. Phases of human-centred design activities showing the iterative nature of design and development (ISO, 2010). The evaluation box is highlighted to show the focus of this thesis.

Phases of human-centric research activities in this thesis

This thesis focuses on user evaluations of solutions produced during the first iteration rounds. The solutions used in the case studies were mostly demonstrators or concept level ideas, although some commercial products were also used as parts of a larger system. In the research, a strong emphasis was laid on understanding the user and the use context, which formed the basis against which the solutions were evaluated.

1.1.3 Data collection and evaluation methods

Human-centred evaluation typically involves using a combination of data collection methods (Sharp et al., 2007). For example, questionnaires systematically measuring the user's subjective opinion can be complemented with interviews and performance measures. In the technology development context, data can be collected both before and after the introduction of new technology. In the former case, the data describes the users and their needs, and in the latter case, the data reflects the technologies' usability and actual use. The data collection methods can be applied in laboratory conditions and in the field, i.e., in the real context of intended use (Sharp et al., 2007).

Many of the methods provide both quantitative and qualitative data. Quantitative data is data that is easily translatable to numerical format. Examples of quantitative data include participants' demographic data (e.g., age), and performance measures, such as time to complete a task and the number and type of errors done (Sharp et al., 2007). Qualitative data is difficult to express in a numerical format, because it is more descriptive in nature. For example, qualitative data can describe how an activity was performed and what kind of interaction took place in the process.

The most typically used data collection methods in human-centred evaluation are described below.

- Interview

Interviews are used to gather information regarding a particular subject. Depending on how comprehensively the questions are predetermined, the interviews can be structured, semi-structured or unstructured (Stanton et al., 2013). The interviews are typically audio-recorded and the data is transcribed for further analysis (e.g., qualitative thematic analysis, Braun and Clarke, 2008). The interview data is mostly qualitative and subjective.

- Focus group

A focus group is a form of group interview. A group of 3–10 people are invited to participate, and a trained facilitator leads the discussion on a particular topic (Sharp et al., 2007). The data is mostly qualitative and subjective.

- Questionnaire

Questionnaires offer a systematic means to collect the participants' subjective opinion and demographic data. The response format can use check boxes and ranges (e.g., tick a box for a certain age range), rating scales such as the Likert scale (e.g., a 5-point scale, strongly agree–agree–neutral–disagree–strongly disagree with/on given statements) and semantic differential scales (i.e., word pairs such as a slider scale to choose between two words such as helpful–unhelpful; Sharp et al., 2007). The questionnaires can also include open-ended questions (Stanton et al., 2013). The data can be both quantitative and qualitative, and it is mostly subjective.

Several questionnaires and models for measuring usability and related issues are available, including the System Usability Scale (SUS; Brooke, 1996), the Questionnaire for User Interface Satisfaction (QUIS; Chin et al., 1988), the Technology Acceptance Model (TAM; Davis, 1989), the Unified Theory of Acceptance and Use of Technology (UTAUT; Venkatesh et al., 2003), AttrakDiff (Hassenzahl et al., 2003, 2015), and systems usability framework (Savioja and Norros, 2013; Savioja et al., 2014). Additionally, situational awareness (Situational

Awareness Rating Technique (SART; Taylor, 1990)) and workload (NASA Task Load Index (NASA-TLX); Hart and Staveland, 1988) are often measured.

- Observation and ethnography

Participant observation is a method with which the participants' activities are observed during a task or a scenario (Sharp et al., 2007). The activities can take place in a controlled environment or in the field. Data can be collected using real-time observation (e.g., with the help of observation forms) or video analysis. The participants can also be prompted to think aloud during the interaction (think-aloud technique). Additionally, indirect observation allows data collection using system logs, such as numbers of button presses, or by asking the users to keep diaries of their activities (Sharp et al., 2007). Both quantitative and qualitative data can be collected.

Participant observation is a constituent part of ethnography. Ethnographic studies gather information about human activities in the settings in which they naturally occur, and also consider the larger context of the activity (Blomberg and Karasti, 2013). Understanding the users, tasks and environments is the basis for human-centred design (ISO, 2010), and therefore ethnography is especially applicable in field studies.

The evaluation can also be done by experts as in heuristic evaluation (Nielsen, 1994, 1995). Additionally, some methods can support both the evaluation and the design aspects. For example, focus groups and future workshops can serve this function by engaging the users in collaborative discussion. Future workshops are introduced below because the method is used in two of the case studies of this thesis.

- Future workshop

Future workshops are collaborative research methods for envisioning and co-designing the interactions between current and future technology and the activity in small groups. In the workshop, participants are encouraged to envision future solutions or possibilities, for instance, related to a given problem or as part of technology design. Examples include Future Workshop (Jungk and Müllert, 1987), Future Technology Workshop (Vavoula and Sharples, 2007) and Anticipation Dialogue Method (Laarni and Aaltonen, 2013). The methods have been successfully applied in the development of scenarios for the future to support the design of information and communication technologies (ICT) tools for complex work systems, and in workplace development and product design.

Methods used in this thesis
In each of the user studies described in this thesis, several user research methods were used. Data was collected using questionnaires, interviews, observations, and methods involving groups of people such as focus groups and future workshops. The collected data was mostly qualitative.

1.2 Interaction with future technologies

This section describes the four aspects of technologies that were selected to be studied in this thesis and explains relevant issues concerning user interaction. The studied aspects are electronic information exchange, and wearable, multimodal, and augmented reality solutions. This selection was made to provide a framework under which it is easier to approach the various technologies introduced in the case studies.

1.2.1 Electronic information exchange

Workers face a diversified flow of information in their everyday work (Figure 2). The information flow entails the communication between people, the objects of work and the work environment, tools, documents and databases. In modern work, this information is increasingly exchanged electronically.

Electronic information exchange refers to the information that is stored, retrieved or transferred electronically so that the information is widely and effectively available (Johnson, 1994). The electronic information can be "passive", that is, electronic books, manuals or data sheets that are retrieved when needed. It can also be constantly updated, for example, through the inventory of a shop or the acquisition of the most recent readings of an automation process, which can happen automatically or with the input of a worker. The information can also be communicated between individuals, for example, through e-mails and text messages.

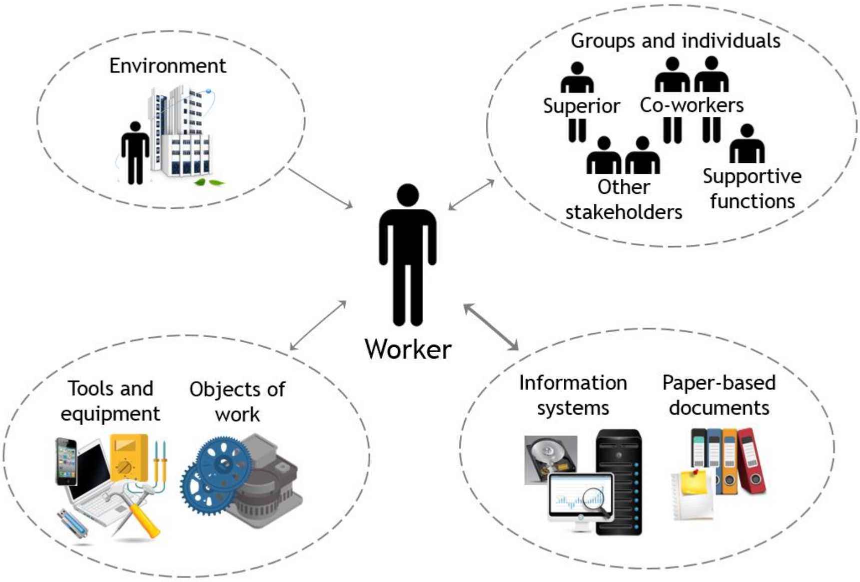


Figure 2. A generic view of information flow (arrows) to and from worker, adapted and modified after (Aromaa et al., 2015). The human agents include groups and individuals with various roles. The environment and other non-human agents are also shown to visualize the information that flows between the worker and information systems, tools, and the objects of work. The arrow connecting the worker to the information systems is emphasized to denote the importance of electronic information exchange.

User interaction related to electronic information exchange depends primarily on the physical devices or interfaces used to access or create it and their usability. On the other hand, information quality, reliability and up-to-dateness, network connection, data security, and knowledge management are issues closely affecting the worker.

Electronic information exchange in this thesis

Electronic information exchange is a requisite in modern work. In this thesis, electronic information exchange plays a crucial role as it forms the basis on which other technologies can operate. Electronic information exchange refers to the information that is stored, retrieved or transferred electronically.

1.2.2 Multimodal systems

In multimodal interaction, the user interacts with a system using several modalities (Figure 3). The modalities can refer to sensory modalities (e.g., sense of touch, hearing, Möller et al., 2009) or input modes (e.g., speech, gesture, Dumas et al., 2009). A bimodal system uses two modalities and a trimodal system uses three modalities. According to Wickens' Multiple Resource Theory (Wickens, 2008), humans can process information in parallel if different sensory resources are required. Therefore, based on humans processing modalities partially independently, human performance can be improved by multimodal interaction (Dumas et al., 2009). For instance, multimodal cues can shorten response times in complex environments (Ferris and Sarter, 2008) and be more effective at capturing persons' attention while they are under perceptual load or performing dual tasks (Spence and Santangelo, 2009). In the same vein, tactile and auditory cues can facilitate visual target search (Hancock et al., 2013).

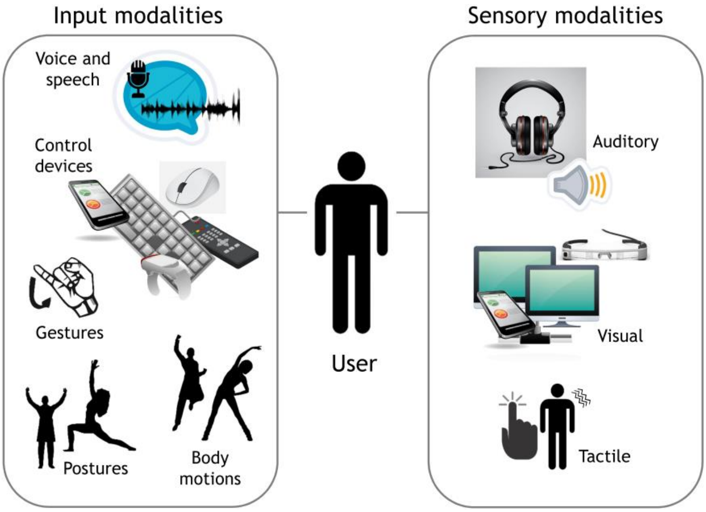


Figure 3. Multimodal interaction. The user can receive stimuli through multiple senses: visual, auditory and tactile. The user can also use combinations of different input modalities for control: speech and various devices and body motions.

In addition, multimodal displays and controls have been suggested to mitigate operator workload, decrease task difficulty and promote a sense of immersion (Chen et al., 2007). The usability evaluation of multimodal interaction is not straightforward. Wechsung (2014) argued that usability questionnaires designed for unimodal systems are inapplicable for the usability evaluation of multimodal systems, and developed a taxonomy for describing multimodal quality aspects of interaction and a MultiModal Quality Questionnaire (MMQQ). Kühnel et al. (2010), however, found the usability questionnaires AttrakDiff, System Usability Scale (SUS), and "Usefulness, Satisfaction, and Ease of Use" (USE Questionnaire) suitable, but stated that the selection of questionnaire depends on the purpose of evaluation. Other suggested methods for evaluating multimodal systems include PROMISE (Procedure for Multimodal Interactive System Evaluation) developed for multimodal dialogue systems (Beringer et al., 2002) and SUXES for spoken and multimodal interaction (Turunen et al., 2009).

On a more general level, multimodal interaction can be described using categories along two axes: use of modalities (parallel or sequential) and data fusion of different modalities (combined or independent; Nigay and Coutaz, 1993). The EMU (Evaluating Multimodal Usability) method takes the description of the interaction a step further and also covers the environmental interactions occurring in the situation (Blandford et al., 2008). The EMU analysis can identify the quality of interaction, the integration of the modalities, and interactions breakdowns due to clashes between modalities (e.g., difficulties in interpreting or performing simultaneous actions using different modalities), synchronisation issues and distractions. In addition, Kong et al. (2011) have proposed a framework for quantifying user preferences for input and output modalities, especially for autonomously adaptive modalities (i.e., adapting a multimodal interface to different interaction contexts).

Multimodal interaction in this thesis
The multimodal systems evaluated in this thesis use either multiple sensory modalities (visual, auditory and tactile feedback) and/or multiple input modes (multiple devices, gestures using different body parts, button presses etc.).

1.2.3 Augmented reality

Augmented reality (AR) means that virtual (i.e., computer-generated) three-dimensional (3D) objects are superimposed upon the real world (Milgram and Kishino, 1994; Azuma, 1997; van Krevelen and Poelman, 2010). Real-life objects can be either tracked based on their natural features or by using visual markers attached to the objects, enabling the registration and display of the virtual objects on the correct position upon the real world (Nee et al., 2012; see Figure 4c). Therefore, augmented objects stay upon the real objects even if the visual angle changes, unlike visual information that is simply overlaid on the visual feed without registration (Figure 4e).

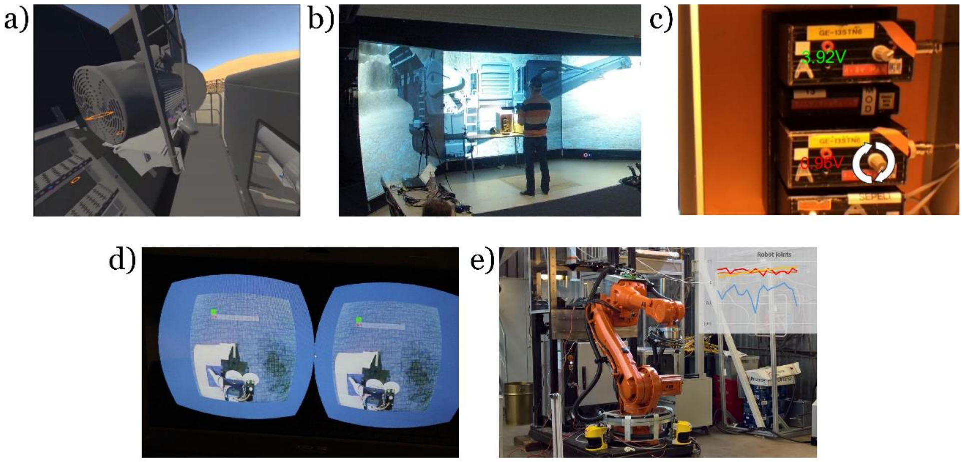


Figure 4. Examples of different forms of virtuality. a) Virtual reality, b) Mixed reality, c) Augmented reality (the red and green numbers and the white arrow are augmented onto the control modules), d) Telepresence (a view of remote video displayed on a virtual reality-set head-mounted display), e) Information overlay (displayed, e.g., via smartglasses).

AR can be positioned on the virtuality continuum (Figure 5) as part of mixed reality (Figure 4b), in between the real and virtual environments. Virtual environment (Figure 4a) consists of an entirely computer-generated world, whereas augmented reality (Figure 4c) considers the augmentation of the real world, and augmented virtuality the merging of real objects into the virtual environment (Milgram and Kishino, 1994).

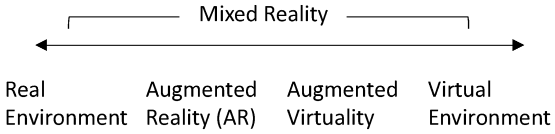


Figure 5. Virtuality continuum showing the position of AR with respect to real and virtual environments, adapted from (Milgram and Kishino, 1994).

Furthermore, AR can be distinguished from telepresence (Figures 6 and 4d), where the user interacts with the real world while being physically remote (Benford et al., 1998). Videoconferencing is a common example of telepresence. Similar concepts to telepresence are (spatial) presence and immersion. Immersion refers to the psychological state of perceiving oneself being present in or enveloped by an environment and interacting with it (Witmer and Singer, 1998), often used in the context of virtual environments (Benford et al., 1998; see the transportation axis in Figure 6). Presence refers to the subjective experience of being in one place while being physically in another (Witmer and Singer, 1998). A discussion on the distinction between different types of presence can be found in (Lombard and Jones, 2015). Further, if the user is able to physically interact with the remote environment, they are typically teleoperating a device through which the interaction is actualised. If the teleoperated device is a robot, the respective area of research is called telerobotics.

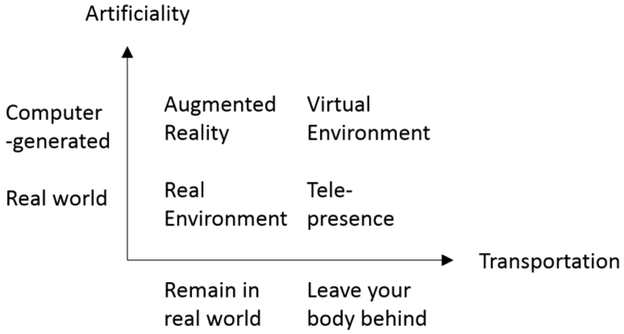


Figure 6. AR positioned on the artificiality and transportation axes, adapted and simplified from (Benford et al., 1998).

AR applications are used in many domains, for example, in maintenance, assembly, surgery, military training, and entertainment (Ong et al., 2008). Most often, the applications are focussed on the visual sense, but the augmentation can also apply to other senses such as sounds, or even multimodal displays (Azuma, 1997; van Krevelen and Poelman, 2010). The devices used to display augmented images include head-mounted displays, handheld devices (e.g., tablets and mobile phones), and projectors (Zhou et al., 2008; Nee et al., 2012).

User studies with AR systems have considered human perception, task performance, collaboration between multiple users, and usability (Dünser, A., Grasset, R., & Billinghurst, 2008). The subjective experience has been typically studied by measuring user preferences, ease of use, perceived performance and intuitiveness (Bai and Blackwell, 2012). The evaluation methods have included questionnaires and/or performance measures (Bai and Blackwell, 2012), and also direct observations, video analysis and interviews (Dünser and Billinghurst, 2011). Additionally, scenario-based methods have been suggested (Olsson et al., 2012).

Regarding user interaction, Dünser et al. (2007) collected a list of HCI design principles that could be applied to AR settings. The list included examples of affordance (the inferred connection between an interface and its functional and physical properties), reduction of cognitive load, physical effort, learnability, user satisfaction, flexibility in use, responsiveness and feedback, and error tolerance. Ko et al. (2013) extended these principles for AR applications running on smartphones based on other usability guidelines available for graphical user interfaces. Examples of these principles are hierarchy (large quantities of information should be displayed in phases), multimodality (notification of information should be displayed using more than one modality), navigation (users should be allowed to navigate the application freely), and context (applications should support various kinds of usage environments).

Perceptual and ergonomics issues related to the usability of AR were collected by Santos et al. (2015). The perceptual issues included unstable tracking and poor registration (alignment on objects), long latency, excessive or poor-quality content, high cognitive load, illegibility due to ambient light, and an underestimated or overestimated depth. The ergonomics issues included fatigue, bulky or heavy devices, difficulty with hand interactions, non-responsive application or poor feedback, and too small a keypad. The authors introduced two concepts: comprehensibility, i.e., ease of understanding the information presented, and manipulability, i.e., the ease of handling the device while performing a task. Additionally, a handheld augmented reality usability scale (HARUS) questionnaire that uses 16 statements to measure these concepts was introduced (Santos et al., 2015).

Issues related to the input techniques for handheld devices have also been studied. Typical user tasks for handheld AR systems were object selection and manipulation, viewpoint manipulation, manoeuvring, system control, and numerical or text input (Veas and Kruijff, 2008). Characteristics of the interaction requirements related to these tasks listed accuracy, speed, frequency, duration, input (discreet or continuous), handedness, degrees of freedom, type of graphics and the used control devices; additionally, ergonomics, pose and grip on the devices, weight balance affected by the user's pose, and movements required to use the controller were considered (Veas and Kruijff, 2008). Handheld devices often need support to hold them steady (Henrysson et al., 2007; Veas and Kruijff, 2008). Further, AR systems that are handheld but placed over the eyes need to be lightweight, comfortable, aesthetic, and easy to manipulate to avoid fatigue, and they should be designed so that they are naturally positioned on the face and the handle is easy to grip and hold (Grasset et al., 2007).

For virtual reality applications, specific methods for user evaluation have been suggested, including heuristics (Sutcliffe and Gault, 2004) and usability questionnaires. An example of these questionnaires is the Multi-criteria Assessment of Usability for Virtual Environments (MAUVE) that measures interaction, multimodal system output, engagement and side effects (Stanney et al., 2003). On top of traditional aspects of usability, the user studies consider the feeling of presence and immersion, comfort, simulator sickness (see especially Kennedy et al., 1993), and situational awareness (Gabbard and Hix, 1997; Kalawsky et al., 1999; Stanney et al., 2003; Sutcliffe and Gault, 2004).

Augmented reality in this thesis

In this thesis, the term AR is used in a broad sense to cover a multitude of situations where the user is presented with augmented information. The information can be either in the form of "true" AR overlay (virtual images registered and displayed over local, physical objects, e.g., a visualised arrow pointing to a specific object), or any overlaid information shown in a real-world environment using see-through displays or remote video feeds. Additionally, telepresence systems are considered in this context as well because it also mixes the physically present and the computer-relayed world.

1.2.4 Wearable devices

Wearable devices are pieces of body-worn technology such as smart watches and head-mounted displays (Figures 7 and 8). Knight et al. (2006) proposed criteria for distinguishing wearable technology from portable technology: a wearable device remains attached to the body without the user having to hold it and regardless of the body's orientation or activity; and the user can interact with the device without having to detach it from the body. An earlier effort took a slightly different perspective to wearable computers by emphasising their situatedness in the environment; Billinghurst and Starner (1999) suggested that wearable computers should satisfy three goals: mobility; augmentation or enhancement of the real environment; provision of context sensitivity, meaning that the worn computer is aware of the user's surroundings and state. Wearable computers have applications in many fields, for instance in the military, healthcare, maintenance and manufacturing (Barfield and Caudell, 2001; Lukowicz et al., 2007). Benefits of wearables in the working context include an increase in productivity by simplifying access to enterprise information; documentation of work processes; and increased quality and safety (Pasher et al., 2010).

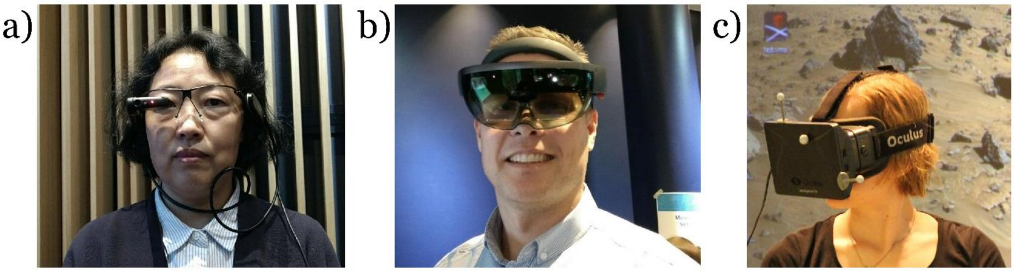


Figure 7. Head-mounted displays. a) Smartglasses with a display over the right eye (Vuzix M300). b) A head-mounted display with a visor onto which the image is projected (Microsoft Hololens). c) Virtual reality headset (Oculus Rift DK1).

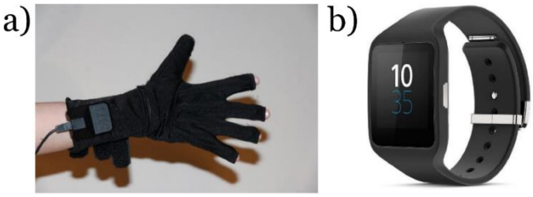


Figure 8. Hand/arm-worn devices. a) Data glove (5DT-5 Ultra). b) Smartwatch (Sony SmartWatch 3 SWR50, source: https://www.sonymobile.com/global-en/products/smart-products/smartwatch-3-swr50/#black, downloaded 22 Nov 2017, with permission).

The users' perceptions of body-worn products include several qualities such as pleasing aesthetics, novelty, wearability, interactivity, usefulness, technological appeal, usability and expressiveness (Kuru and Erbuğ, 2013). Wearability affects the usability of wearable systems (Knight et al., 2006; Kuru and Erbuğ, 2013), and therefore it has been suggested that wearability evaluations should cover usability, satisfaction and safety (Knight et al., 2006).

Wearability can be defined as "the interaction between the human body and the wearable object" (Gemperle et al., 1998). The wearability guidelines consider the placement, form language (fitted shape), human movement, proxemics, sizing, attachment, containment (fitting technology within), weight, accessibility, sensory interaction (for user input), thermal, aesthetic and long-term use of the wearable devices (Gemperle et al., 1998). The physiological (e.g., heart rate, exertion), biomechanical (e.g., musculoskeletal loading and body posture) and comfort effects are also factors to be assessed in ensuring wearability (Knight et al., 2006). The suggested comfort assessment includes six aspects: emotion, attachment, harm, perceived change, movement, and anxiety (Knight and Baber, 2005).

Wearability in this thesis
In this thesis, wearable devices mean body-worn computer interfaces through which the user can control the system and/or receive feedback. The devices worn in the case studies include smartglasses and other head-mounted displays, a smartwatch, a data glove and a tactile vest. The devices can be used on their own or as a combination, forming a multimodal system.

1.3 Motivation for research and research gap

Mechanisation of work, automation, and computerisation have changed the nature of work starting from the end of the 19th century (Vicente, 1999). These changes have been accompanied by evolving technology, bringing with them changes in the worker's role from manual labourer to intellectual worker, and developing a greater demand for communication, collaboration, and problem solving. These changes also brought forward the need to develop new ways to analyse human work (e.g., cognitive work analysis); by ensuring that the technology suits the work demands, full advantage of the potential of information technology could be gained (Vicente, 1999; Figure 9a and b).

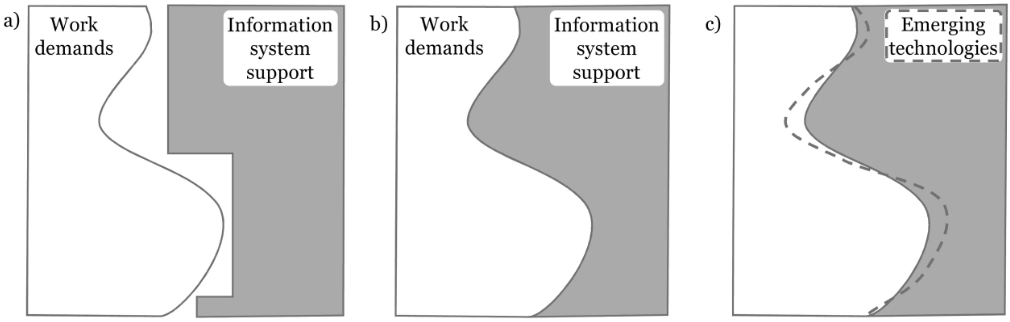


Figure 9. Relationship between work demands and system support. a) An information system that supports the work poorly: there is a gap between the work demands and the support offered by the system (adapted from (Vicente, 1999)). b) An information system tailored to suit the work demands (adapted from Vicente, 1999). c) With the introduction of emerging technologies, the relationship can change (dashed line). The technologies may change the work and provide new kinds of support, but the suitability of the technologies for the work context will determine if a new gap is created.

The emerging technologies that are under focus in this thesis (i.e., wearable, multimodal, and augmented reality solutions) are still under development, and their impact on working life and the users or workers themselves is under discussion.

Wearable technologies have been suggested to affect the work outside the office as much as computers originally changed office work (Lukowicz et al., 2007). The wearables also have the ability to improve organisations' ways of working because they enable bringing information to where it is needed and thus save time and introduce flexibility (Pasher et al., 2010). On the other hand, new skills and knowledge may be needed to bridge the difference between old and new ways of working (Pasher et al., 2010). Additionally, the way information is presented to the users using wearables needs further work (Lukowicz et al., 2007).

The importance of user experience in the context of augmented reality systems has been raised (Dünser and Billinghurst, 2011; Olsson et al., 2012). There is an acknowledged need for AR systems to be convenient for the users (Ong et al., 2008; Nee et al., 2012). In the same vein, a strong user-centred design approach has been recommended along with evaluations featuring actual users (Dünser and Billinghurst, 2011). Additionally, a better understanding of the applications for which AR is a useful interface methodology has been called for (Livingston, 2005). However, for example, in the assembly industry, only a small percentage of studies have included usability evaluations (Wang et al., 2016). Traditional user evaluation methods are likely to neglect some aspects of AR technologies, and therefore there is a clear need for developing user evaluation methods that are specifically targeted at AR systems (Livingston, 2005; Dünser and Billinghurst, 2011; Santos et al., 2015; Wang et al., 2016).

The field of research on multimodal interaction is still young (Dumas et al., 2009). Although the psychological aspects of multimodal processing have awoken interest for quite some time, it is not well recognised that multimodal interaction takes place exceedingly with wearable devices and, especially due to head-mounted displays (HMDs), also with AR systems. Besides system designers not recognising the multimodal nature of interaction, it seems that traditional usability evaluation methods do not cover these multimodality characteristics (Stanney et al., 2003; Wechsung, 2014). Furthermore, there is a need for more research on the transition between interaction modes and the interface elements on different devices (Grubert et al., 2015).

With the introduction of these emerging technologies that go beyond the traditional computer-based systems (Figure 9c), it is likely that there are effects similar to those that arose with computerisation. The work itself may change, and new needs for analysing these new technologies and their suitability for work arise with the changes (Figure 9c). Additionally, what the new offering for work provided by these technologies is not yet clear because a lot of the development is still technical in nature. At the moment, we do not know how the work changes with these technologies—what are the possibilities and limitations—and how the workers experience the technologies in their work context. This thesis tackles the issues related to future interaction with emerging technologies by means of user evaluations in both laboratory and field conditions, and future workshops.

Research gap
Existing research on the emerging technologies is still mostly technical in nature, and there is a lack of user evaluations in the working context. Because the technologies are still novel, workers, employers, and even system designers have yet to recognise the characteristics that are special to these technologies. There is a need to ensure the usability, suitability and usefulness of these technologies for work, and to understand the technologies' potential and limitations in the work context. The usability evaluation methods of the emerging technologies are not well-established, but there is a consensus that traditional usability methods for computer-based systems are unable to capture these characteristics and new methods are needed.

1.4 Objectives and scope

This thesis examines the practical issues of introducing emerging technologies into the context of work. These issues are approached from three angles in the research questions (RQs). Firstly, this thesis examines the user's experience and the usability of the technologies (RQ1). Secondly, the technologies' suitability to and the inflicted change on work are considered (RQ2). Thirdly, taking a research and design perspective, the evaluation of the emerging technologies is considered (RQ3). The research questions are inevitably overlapping but each of them provides a different perspective. The objective of this work is to ensure that the future workers have useful and easy-to-use tools that are appropriate for the working context.

Research questions

RQ1 considers the user's perspective of the practical issues of using emerging technologies with characteristics of electronic information exchange and wearable, multimodal, and augmented reality solutions:

RQ1a: What benefits did the users experience or expect from emerging technologies?

RQ1b: What concerns or problems did the users experience or expect from emerging technologies?

RQ2 considers the context of work:

RQ2a: Would the emerging technologies be useful and suitable for the context of work?

RQ2b: With the adoption of these technologies, how would everyday work change?

RQ3 considers the evaluation aspects:

RQ3: What aspects should be considered in the evaluation of emerging technologies?

The six case studies included in this thesis examine the use of emerging technologies in the context of navigation (Study I), maintenance (Studies II & III), telerobotics (Study IV), robotic surgery (Study V), and e-justice in courts (Study VI). The studies' relation to the technological aspects considered in this thesis are illustrated in Figure 10. The case studies' contributions to the research questions are shown in Table 1.

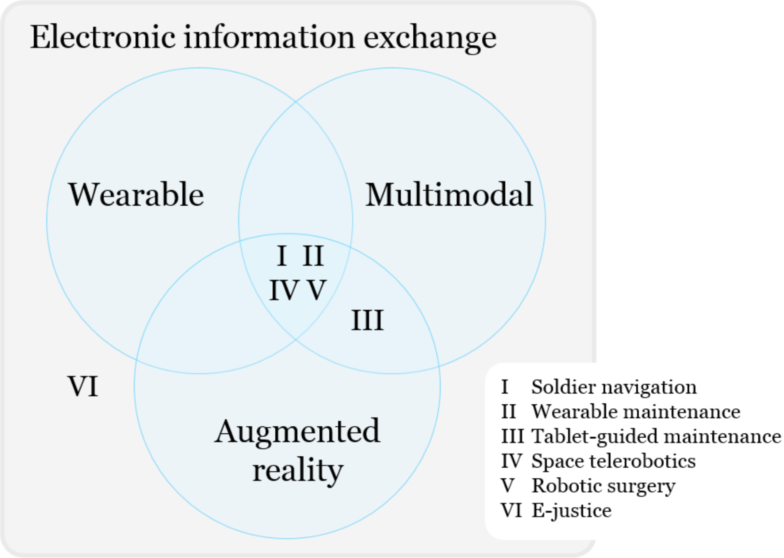


Figure 10. Case studies and their relation to the technology aspects considered in this thesis: electronic information exchange and wearable, multimodal, and augmented reality solutions.

Table 1. The contribution of each case study to the research questions. The studies marked with the tick mark in parentheses (✓) indirectly influenced the third research question.

RQ	Study I Soldier navigation	Study II Wearable maintenance	Study III Tablet-guided maintenance	Study IV Space telero-botics	Study V Robotic surgery	Study VI E-justice
RQ1a	✓	✓	✓	✓	✓	✓
RQ1b	✓	✓	✓	✓	✓	✓
RQ2a	✓	✓	✓		✓	✓
RQ2b	✓	✓			✓	✓
RQ3	✓	(✓)	✓	✓	(✓)	(✓)

1.4.1 Research process

Each case study was a part of a different research project. In the research projects, the user evaluations followed a similar process. The users or workers were first introduced with new technologies. They were either able to practise and use the technologies in the context of work tasks, or the technologies were presented to them in a future workshop. In the former case, the technologies were evaluated both during use and after using them. In each study, the participants gave their written informed consent before participating.

Each of the studies used a combination of data collection methods. Using a combination of methods (also termed data triangulation, Sharp et al., 2007) enables access to different perspectives and provides stronger support for findings. The methods were mostly qualitative and measured the participants' subjective opinion, because the tested systems were mostly in the early stages of development (demonstrators, prototypes, or concept-level ideas). Qualitative content analysis (Patton, 2002) was used to analyse the data and identify emerging core themes. Table 2 summarises the methods used in each of the studies. They are described in more detail with each case study.

Table 2. Methods used in the case studies.

Methods	Study I Soldier navigation	Study II Wearable maintenance	Study III Tablet-guided maintenance	Study IV Space telerobotics	Study V Robotic surgery	Study VI E-justice
Interview	✓	✓	✓	✓	✓	✓
Questionnaire	✓	✓	✓	✓	✓	
Focus group	✓					
Future workshop					✓	✓

In the studies done in real work contexts (Studies I, II, V & VI), ethnographic methods and interviews enabled the researchers to familiarise themselves with the working context prior to engaging the users in the evaluations and workshops. This facilitated the evaluation, and in some of the case studies, contributed to the technology's development. Understanding the use context and building on the existing knowledge and experience of developing technologies that are suit the context is an essential part of human-centred design—and important for the success of the technologies (ISO, 2010; Pasher et al., 2010).

1.4.2 Dissertation structure

The rest of the dissertation is organised as follows: Section 2 describes the research domains and reviews related work. Section 3 describes the case studies and their results, with a summary of answers to research questions found in subsection 3.7. Section 4 discusses the results and suggests future work.

2. Related work

This section reviews literature on the usability and user interaction with emerging technologies in similar contexts to those included in this thesis. Additionally, some evaluation methods used in the user studies are described. The related work is introduced under three themes: digitalisation of information flow, guidance provided by wearable and AR systems, and robot teleoperation.

2.1 Digitalisation of information flow

Digitalised information is a prerequisite for accessing, using and sharing information with the help of new technologies. Many factors affect the flow of information, for example, existing information systems and the communication between these systems; the extent to which these systems can serve the users (both in terms of user interfaces and technologies, but also by the type of data available in the system); the possibilities for transferring non-quantifiable knowledge into an electronic format; and the organisational culture of using the systems.

2.1.1 Knowledge transfer in maintenance

In addition to doing the physical and technical work related to fixing machines, an important part of maintenance work is the gathering and sharing of knowledge (Aromaa et al., 2015). Knowledge management in maintenance work, however, has been identified with several challenges. Franssila (2008) examined these challenges, which included inadequate formal documentation, unreliable networks, difficulty of sharing information on new products in the field, the fast pace of new product development, and the difficulty of transferring tacit knowledge (i.e., knowledge that is difficult to formalise and communicate; the opposite of explicit knowledge) to others. In practice, the method for relaying information to others was accomplished via oral conversations over mobile phones. As a solution to the challenges, the author suggested design goals for knowledge management in field maintenance: the methods and tools have to provide support that the information can be easily accessed, retrieved, combined, filtrated, saved and edited (Franssila, 2008).

Aromaa et al. (2015) suggested a model for sharing and gathering knowledge in maintenance work. The model endorsed the importance of communication between different stakeholders, which has also been noticed as a major difficulty by others (Anastassova et al., 2005). A maintenance technician shares knowledge with other people (co-workers, superiors, technical support and customers), but also with the environment, information systems, tools and equipment, and the maintenance objects (Aromaa et al., 2015).

An example of the way data is currently collected and reported in the field was described by Aromaa et al. (2016). The maintenance technicians take notes in a notebook, and possibly take photos using mobile phones. Then they go back to an office to use a computer for typing the handwritten notes into a reporting software and transferring the photos. Communication was mainly done face-to-face or via mobile phones. The maintenance technicians reported of challenges with finding the right information, which could be located in multiple places: information systems, e-mails, manuals, notebooks or other systems. Further, it was difficult to evaluate if the paper-based manuals were up-to-date (Aromaa et al., 2016). The study suggested new technology concepts for improving knowledge sharing in the field. These concepts were tested in Study II: Wearable Maintenance. Other concepts for supporting maintenance work are reviewed in Section 2.2.2.

Summary of knowledge transfer in maintenance
In maintenance, knowledge sharing currently relies on oral conversation and paper-based notebooks, from which information is transferred manually to information systems. Communication between stakeholders and access and up-to-dateness of information are recognised challenges in the field. It seems that knowledge transfer in maintenance is less in the research focus than the technologies that could support the work.

2.1.2 E-justice: digitalisation of judicial administration, case management systems and court rooms

The term e-justice is used when referring to the use of ICT in crime prevention, administration of justice and law enforcement (Xanthoulis, 2010). Regarding the administration of justice, e-justice covers ICT use in general, electronic communication (e.g., e-mail, videoconferencing), electronic case management systems, technology used in court rooms, and also electronic services offered to citizens (e.g., online access to case files). Several countries have attempted to adopt ICT systems for the public sector in order to achieve cost savings and information that is more accessible. However, the task is quite challenging, and many of the projects have been either suspended or they have exceeded the planned timetables and budgets (Gole and Shinsky, 2013). Many of the reasons for failure include administrative and project management problems, but the solutions have also lacked the needed input from the actual end users (Gole and Shinsky, 2013).

In the judicial sector, a recent European report summarised that information systems have, to some extent, enabled improvements in the efficiency and quality judicial systems (European Commission for the Efficiency of Justice, 2016). The level of ICT equipment, however, is not necessarily reflected in the efficiency indicators. The report suggests that the integration of IT with the organisational processes could be a success factor when combined with a change management policy involving all stakeholders (European Commission for the Efficiency of Justice, 2016). A successful example in the judicial sector in British Columbia emphasises the same: the consultation with the judges and other staff in judicial administration—and the understanding of their needs—can be critical (Lupo and Bailey, 2014). In addition to the communication and collaboration between key stakeholders, an iterative design process is important in the development of e-justice (Lupo and Bailey, 2014).

From the user perspective, simplicity and accessibility were emphasised in the e-justice development, and the systems should be perceived as attractive and convenient to use by the users (Lupo and Bailey, 2014). On one hand, however, the attempt to meet a broad set of user demands was reported to lead to overly complex systems. On the other hand, if the system is made excessively simple to the point that the system's functionalities, usefulness, value, and legal validity are affected, users are unlikely to utilise them. Therefore, the right balance should be found between usability and complexity (Lupo and Bailey, 2014).

Similarly, Langbroek and Tjaden (2009) also mentioned the balance of user involvement and the complexity of the system. Distancing the users, however, led to a situation where the system developers had not understood the complexity of the judicial processes due to the exceptions and changes in laws. In one piloting project, prosecutors and judges found an integrated tool quite handy (Langbroek and Tjaden, 2009). The tool could be used in the courtroom, but in practice, the system was unstable, computers had to be restarted, and the interface was problematic for the users. As a result, the users started printing their screen to make the paper workflow visible. Another reason for using paper files was that some courts had not implemented the case management system. Simpler solutions seemed to have more success over all-in-one solutions (covering the whole justice chain from police to the court) because data could be exchanged without the need to reorganise working processes. However, the use of less extensive, but more numerous solutions suffers from the requirement of different passwords and authorisations (Langbroek and Tjaden, 2009).

In the French e-Barreau experience, there was an attempt to achieve electronic filing and the digitisation of proceedings' documents (Velicogna et al., 2011). In practice, the system was used for accessing cases that had already been filed but not for the filing of the cases. Simply put, the system was largely based on attaching documents to emails. The documents were electronic versions of the paper documents, designed in a way that users would not need to make any major changes to the old procedures and work practices. The transfer from paper-based practices to digital ones suffered from several issues (Velicogna et al., 2011). For example, the courts did not have the means to recognise and prove digital signatures, and handwritten signatures were partially transmitted on paper. Moreover, although the system sent an automatic receipt mentioning the time of reception of a file, and the guidelines promoted using digital documents, some guidelines asked the clerks to print these acknowledgements of receipt and sort them in a paper version of the case file. The lawyers using the system had concerns about the legitimacy of the system, the high monthly fees required by the subscription of the system and the technical solutions chosen. Most initial end-users refused to adopt the technology because they did not see advantages of using it, but lawyers still felt that the electronic systems are the way forward (Velicogna et al., 2011).

In France, there was also another e-justice system in use in higher court, which covered e-filing and an electronic document exchange system based on PDF files (Velicogna et al., 2011). The system was a success because it was based on a more comprehensive innovation programme, including the training of staff, the option to access the system and do remote work from home, and to provide computers and displays to the users. In addition, the programme had considered all aspects of the work in court. However, this system was easier to develop than those for district courts because there were fewer actors involved in the higher court (Velicogna et al., 2011).

Wiggins (2006) elaborated on the effects of emerging technologies in the legal system. The technologies included videoconferencing, digital presentation of evidence, courtroom interpreting, demonstrations of interactive simulations and immersive virtual environments. The presumed benefits of using these technologies were temporal and monetary savings, reduced security risks to defendants or witnesses, and aids for jurors in the decision-making process

(Wiggins, 2006). A general concern with new, and possibly expensive, technologies, was the fairness of the playing field: whether lawyers have equal financial means and technical expertise to use the technologies. The sense of presence was a concern with videoconferencing. The use of simulated virtual reality depictions of events can be problematic if they are taken as representations of fact. With the immersive technologies, the author speculated that the related concerns were actually extensions of the concerns about other digital evidence, for example, digitally altered photos and simulations (Wiggins, 2006).

Summary of e-justice
In the reviewed e-justice studies, many digitalisation attempts have failed because there has not been enough understanding of the complexity of the work. Therefore, iterative design with key stakeholders, and finding the right balance between complexity and simplicity was emphasised. In the successful cases, there were a limited number of actors that were using the systems. Additionally, in these cases, the electronic documents were mostly electronic versions of paper documents, and the work practices did not change further. Appropriate devices and skills should be provided for accessing the data—for all parties equally. A concern has been raised regarding authenticity of digital evidence and the sense of presence in videoconferences. It seems that advanced technologies are rarely in the research focus in this domain.

2.2 Guidance using wearable and AR systems

Two domains for guidance are introduced in this section: navigation support for wayfinding in challenging environments and AR guidance for maintenance work.

2.2.1 Navigation support for wayfinding in the military context

In addition to aiding navigation for pedestrians and drivers, navigation support has been suggested for safety-critical tasks, such as those of first responders (Smets et al., 2008), firefighters (Streefkerk et al., 2012), and infantry soldiers (Kumagai et al., 2005; Eriksson et al., 2008; Elliott et al., 2010). In the latter cases, the navigation conditions may be complicated by bad weather, smoky or foggy air, uneven terrain; and the situation itself may posit a high mental load on the navigating person. Wearable systems (Figures 7 and 8) that provide multimodal feedback to the user have been suggested to overcome or mitigate these challenges.

Elliott et al. (2010) studied a wearable, multimodal navigation system for waypoint finding in the military context. The system included combinations of visual (handheld or HMD) and tactile (vibrating belt) feedback. With the wearable devices, rerouting obstacles and situational awareness were better than with the handheld. Mental workload was better with a multimodal combination of the tactile and handheld visual devices. The tactile modality was easy to use and required less training and visual attention. The ability to act hands-free was appreciated. A visual arrow was found to be simple to follow. The participants suggested combining the wearable visual display and the tactile belt to complement each other. The experiment was done in the field in wooded terrain, and the evaluation included performance measures (e.g., navigation time), and several subjective questionnaires (e.g., usability, usefulness, moving) and some oral questions.

Another navigation example in the military domain included three wearable devices: an HMD, helmet-embedded speakers and a tactile belt (Kumagai et al., 2005). The devices were used unimodally. All devices helped in finding the waypoints and they were easy-to-learn and suitable for travel. The tactile guidance was especially enjoyed for movement. However, the visual display needed adjustment, the tactile belt was uncomfortable and restricted mobility, and the direction of auditory feedback was difficult to determine. Low overall mental workload for the wearable devices was reported.

Similarly, Eriksson et al. (2008) tested unimodal wearable devices (a handheld visual device, headphones and a tactile belt) for waypoint navigation in the military context. Tactile feedback was well liked, and it did not direct attention away from the terrain as other modalities did, but its usability and integration with equipment could be improved. The auditory feedback blocked sounds and delimited the participants' attention.

In other domains besides the military, user experiments on navigation have reported similar findings on the wearable devices. Mental workload using wearables was low, and the usability of "eyes-free" conditions (auditory and tactile) was found good good (Calvo et al., 2014). However, the vibrating elements suffered from misalignment (Calvo et al., 2014). With a multimodal system, a slightly higher workload has been observed (compared to baseline), and information overload and the interfaces presenting inaccurate or irrelevant information for the task were reported (Streefkerk et al., 2012).

Regarding the user evaluation of multimodal systems, it seems there are no other reports examining wearable systems for navigation in the military domain besides the study by Elliott et al. (2010). Considering that study, and also taking into account similar systems in navigation tasks in other domains and other tasks in the military domain using multimodal and wearable devices, the evaluations have typically included performance measures—most often the completion time—and questionnaires measuring preferences, usability, comfort, mental effort, perceptivity of signals, and effects on movement (Andersson and Lundberg, 2004; Ferris and Sarter, 2008; Smets et al., 2008; Mynttinen, 2010; Garcia et al., 2012; Oskarsson et al., 2012; Streefkerk et al., 2012). Some of these studies also included video analysis or observations (Andersson and Lundberg, 2004; Ferris and Sarter, 2008; Mynttinen, 2010) and interviews (Mynttinen, 2010). These studies were mostly done in simulated or game environments. The details are summarised in table format in the Study I: Soldier navigation article.

Summary of navigation support

In navigation support, simplicity and the eyes-free and hands-free characteristics were appreciated, and the mental workload was estimated low with wearables. Tactile guidance was easy to use, needed little training, and could support moving, but the devices needed better integration with equipment, and were sometimes uncomfortable and restricted users' mobility. Visual arrows were easy to follow, but the HMDs needed adjustment. Auditory feedback could block surrounding sounds, and its direction was difficult to determine. Different modalities could be beneficial when used so that they complement each other, but the information presented should be considered carefully to prevent information overload.

There are very few reports of user evaluations of wearable, multimodal systems that are done in the field. The data collection methods have included performance measures, interviews, observations and questionnaires on preferences, usability, comfort and workload.

2.2.2 Guidance for maintenance work

Several emerging solutions have been introduced to aid maintenance work in the near future. These include wearable devices (Figures 7 and 8), which can be used for collecting and accessing information, and AR guidance, which means that context-related instructions are given to the worker in the form of text, symbols, or shapes augmented on a visual display (Figure 4c). Typical displays for AR guidance are smart glasses, or tablets and smartphones that have a camera and a screen. Other modalities such as sounds (e.g., Livingston, 2005; van Krevelen and Poelman, 2010) are possible, but are less frequently used.

Aspects in which AR guidance could assist maintenance technicians include procedural guidance; facilitation of information access; enhancement of motivation; reduction of paper-based documentation; and support for on-the-job training; although it has also been suggested that AR guidance should in fact support the understanding of the functioning of the maintained systems and their diagnostic activity, both during repair and training (Anastassova et al., 2005). Additionally, AR could facilitate communication and visualisation in finding, recording and transmitting novel system faults to designers (Anastassova et al., 2005). Remote maintenance support can be considered a special case of AR guidance, where a remotely located expert provides the guidance in real time.

In the assembly industry, which is closely related to maintenance, Wang et al. (2016) recently collected some key features and limitations observed in AR assembly research. In many research projects, the ergonomic problems of HMDs were listed, as well as limited field of view and time lag issues. There were also some uncertainties on which information visualisation should be used for which device (hand-held vs. HMD), and on the trade-off between haptic feedback and bare-hand interfaces. Only 11% of the reviewed papers included usability evaluations (Wang et al., 2016). Additionally, only a minority of research papers report on industrial applications (Nee et al., 2012).

Some guidelines for supporting the design of AR guidance have been suggested. Based on earlier work on the design of assembly instructions by Heiser et al. (2004), Henderson and Feiner (2011) highlighted two heuristics for AR-based maintenance and repair instructions: 1) one diagram should be displayed for each major step, and 2) arrows and guidelines should be used to indicate action (e.g., attachment, alignment, and removal). The authors suggested using more arrows in future AR applications (Henderson and Feiner, 2011). Additionally, there should be a unified in situ view of the task environment and the instructional content (Henderson and Feiner, 2011).

Similarly, Chimienti et al. (2010) introduced guidelines for implementing augmented reality procedures for assembly training. The assembly instructions were subdivided into tasks, sub-tasks and elementary operations (e.g., "Take output casing"). For each operation, suitable instructions were identified using textual messages, 2D pictures and 3D models. The assembly process was also depicted using logic flow charts. The authors also created a selection chart for choosing the right device (HMD, handheld or spatial display) for the task and listing the devices' pros and cons. For example, the pros of HMD included portability and the cons included low comfort; additionally, the handheld devices are listed in the chart as being easy to purchase, but their use is not hands-free (Chimienti et al., 2010).

The rest of this section describes user studies of wearable and AR guidance in the maintenance domain although examples from other domains—mainly from assembly—are introduced to complement the picture.

Wearables for guidance

Siegel and Bauer (1997) tested a wearable maintenance aid with aircraft maintenance technicians. The wearable system included an HMD and a physical dial for scrolling up and down a technical orders document shown on the display. The user evaluation comprised a combination of questionnaires, interviews and videos. The HMD had to be repositioned several times and shielded from intense sunlight. Further, a cap-style HMD was described as being bulky and too warm, and the angle at which it was positioned on the head was problematic for seeing the full screen. The buttons on the dial were sometimes accidentally pushed, but otherwise it was advantageous that it could be operated using only one hand. The technicians asked for improvements on the ease of navigating within the system and finding information, providing documents online without needing to use large documents, and the documents would be easier to keep up-to-date, offer the option to call people (e.g., aircraft company representatives), and enable linkage to a parts ordering system.

Lukowicz et al. (2007) considered the use of wearables in aircraft maintenance, car production, healthcare, and emergency response. For maintenance, the main required functionalities were access to electronic manuals, electronic procedure documentation, and collaboration with experts. The issues of the quality of HMDs and the user interface were also raised. The authors ended up with a tailored vest with multipurpose pockets for devices. The users also suggested integrating other devices such as lights for illuminating the working space. A major issue was the conversion of existing electronic content into a format suitable for wearable use. A combination of various input modalities, such as sounds, gestures and simple buttons were tried out, but they chose to use a wrist- or glove-integrated interface. An HMD was chosen for a display. The HMD with a simplified means of data presentation (the toolkit is described, e.g., in Witt, 2007) was found better than audio or direct text output. Additionally, new sensors were suggested for context recognition.

Other findings in the same research project as Lukowicz et al. (2007) were reported by Pasher et al. (2010). The use case was related to assembly work. The findings showed that wearables did not alter the workflow much (Pasher et al., 2010). There was less paperwork and fewer chances to make mistakes in the paperwork. Additionally, the results were logged real-time. The users appreciated that the devices were lightweight and integrated onto a belt. There were some issues with heat dissipation, power supply, and the devices' robustness for industrial applications. Regarding the HMD, the users liked that the image quality was high and the eye glass could be partially removed from the field of view. From the acceptance point of view, the users mentioned that they sometimes felt ridiculous wearing the devices, and the possibility to switch of the device should be offered to ensure the workers' privacy (Pasher et al., 2010).

Webel et al. (2011) focussed on AR-based training in maintenance. In a preliminary test intended for maintenance training, users were provided with visual instructions displayed on a screen (e.g., video of an expert's performance, 3D animation, or symbols augmented on the image) and haptic feedback via a vibrotactile bracelet. The haptic feedback gave the user additional motion hints during the task training, for example, guidance to specific targets or rotational or translational movement cues, which may be difficult to observe from videos. The test included a usability questionnaire also covering the functionality of the system and the design strategies. The authors commented that the haptic feedback has great potential for training but the realisation of the vibration stimuli needs to be refined.

There are also studies comparing wearable devices and other interfaces. Typical comparisons include HMDs and paper-based instructions and traditional screen displays, although orally given instructions and speech-based interfaces have also been experimented with.

Nakanishi et al. (2007) compared paper-based and AR-based manuals. The AR-based manuals were shown on two different HMDs, a see-through display and a retinal-scanning display, both of which are monocular where the image is shown only to one eye. Six points were examined: the effects of eyesight correction, eye dominance and surrounding illumination, workload, attention to surroundings and troublesomeness of preparation. The authors measured workload using questionnaires, performance measures (time per task), and an electrocardiogram. Attention to surroundings was measured by observing whether the participants detected flashing lights displayed at various angles. The authors concluded that both displays are easy to put on and take into use, contact lenses can be used with the HMDs, and the display should be worn over the non-dominant eye. The AR manuals did not increase workload compared with the paper-based manual. Additionally, it was easier to observe changes in the surroundings with the see-through HMD than with the paper manual, but the frame of the retinal-scanning display blocked the upper visual field. Under high illumination conditions, the retinal-scanning display was better than the see-through HMD, with which it was hard to read the displayed information.

Kunze et al. (2009) compared paper-based documentation to HMD display documentation in a maintenance task with a metrology system. The user controlled the HMD either using speech only or speech combined with context-dependent control. The HMD control was actualised by a human observer (a Wizard of Oz conductor). The users' performance was evaluated using performance metrics (time needed to perform and number of mistakes), questionnaires, and an interview. The questionnaires measured workload (NASA-TLX), overall impression, preferences, comfort and wearability, HMD image, navigation, readability and motivation to use the system. Some participants felt the system was obtrusive and felt relieved after taking it off, but on average it was rated as being comfortable. The use of context information speeded up the procedures significantly, and it was found more useful for less proficient technicians. In general, the HMD was preferred over paper, but there was a less clear distinction between the two HMD conditions.

Nakanishi et al. (2010) compared orally given instructions to overlaid visual instructions on a see-through HMD. The participants' task was to move an object on a computer screen according to the given instructions. The authors categorised the tasks according to their difficulty, and gave suggestions for the applicability of visual instructions with HMDs with (multimodal condition) and without the oral instructions. During simple tasks, visual instructions are effective at preventing careless errors, but multimodal instructions should be avoided as they may cause confusion in monotonous tasks. For tasks where the user follows given rules, multimodal instructions are effective and they do not seem to interrupt cognitive processes. During complicated tasks, multimodal instructions are also effective because the users can receive them at any convenient moment during a complicated cognitive process (the visual display was available at all times), but if auditory instructions are inconvenient, visual instructions alone suffice.

Henderson and Feiner (2011) compared three displays for maintenance instructions: a computer screen, and an HMD with and without instruction augmentation; similar content was displayed on each display. Test participants also had a wrist-worn controller with which they could navigate between tasks and replay animated sequences. The user evaluation included objective (mistakes, target localisation time, task completion time) and subjective measures (ease of use, satisfaction level, intuitiveness). The users mostly preferred the screen and found it easiest to use, although the HMD condition with AR was found most intuitive and came a close second. The users commented that the screen did not occlude objects, block light, or restrict their head movements. Some users found the augmented AR objects easy to follow, but some criticised that even the fading objects blocked their line of sight, the augmented arrows were not pointing exactly to the right position or the animations indicated wrong directions. Nevertheless, the arrows were assumed to help less experienced mechanics. The wrist-worn controller was not analysed, but users were reported to have done accidental double gestures after which they navigated back to reload the appropriate task. The authors concluded that the AR system was found to be intuitive and satisfactory, and technical shortcomings might be tolerated by mechanics if the system provided value. Additionally, AR can reduce head and neck movements during a repair and the time required to locate a task. In general, more control over dismissing unneeded content and controlling the fading of AR objects should be given to the users.

Zheng et al. (2015a) compared four approaches for displaying instructions in a machine maintenance task. The instructions were either shown on paper, or augmented on a tablet or on see-through smart glasses, where instructions were displayed either directly in front of (eyewear-central) or above line-of-sight (eyewear-peripheral). A human observer interpreted the participant's command and initiated a needed response (Wizard of Oz technique). The test participants' completion time and errors were collected and their preferences were requested. There was no difference between the wearable and non-wearable approaches. Comparing the two smart-glasses conditions, the completion times were shorter for the eyewear-central approach. On the other hand, the eyewear-peripheral was preferred over all other approaches because it was hands-free, convenient, light and comfortable, and unobtrusive and non-distracting. However, some participants commented that the smart glasses were heavy and uncomfortable and they did not like always having the information in front of them. Furthermore, it was harder to see texts and pictures on the semi-transparent screen of the smart glasses, whereas things could be seen clearly on the tablet and on paper and the participants did not have to adapt their vision for them. The tablet was found to be easy to carry around and use although both hands were used for holding it to get a better view of the situation. The participants seemed to find convenient places to place the paper and tablet when two hands were needed, but also expressed worry about dropping them or getting them dirty.

Summary of wearables for guidance

To summarise, AR has been found to be an intuitive way to provide guidance. Visual arrows or haptic motion hints can represent motion or direction of action. Wearable devices should be integrated and lightweight, and hands-free or one-handed operability is preferred. The challenge is in finding the right way to present information for the users with wearables, but also the (lack of) power supply and robustness can be issues, as well as the registration of symbols on the correct objects. It seems that using context information is more useful for less-experienced technicians and it can speed up the procedure. Multimodal systems can be effective because different modalities can offer information at different times and enable utilisation of the information when it is needed.

There is a lack of user studies. The existing user studies have typically used a combination of a few methods to measure usability, user preferences, workload, comfort, wearability and completion time and errors. Many of the user studies have included HMDs. The HMDs can be comfortable, intuitive, and convenient, and they have been found to be preferred over paper. On the other hand, HMDs can be bulky and obtrusive, the viewing angle and surrounding lighting conditions can be problematic, and the device often needs repositioning and blocks the view in general. Tablets have been found to be easy to purchase, carry around and use, and the instructions can be displayed clearly.

Remote guidance

Remote guidance, sometimes termed teleassistance, means that an expert provides guidance to a maintenance technician over a distance, for example, from company headquarters. There are several benefits for remote guidance, such as faster diagnosis, shorter maintenance times, and lower transport costs (Bottecchia et al., 2009). The learning costs can also be reduced because the training can be partially provided remotely. Additionally, collaboration of experts and technicians enables the expert to do quality control and the technician to pass on feedback (Bottecchia et al., 2009). Remote monitoring also enables companies to collect a maintenance history of their machines (Re and Bordegoni, 2014). Remote guidance can be provided orally (the traditional way), or by using AR techniques with hand-held and wearable devices.

Bottecchia et al. (2009) suggested a wearable system where the technician would be wearing an audio headset and a monocular HMD. In this interaction paradigm, the remote expert would enhance orally given instruction by AR. The expert would be able to provide information to the HMD in three ways: pointing at objects (indicating they need to be picked up), outlining them (to identify them or show properties related to them), and adding animations. The authors emphasised that the interaction between the expert and the technician needs to be synchronous. Additionally, the motivation behind developing the HMD-based guidance was to not to burden the technician’s sight and endanger them by providing a false perception of the visual area (Bottecchia et al., 2009). Hands-free activity was also mentioned.

Zheng et al. (2015b) have presented a wearable solution to provide guidance to the user, to support hands-free operation, and to enable collaboration with a remote expert in industrial maintenance. Workflow guidance was shown visually via smart glasses (Google Glass), and communication with the remote expert was done orally and via real-time streaming of video captured using the smart glasses. The users could also document their activities using pictures, voice notes, time tracking and visual markers. The design of the workflow was validated by professional train engineers, but the system had yet to be empirically tested (Zheng et al., 2015b).

Ferrise et al. (2013) tested a teleassistance system for maintenance. A remote operator, who did the actual maintenance on a physical machine, had a laptop and a camera positioned in front of the machine on a trolley. The system worked so that an expert operator manipulated a virtual model of the maintained machine, and these manipulations were then augmented onto the camera image of the real machine shown on the laptop's display. The operators could communicate orally. The user study was performed in a laboratory, and it included a questionnaire measuring the completeness and correctness of the visual information, intuitiveness, ease of use, and task support. The system was intuitive and easy to use but the task support could have been improved by adding more interaction elements such as virtual pointers that the expert operator could control.

Lamberti et al. (2014) described a remote guidance system that was based on AR guidance. The on-site technician was performing maintenance based on AR guidance displayed on a mobile device. The technician could also call for help. Help was provided by a remote operator, who could see the AR procedures that the on-site technician was seeing, and the remote operator could either modify the AR procedures or bring in new procedures if needed. The authors concluded that the remotely reconfigurable AR guidance was promising as a complementary solution or an alternative to paper-based procedures and traditional teleassistance.

Summary of remote guidance

It seems that there are only a few reports of using remote AR guidance in industrial applications and even fewer empirical tests. In the described cases, help was provided orally and by visual AR. The applications seemed to have potential, although there was not much reported on user experience. The remote expert could benefit from readily available interaction elements, such as virtual pointers, or the option of modifying existing AR instructions.

2.3 Robot teleoperation

Teleoperation means that a system, for example a robot, is operated from a distance using a control device. Traditionally, the control interface has been a computer keyboard and a mouse, or a joystick or gamepad with control sticks and buttons operated using fingers. More recently, the possibilities of using gestures and wearable interfaces has been explored. In the robotics research context, the teleoperation of a robot using wearable interfaces, enabling the user to experience being present at the site of the robot, is referred to as immersive telerobotics. Examples of telerobotics domains include space exploration (Brooks, 1992; Bualat et al., 2013), mining (Varadarajan and Vincze, 2011), nuclear power plants (Eickelpasch et al., 1997), high-pressure ocean missions (Yuh, 2000), and robotic surgery (Zareinia et al., 2015).

The first part of this section describes evaluations of user interfaces—especially with wearable and multimodal characteristics—for teleoperating robots. The second part of this section introduces robotic surgery and its expected future developments.

2.3.1 User interaction with wearable and multimodal teleoperation systems

This section reviews studies describing user interaction with teleoperated robots using wearable and multimodal interfaces. In this case, multimodal refers mainly to multiple control modes, whereas in robotics research in general—especially with social and human-like robots—multimodal is often synonymous with human-robot dialogue with speech and auditory components. Additionally, a few examples of multimodal (tactile or haptic) feedback (Yang et al., 2004; Ryu et al., 2005; Randelli et al., 2011; Franz et al., 2013; Corujeira et al., 2017) are included in the review.

The teleoperation studies mostly concentrate on performance evaluations, and the interaction is rarely evaluated or reported from the user's perspective. However, some studies have included a broad range of evaluation methods (Kechavarzi et al., 2012; Fernandes et al., 2014; Livatino et al., 2015; Zareinia et al., 2015). Additionally, the recently published guidelines for the design of robot teleoperation include platform architecture, error prevention, visual design, information presentation, robot state awareness, interaction effectiveness, awareness of surroundings, and cognitive factors such as cognitive load (Adamides et al., 2015). The guidelines remain on a general level, and wearable and multimodal interfaces are not considered.

The literature is organised according to the interface characteristics used for robot control, including either data gloves and gestures, or gamepads and control sticks (the study by Boudoin et al. (2008) considers both approaches). Several studies included HMDs (Yang et al., 2004; Ryu et al., 2005; Jankowski and Grabowski, 2015; Livatino et al., 2015; Martins et al., 2015), and these studies are listed first in each subsection.

Both mobile and stationary robots are included. The main difference between these types of robots is that with mobile robots, the user is required to focus more on navigating the environment. Four of the studies reviewed below include a mobile robot base equipped with a robotic arm—systems similar to those described in Study IV (Ryu et al., 2005; Brice et al., 2010; Pham et al., 2014; Jankowski and Grabowski, 2015). In terms of user interaction, the closest study is that of Jankowski and Grabowski (2015).

Teleoperation using gestures and data gloves

Jankowski and Grabowski (2015) tested a mobile inspection robot equipped with an arm. The system included an HMD for visual feedback and for controlling a camera, a joystick for movement control of the mobile robot, data gloves for gripper control, and a motion tracking system for mapping the user's hand position and moving the robot's arm respectively. In a comparison of two traditional displays and a joystick, the participants felt the wearable multimodal interface had several benefits over the others. They evaluated their performance better, and the interfaces were evaluated as being intuitive, easy to use and comfortable, and needed relatively little time to adapt to. The interface components were evaluated separately from one another, and the multimodal nature of the interaction was not commented on.

Yang et al. (2004) experimented with a humanoid robot (i.e., a robot with body parts similar to those of humans) with a mobile base, head, and two arms. The user wore an HMD, two gloves with vibrators, a microphone and speaker, and the arm and head motions were tracked. The user commanded the robot to approach a table and pick up an object using voice commands and arm motions, and received both visual and haptic feedback (force readings in the form of vibrations transmitted to the gloves). The system was demonstrated with users, but the users' experience was not reported.

Ryu et al. (2005) tested a field robot equipped with an arm in an explosive ordnance disposal demonstration task. The system included an HMD, a speech and auditory interface, and a wearable haptic interface with a belt–wrist device. All three devices (head movements, speech, body movements) were used for controlling the robot and its camera, and visual, auditory, and force feedback were transmitted to the user. The experiment was done to verify the usefulness and effectiveness of the system, but details of the results were not reported.

Brice et al. (2010) used speech and arm gestures to command a mobile robot with an arm. The described multimodal interface aimed for more natural interaction between humans and a mobile robot. The study did not examine user acceptance and usability in detail, but the authors pointed out that test participants tended to look at the pointing target when performing gestures and therefore the head movements should also be tracked to improve the fusion of the multimodal inputs.

Fernandes et al. (2014) tested three interfaces (a wearable one that was mounted onto the arm and hand, a gamepad, and a tablet) for operating a stationary robotic arm in a pick-and-place task. With the wearable interface, the user's arm and hand position and movements are channeled onto the robot's arm. In the evaluation, both objective (time to complete, distance travelled, outcome of task) and subjective (a survey, six questions concerning ease of use and user satisfaction) measures were used. The task completion times were the smallest with the wearable interface. Overall, expert users performed better than non-experts, but the expertise had the least effect with the wearable interface. From the user interaction perspective, using the wearable interface was mentioned to shift the user's attention away from the wearable hardware to seamlessly completing the task and to allow the users to feel the robot arm as an extension of their own arm. The wearable interface was also preferred over the other interfaces, although the game controller was nearly equally liked, and with it, precise movements were easy to perform.

Randelli et al. (2011) operated a mobile robot in a simulated rescue environment with a simulated and a real robot. The study compared three interfaces: a motion-sensing Wiimote controller (a hand-held controller with vibrating tactile feedback), a gamepad, and a keyboard. The user evaluation covered mission-related performance, environmental conditions, robot operation degree, and human cognitive effort (operator-cognitive load, interaction comfort, learning rate). The Wiimote provided lower overall navigation times than the other interfaces and its learning rate was high, but the tactile feedback did not significantly enhance the robot control and did not seem to prevent collisions. The users evaluated the keyboard to best support movements in narrow spaces, whereas the Wiimote was too reactive for conditions featuring difficult terrain.

Boudoin et al. (2008) compared tracked data gloves and a Flystick (a hand-held, wireless, tracked joystick with buttons) for controlling a virtual model of an industrial robotic arm. Experienced users were better at controlling the robot with the tracked gloves. However, the authors observed that the Flystick is more adapted for novice users and offered a possible explanation that the use of the data gloves feels so natural that the user does not realise the robotic arm is mechanically more constrained than the user's own movements would allow. Further user-related results were not elaborated upon, but the article discusses the management of multimodal inputs from a technical perspective, and the authors emphasise that systems combining multiple devices should support natural interaction, transparency to the user, usability, efficiency and flexibility.

Summary of teleoperation with gestures and data gloves

Several of the reviewed studies remarked that the interaction with wearables was intuitive and natural. Wearables also needed little time for training, and the teleoperation was fast. On the other hand, the precision of control with wearables could be improved, and the users did not necessarily realise the constraints of the robot's movements if the users' movements were directly mapped onto the robot. Most studies did not explore the user interaction aspects in detail. Multimodal interaction and comfort were mentioned very briefly, but were not elaborated upon further.

Teleoperation using gamepads and control sticks

Martins et al. (2015) tested three configurations in the control of a mobile robot in a simulated search-and-rescue. A stereoscopic camera was fixed in the frontal body of the robot, and the user received visual feedback via a computer screen or an HMD. A gamepad was primarily used for controlling the robot movements, but with the HMD, the user's tracked head position affected the angle of the visual feed (rotation of the robot's frontal body and the attached camera) and in one HMD configuration, also the whole orientation of the robot's body. The study mainly evaluated the performance with the different display configurations, finding the HMDs better than the standard display. However, the authors noted that it is less effective and potentially confusing to control the robot's body orientation (instead of only the camera) using head movements, because of the change in the user's frame of reference.

Livatino et al. (2015) evaluated different screen and display types, including an HMD, in a virtual medical endoscopic teleoperation task. Both quantitative (collision number, time and rate), and qualitative variables (questionnaires covering, e.g., depth impression, presence, and comfort) were used. Stereo viewing enabled fewer collisions, increased the sense of presence, and improved users' performance. The performance with HMDs both under monoscopic and stereoscopic viewing, however, was worse than with any other display. The HMD was found uncomfortable, and its display size and perceived field of view were small. The users also reported a high sense of isolation with the HMD, which made them pay more attention to the field of view, leading to a tunnel-vision effect.

Franz et al. (2013) used a multimodal control setting in teleoperating a robotic arm. The main control device was a control stick (Phantom Omni) with and without force feedback, and the camera view was controlled using head tracking or a joystick. Performance measurements and subjective measurements targeted on individual components (easiness to operate and learn, effect on perception, tiredness, preferences) showed that the control setting was natural, as well as easy to learn and use. The head tracking was especially effective, whereas the effectiveness of the force feedback was unclear and the negative results were possibly due to the coarseness of the tactile feedback.

Horan et al. (2009) introduced a technical description of a multi-handed approach to controlling a virtual rover-type robot equipped with a camera. Both hands grapped haptic controllers (fingers attached to and touching small pads); one hand controlled the mobile robot and the other manipulated the visual perspective of the camera through a camera-in-hand metaphor. The paper did not include a user study.

Pham et al. (2014) evaluated a mobile robot with an arm and an on-board camera that is fixed in one direction in the robot frame. The test participants used a single haptic device (a manipulator arm) to control both the locomotion and the robot arm. Given that they were using only a single device, the participants had to switch between the two control modes to move around and grasp an object; the tests included three different switching schemes where the active control mode depended on the positions of either the robot's arm or the manipulator arm used by the participant. The switching scheme where the user could neglect the control of the vehicle's motion and focus only on the arm motion was the most intuitive. Visual feedback from the robot's camera was viewed from a screen. The study relied mainly on performance evaluation. The evaluation included objective performance metrics (execution time, number of failures, arm manipulability) and subjective performance metrics (NASA-TLX, interview). There was variance in the NASA-TXL workload results for the three control modes, and the authors concluded that there was more correspondence between the interview feedback and objective metrics, and therefore recommended using objective metrics for performance evaluation of control schemes.

Corujeira et al. (2017) studied the use of haptic feedback for alerting users while they were teleoperating a simulated mobile robot. The control device was a game controller that vibrated when the user was about to collide with a wall. The user evaluation consisted of performance metrics (time to complete; number and duration of collisions) and a questionnaire measuring collision awareness, turning awareness, location awareness, and the usefulness of limiting the maximum velocity. The authors concluded that the haptic feedback improved the teleoperation efficacy when the users were performing a concurrent task.

Zareinia et al. (2015) tested three haptic hand-controllers (a stick, a bar and a pad grasped by hand and fingers) for teleoperating a robot equipped with a surgical microscope. Visual 3D feedback was displayed on a monitor. Ten performance measures (e.g., operator effort, speed, learning curve) and an 8-item questionnaire (e.g., easiness to understand, learn and use the system, and comfort and movability) were used. The comments regarding the hand controllers considered ergonomics, the precision and oscillations of movement, the effort and felt resistance to move the controller, and the manoeuvrability of the tool tip. The authors concluded that a hand controller with linkage structures similar to those in the human hand would optimise the performance.

Kechavarzi et al. (2012) evaluated three user interfaces (a keyboard, a game controller, and a touchpad) for controlling a teleoperated mobile robot. Visual feedback was provided on regular computer or tablet screens. The evaluation methods included a survey of participants' attitudes toward technology, perceptions of robots, and immersive tendencies; performance measures (e.g., time to perform, bumping walls); questionnaires to measure immersion, satisfaction, overall performance, and also intuitiveness, easiness, comfort, and confidence; and a semi-structured interview. Although devices typically associated with immersion—HMDs as an example—were not used, the authors observed that the participants who rated the controllability of a device higher also felt better at manipulating the robot and immersing themselves in the tasks they are performing. Therefore, increasing the users' feeling of control could facilitate creating more immersive experiences for teleoperators (Kechavarzi et al., 2012).

Summary of teleoperation with gamepads and control sticks

During concurrent tasks, tactile feedback to a hand controller could be beneficial. Additionally, it has been suggested that hand controllers with linkage structures similar to those in the human hand could also be advantageous. Further, the controllability of a device could also contribute to the feeling of immersion in a task. In these studies, it was found that using head movements with or without HMDs to control a camera was effective. However, there were issues with HMDs regarding comfort and the small field of view.

Methodologically, many of these studies used both objective and subjective measures although the research focus seemed to be targeted more on the efficacy than user aspects, and multimodality aspects were not discussed.

2.3.2 Robotic surgery

This section introduces a special case of teleoperation: robotic surgery. The general principles of what happens are in an operating theatre are described first to facilitate understanding of the study setting of Study V. Then, user perspectives and future directions in this field are outlined.

The presently used surgical robots are teleoperated. The surgical robot discussed in this thesis is the market-dominant da Vinci S Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA, Figure 11). The surgery is performed laparoscopically, meaning that the operation takes place within the patient's body while the patient's skin and outer tissues remain almost intact as the robot's arms and camera enter the patient through incisions, or "ports".

Figure 11. The da Vinci da Vinci S® System robot and operating console ©2018 Intuitive Surgical, Inc.

The surgeon teleoperates the robot using a surgical console (Figure 11). The surgical console includes a 3-D stereo viewer, hand motion controls, and foot pedals. With the hand motion controls, the surgeon can control two robot arms simultaneously. Additionally, the surgeon can switch to controlling a third arm mostly used for providing static hold. The hand motion controls use tremor filtration and motion scaling, but no haptic (tactile) feedback is provided. Because of the lack of haptic feedback, the surgeons need to develop a sense of "visual haptics", that is, they need to learn using the visual cues (e.g., tissue blanching, colour and deformation) in identifying and manipulating tissues (Van Der Meijden and Schijven, 2009). The foot pedals are used for selecting monopolar or bipolar cautery (burning tissue to cut it or stop bleeding), clutching, or switching the hand motion controls from moving the robot arms to steering the camera.

In the operating theatres in Finland, the patient bed is typically located in the middle of the room whereas the console is positioned next to a wall. When the operation starts, the robot is wheeled to stand next to the patient bed. In addition to the surgeon operating the robot, the operating theatre staff includes an anaesthesiologist, nurses and an assistant surgeon. The assistant surgeon sits or stands next to the patient with one of the nurses in order to manually apply suction through a port, place clips to staunch bleeding, provide needle and thread, or help with the robot (e.g., to clean the camera lens). Typically, they assist the operating surgeon with the placement of the ports and they perform, depending on their expertise if they are still in training, some parts of the operation by taking turns with the operating surgeon at the console. The operating surgeon can give verbal instructions to the assistant, and additionally use the robot instruments or the suction device for pointing.

The surgical team can follow the operation in real-time on several displays. For example, in one hospital in Finland, there are two large screens at the end of the room and two smaller screens that can be tilted in different directions. The assistant surgeon relies on these displays when guiding the instruments within the patient.

User perspective to robotic surgery

User aspects have not attracted very much attention in robotic surgery, although a multidisciplinary view is called for by several experts (Camarillo et al., 2004; Taylor, 2007; Marcus et al., 2013; Marescaux and Diana, 2015). Some difficulties with the current, minimally invasive techniques are recognised in the robotic surgery community, for example, access, dexterity, and ergonomic issues; and the need for user-friendly devices has been raised (Taylor, 2007). The aspects regarding user interaction in the robotic surgery are briefly introduced below.

The ergonomics and the quality of 2-D and 3-D vision of laparoscopy and robotic surgery have been compared in various studies. For example, Moorthy et al. (2004) reported that compared to laparoscopic surgery, the robot instrumentation, with the help of tremor abolition and motion scaling, enhanced dexterity by nearly 50% in a suturing task. Additionally, 3-D vision enhanced the dexterity further by 10-15%. Similarly, Van Der Schatte Olivier et al. (2009) reported that both cognitive and physical stress were reduced and performance was improved when using a robot-assited surgical system compared to standard laparoscopy.

Okamura et al. (2010) have reviewed the literature for haptic feedback in robotic surgery. Haptic feedback is believed to improve the accuracy and dexterity of a surgeon, but it is difficult to ascertain it because presently haptic feedback is not available in clinical systems. The technical challenge lies in the force sensing and estimation, not in how the force is presented to the surgeon. Two methods have been suggested for presenting this information: direct force feedback to the surgeon's hands or sensory substitution, meaning that the information is presented using another sensory channel such as vision or audition (Okamura et al., 2010). Due to the lack of haptic feedback, the surgeons performing robotic surgery can develop a sense of "visual haptics" (Roulette and Curet, 2015), which means that they use visual cues to deduce the properties of tissues.

Schreuder et al. (2012) have discussed the training modalities involved in learning robotic surgery: animal and human cadaver training, live case observation (i.e., being present in the operation room during surgery), and performing under the direct supervision of an expert. Available technical means to support learning include virtual reality (which, however, lacks proper validation) and a mentoring console (i.e., the trainee and the expert have their own consoles and they can actively swap control of the robot). The robot also provides some assets to the evaluation of surgical performance: using the robot instrument parameters recorded during the operation, it is possible to describe aspects of performance (Judkins et al., 2009). The learning curve on robotic surgery varies depending on the complexity of the procedures, and the surgeon's experience of similar technology and familiarity with the procedure in question (Schreuder et al., 2012).

Cunningham et al. (2013) have studied human-robot team interaction in robotic surgery. By comparing different surgical teams, they found differences in the workflow, roles, timeline, and communication patterns as a function of workplace culture and experience. These factors need to be accounted for when designing collaboration between surgical teams, which may become an especially important issue in remote teams in the future. Nyssen and Blavier (2013) concentrated on the verbal communication between the operating surgeon and the assistant. Compared to laparoscopic operations, there was more communication in robotic surgery operations regarding actualising the operation, for example, orders and clarifications, and the robot console was suggested to reduce gestures related to face-to-face communication and favour speech instead (Nyssen and Blavier, 2013).

Future developments in robotic surgery

There are several barriers related to the development of robotic surgery. They include costs, legislative issues, robot size and mobility, haptic feedback, imaging capabilities, latency, and signal security (Lendvay et al., 2013). Despite these issues, the technology development is ongoing in various directions: improvements in visual and haptic feedback; use of imaging technologies (e.g., magnetic resonance images of the patient); applications of augmented and virtual reality technologies; improved computational and autonomous capabilities; probes, sensors and other instrument improvements; and fewer invasive and smaller robots to allow better access to the patient (see Study V for a recent review on the emerging and state-of-the-art technologies).

For example, in the future, the robot might require only one entry port (termed *single-port surgery*), and the outlines of cancerous tissues could be highlighted for the surgeon (based on magnetic resonance images augmented onto the patient's real organs shown on the camera feed), the surgeon could "feel" the tissues via the hand motion controls (haptic feedback), and parts of the operation such as suturing could be performed automatically under the surgeon's supervision (autonomous functions).

Summary of robotic surgery

In robotic surgery, a surgeon teleoperates the robot using a surgical console. The surgeon is physically co-located with the the rest of the surgical team in the operating theatre and can communicate with them orally and by gesturing with the robot's instruments that are inserted into the patient through ports.

It seems that there is an acknowledged lack of research on user interaction in the robotic surgery domain. The literature addressing user interaction includes the aspects of ergonomics and workload, visual and haptic feedback, learning and training issues and team-level interaction. Robotic surgery development is concentrated on achieving technical advancements especially in haptic feedback, imaging and AR technologies, and less invasive robots.

3. Case studies

Each case study is handled individually. The study and the used technologies are briefly introduced, followed by answers to the research questions.

3.1 Study I: Soldier navigation

This research paper, "Field evaluation of a wearable multimodal soldier navigation system", describes two user studies concerning the evaluation of a wearable multimodal navigation system for military reconnaissance tasks. In the first study, the system was tested in a controlled environment—an outdoor sports field—using unimodal (visual, auditory, or tactile) and trimodal (visual-auditory-tactile) outputs, and in the second study, the system was used bimodally (visual-auditory, tactile-auditory) in the context of a military exercise in a forest.

3.1.1 Methods

The participant's task was to navigate to pre-determined waypoints, i.e., GPS (global positioning system) coordinates entered into the system, using only the navigation instructions received via the wearable devices and an optional compass. There were four civilian participants (aged 20–35, two male, two female) in the first study, and nine conscripts (aged 19–20, all male) in the second. Detailed descriptions of the tests can be found in the case study article (Study I).

Equipment and modalities
The wearable navigation system was a demonstrator that included see-through smartglasses (visual modality, Figure 12), headphones (auditory), and a vibrating vest (tactile, Figure 13).

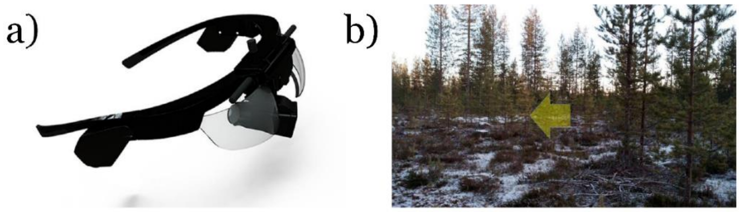


Figure 12. Visual modality in Study I. a) Penny C Wear Interactive Glasses Basic (source: http://www.penny.se/company-media.html, with permission), b) An illustration of a hovering arrow seen via the smartglasses in Sub-study 1. The arrow indicates that the user should turn leftward.

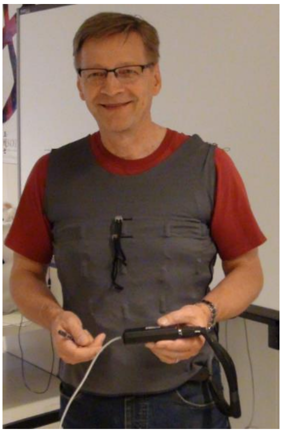


Figure 13. Tactile modality in Study I: A vest with tactors, or tactile elements.

The instructions to the waypoint varied depending on the modality:

- Visual modality: Arrows (in Sub-study 1) or textual cardinal directions and distance to target (in Sub-study 2) overlaid on see-through display
- Auditory modality: Spoken instructions including cardinal directions and distance to target
- Tactile modality: A vibration to the left or right side of the torso via a vibrating vest indicating the direction to turn to.

In addition, the system indicated to the participant when they had reached a waypoint.

Evaluation methods

The participants' behaviour was observed directly or using cameras when possible. Both studies included first impressions interviews regarding participants' self-evaluated performance, their attention to surroundings, and advantages and disadvantages of the system and setup used. In the first study, the participants were also asked about their preferred modalities. In the second study, an additional multi-page usability questionnaire was used. The questionnaire included items regarding usability, usefulness, learning, wearability, situational awareness, and information display. The items were mainly based on the System Usability Scale (SUS; Brooke, 1996), Questionnaire for User Interface Satisfaction (QUIS; Chin et al., 1988), systems usability framework (Savioja and Norros, 2013; Savioja et al., 2014), and Situational awareness rating technique (SART; Taylor, 1990). Some items regarding mental workload were included although the NASA Task Load Index (NASA-TLX; Hart and Staveland, 1988) was not included in full. The participants could also write comments on open field questions and express their opinions in a focus group discussion arranged after all participants had tried out the system. The evaluation design was influenced by earlier work done in the field (Elliott et al., 2010; Mynttinen, 2010).

3.1.2 Results

All participants were able to use the demonstrator system in their navigation tasks. Because the system was a demonstrator, the results are mainly based on the conceptual idea of using the system and the provided information in navigation tasks. Additionally, the physical implementation affected especially the wearability aspects. The answers to RQ1 are primarily based on actual experiences, but the participants also raised potential issues they could foresee in future use (especially RQ2). The system and its parts are listed and characterised in Table 3.

Table 3. Technologies and solutions used in Study I and their characteristics (MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange).

Technology	MM	W	AR	EIE
Navigation system; whole system	✓	✓	✓	✓
Visual modality (Sub-study 1)		✓	✓	
Visual modality (Sub-study 2)		✓	✓	
Auditory modality		✓		
Tactile modality		✓		

Answers to Research Question 1

RQ1a: What benefits did the users experience or expect from emerging technologies?

The system was considered easy to learn, and the given information was easy to interpret. The participants liked that distance information was provided. The whole navigation system and its individual components were evaluated to cause a low mental workload. The auditory instructions were given in a clear and easy-to-notice voice. The visual instructions in Sub-study 1, i.e., arrows, were accurate and simple. The tactile vest was comfortable, easy to put on and take off, and it was easy to notice the vibrations and observe the environment while wearing it. Regarding the multimodal use, the navigation was considered smoother using many modalities compared with only one, and many information sources gave certainty to the users.

RQ1b: What concerns or problems did the users experience or expect from emerging technologies?

The disadvantages of the system were mostly about the wearability issues of the headphones and the HMD, which were evaluated as being distracting and problematic for comfort. Specifically, the HMD suffered from a non-ergonomic fit and it was considered too big, limiting the visual field. Moreover, the arrows shown on the visual display in Sub-study 1 easily disappeared from the field of view. The cables of the system should be attached firmly to support movement.

In addition, the issues of the complexity of interpreting the cardinal directions (both auditory and visual) and knowing how much to turn (tactile) were raised. It was thought to be easier to focus on one device at a time. Furthermore, there is a possibility for information conflict if feedback through different modalities is unsynchronised or input manually.

Answers to Research Question 2

RQ2a: Would the emerging technologies be useful and suitable for the context of work?

The system supported the participants in the navigation. In the military navigation context, however, it is important to be able to monitor the surroundings and move in terrain in various environmental conditions. Firstly, the headphones could block surrounding sounds. Secondly, the system was partially unsuitable for moving in terrain, because of the cabling of the demonstrator and because the HMD limits the visual field and there were ergonomic issues with its fit. The HMD was also felt to force users to target their attention on too many things simultaneously. Regarding the mental demands, the guidance could be simpler.

RQ2b: With the adoption of these technologies, how would everyday work change?

The system could eliminate the need to read a paper map and use a compass in reconnaissance tasks. It would support navigation while moving, and especially with the help of the tactile feedback, support navigation in the dark. Additionally, the system could provide certainty through the redundant modalities while requiring little mental effort, which are valuable aspects in challenging conditions.

Answers to Research Question 3

RQ3: What aspects should be considered in the evaluation of emerging technologies?

The data collection methods used in this study, i.e., interviews, observations, questionnaires and a focus group, gave a good understanding of how the users experienced the multimodal navigation instructions. The combination of a controlled study and a field study was useful, although the controlled study could be more thorough, that is, include baseline, unimodal, bimodal and trimodal conditions.

In future evaluations, more consideration needs to be given to how the modalities are used when there is more than one modality in action:

- Do the users rely on one specific modality?
- How does the task and the usage context affect the choice of modality?
- If there were a conflict between the information relayed with different modalities, what kind of strategy would the users use to cope with the situation?
- Does the strategy of using the modalities evolve with practice?

The usability questionnaire used in the second study could be improved by including items specifically targeted at multimodal interaction, such as those in described in the MultiModal Quality Questionnaire (MMQQ; Wechsung, 2014). Additionally, depending on the maturity of the tested system, objective performance measures (e.g., “time to complete task”) and physiological measurements (e.g., heart rate) could be included. With a more mature system, having a larger number of participants would be valuable to cover various users’ needs.

Finally, the video and log data collected during the user tests could be used in post-trial analysis by replaying the data—video footage and system-generated guidance for each modality—on computer screens (Figure 14).

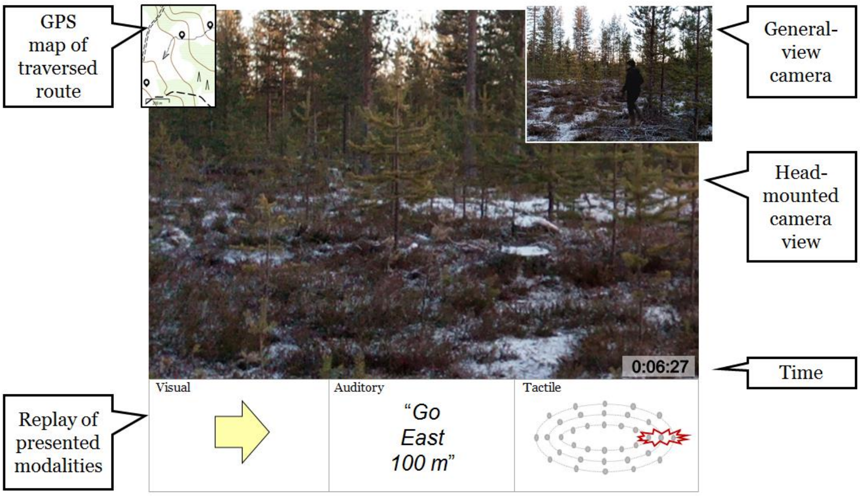


Figure 14. Post-trial replay of multimodal interaction—annotated illustration of the data analysis station described in Study I, showing two camera views, time stamp, and a replay of the presented modalities.

This could add to the evaluation process in three ways:

- Tool for researchers (post-trial video analysis)
- Retrospective interviewing, ("think aloud")
- Stimulus for workshops with potential users and/or system developers (cf. Buur et al., 2010).

The benefits are evident when

- researchers cannot join the user at the site of action
- only a few user trials can be performed
- a specific usage situation requires detailed examination
- determining how and to what extent each modality was used (see Mynttinen, 2010; Oskarsson et al., 2012)
- discussing task-related modality preferences and adaptive modality selection (see Kong et al., 2011; Streefkerk et al., 2012).

3.2 Study II: Wearable maintenance

This paper, "Use of wearable and augmented reality technologies in industrial maintenance work", describes two user studies in practical industrial maintenance work. The first case considers the use of multiple wearable devices for data collection and reporting in the crane industry, and the second case, the use of augmented guidance using a tablet in the marine industry.

3.2.1 Methods

The participants' task was to perform maintenance procedures and reporting according to system-provided instructions. Two maintenance technicians (aged 23 and 54, both male) participated in the first case, and two other maintenance technicians (aged 34 and 49, both male) participated in the second. Detailed descriptions of the cases can be found in the case study article (Study II).

Equipment

In the first case, the maintenance technicians used a wearable, multi-device setup (Figure 15) for inspection and reporting:

- helmet-mounted see-through smart glasses for checking information related to a maintenance target and taking pictures with an embedded camera
- a smartwatch for selecting targets and acting as a remote shutter for the camera embedded in the smart glasses
- a smart phone for starting the inspection and checking the final report.

Figure 15. Devices for the wearable maintenance in Study II. a) Vuzix M100 smart glasses (image courtesy of Vuzix Corporation). The image is displayed in the small screen shown on the black piece over the bottom part of the right lens. b) The smart watch. c) A user using hand gestures to change the information shown in the smart glasses (upper right corner).

In the second case, the participants used a tablet-based AR guidance system to open a maintenance order, selecting the required operation, performing a disassembly task according to augmented instructions displayed on the screen, and acknowledging the completion of the task.

Evaluation methods

In both cases, the same data collection procedure was used. After testing the system in their work, the participants filled a usability questionnaire based on the System Usability Scale (SUS; Brooke, 1996) and the technology acceptance model (TAM; Davis, 1989). The questionnaire responses were then discussed in a follow-up discussion, which also included an interview considering user experience, acceptance, and collaboration. Researchers directly observed the participants' performance in both cases; additionally, the second case was video-recorded.

3.2.2 Results

The workers were able to perform the needed reporting and maintenance tasks in their working environment. The results reflect the conceptual ideas behind the systems, their physical implementations, and partially the interface designs. The answers to RQ1 are primarily based on actual experiences, while RQ2 contains the maintenance technicians' estimations based on their knowledge of the work context requirements. The systems and their parts are listed and characterised in Table 4.

Table 4. Technologies and solutions used in Study II and their characteristics (MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange).

Technology	MM	W	AR	EIE
Wearable system for maintenance	✓	✓	✓	✓
Smartwatch		✓		
Smart glasses		✓	✓	
Smartphone				✓
Tablet-based AR guidance			✓	✓

Answers to Research Question 1

RQ1a: What benefits did the users experience or
expect from emerging technologies?

It was easy to use and learn to use both systems. With the wearable system, it was also easy to understand the role and linkage between each device. The gesture-based interaction of the smart glasses was experienced positively, and the ability to take photographs was evaluated positively. Regarding the AR-based system, the instructions were liked on several accounts: the symbols were easy to understand, it was clear what the user was required to do, and the direction of intended activity (e.g., the direction to which to twist a screw) was visualised using 3-D pictures. The visual instructions were also expected to suffer less from a language barrier.

RQ1b: What concerns or problems did the users experience or
expect from emerging technologies?

The difficulties with the wearable system regarding the multimodal use were four-fold:

- remembering which device to use for which action (e.g., the smartwatch or the smartphone)
- due to the number of devices, the use of the system was slightly complicated and interfered with working and made working slower
- switching between devices during use, and
- the requirement of using two devices simultaneously (e.g., taking a photograph required pressing the camera button on the smartwatch and keeping the target visible in the smart glasses).

Additionally, the position of the buttons on the smartglasses were difficult to remember.

The practical challenges with the AR-based system were mostly related to the work context. However, there was some confusion on how to hold the tablet by hand(s) although stopping the work when holding the tablet was not seen as a considerable drawback.

Answers to Research Question 2

RQ2a: Would the emerging technologies be
useful and suitable for the work context?

The maintenance technicians who used the systems were positive towards using them in their work. The working environment and respective protective gear, however, challenge the use of the systems at work. The protective gloves needed to be taken off for using the tablet and the smartwatch, and the smartwatch tended to slide under the work glove. In a similar vein, the smartglasses being attached to the helmet meant that the display was not visible when not wearing the helmet and taking photographs with the glasses was difficult in small, confined spaces. The wearable system was felt to decrease the amount of hands-free working compared with regular maintenance work—i.e., the workers needed their hands for using the devices—and this was raised as a safety concern. On the other hand, the devices enabled in-the-field reporting. The robustness of the tablet was also questioned.

The electronic databases are easier to keep up-to-date than paper-based manuals or instructions, but the realisation of the updates was questioned because the engine parts change rapidly. Although the system-provided guidance was thought to be useful for early in a career, novice technicians cannot rely solely on the guidance—even the AR instructions in the study were noted to contain a mistake. For experienced technicians, the guidance would be useful only if the maintenance cycles are long and there was a greater possibility for forgetting how the maintenance is performed.

RQ2b: With the adoption of these technologies,
how would everyday work change?

Both systems were thought to have a positive impact on work. The electronic systems could offer better up-to-date information. The workers would not need to search for folders of paper manuals and go to offices to file reports. The team interaction would also change because the systems enable a decrease in the amount of communication between personnel. For example, the workers could access information online and reduce the need to call their colleagues by phone.

3.3 Study III: Tablet-guided maintenance

This paper, “Maintenance Past or Through the Tablet? Examining Tablet Use with AR Guidance System”, describes a user study examining the practicality of using a tablet computer in a maintenance task. The study was done in a virtual laboratory, and the focus was on how the participant handled the simultaneous use of the tablet and the physical objects involved in the maintenance task.

3.3.1 Methods

The participants’ task was to perform a maintenance task on a virtual rock crusher using augmented guidance received via a tablet. The maintenance included identifying a faulty control module (a physical box with cables and a voltage adjustment knob), switching it to a working one, and adjusting the voltages to the correct reading range. Six volunteers (aged 30–43, four male, two female) participated in the user experiment. A detailed description of the experiment can be found in the case study article (Study III).

Equipment
The setup included a virtual reality model of a rock crusher that was projected onto wall-sized screens in the activity area of the virtual laboratory (Figures 4b and 16). There was a desk with a maintenance cabinet—containing the control modules—placed in front of the screens. The virtual rock crusher reacted to the actions done in the cabinet, for example, the flow of rocks the rock crusher “spit out” and the accompanying sounds depended on the voltage adjustments. Additionally, the participants wore a helmet, whose position was tracked, ensuring that the projected rock crusher was visualised from the correct viewpoint with respect to the participant.

The participant held a 9.7-inch tablet through which instructions were displayed based on the currently active subtask and the physical modules being tracked (Figures 4c and 16):

- Visual instructions shown on the tablet screen included overlaid videos, and augmented text and animated symbols.
- Auditory guidance consisted of beeps when a task phase was completed.

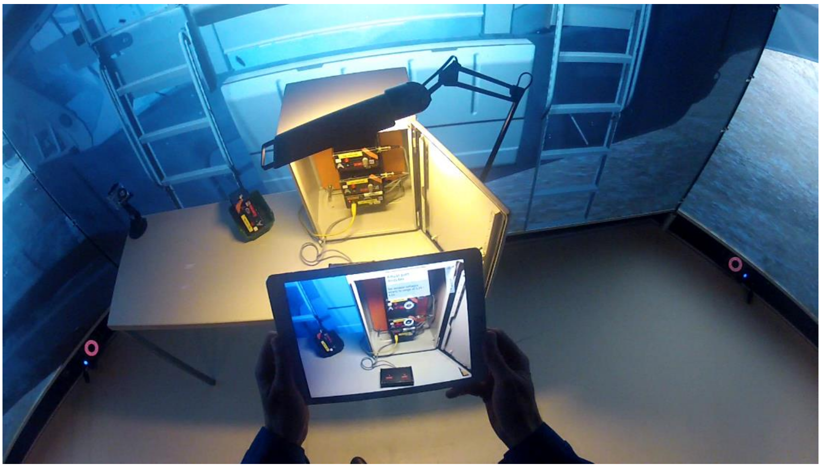


Figure 16. A participant holding a tablet with augmented instructions shown on the screen in Study III. A virtual model of the rock crusher is shown in the background (mixed reality).

Evaluation methods

Researchers observed and video-recorded the participants' activities. The participants filled in questionnaires considering usability, learning and simulation sickness, and they were also interviewed. The analysis of the video recordings comprises the main content of the research paper.

The video analysis of the participants' behaviour included several practical aspects, such as

- how the tablet was held in the participant's hands during the task
- whether the tablet was put on the desk
- reactions to the virtual model or auditory feedback (beeps and sounds of crashing rock)
- participant's actions based on the AR guidance.

3.3.2 Results

All participants accomplished the maintenance task with the help of the AR guidance. Most participants held on to the tablet with at least one hand even during physical manipulation of the modules. Observations also showed that they mostly viewed the surroundings and manipulated the physical objects past the tablet, although, in especially the voltage adjustment phases, many fumbled for the adjustment knob when viewing through the tablet. The virtual model of the rock crusher seemed to have only a small effect on the participants' actions. The results primarily reflect the selected interface design, the chosen symbols, the visual view, and the conveyed information. Additionally, the selected physical device (tablet) influenced the results. The results were based on the actual usage experiences in the laboratory environment. The technologies are characterised in Table 5.

Table 5. Technologies and their parts used in Study III and their characteristics (MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange).

Technology	MM	W	AR	EIE
Tablet-based AR guidance	✓		✓	✓
Visual instructions			✓	
Auditory feedback	(✓)			
Virtual rock crusher	✓		✓	

Answers to Research Question 1

RQ1a: What benefits did the users experience or expect from emerging technologies?

The system helped the participants perform the maintenance task quickly. No prior experience was required in the maintenance or in the use of the AR system.

RQ1b: What concerns or problems did the users experience or expect from emerging technologies?

There was some confusion about the meaning of the visual symbols, either in the interpretation of their meaning or the position at which the symbol was pointing. Other usability issues were related to the tablet. It was awkward to tap a text box while holding the tablet and to manipulate physical objects while viewing the scene through the tablet. Two hands were often used for tilting the tablet for a better angle or to get a better view of the overall situation (the participants could also take a step backward to facilitate this). The participants said they had not heard any auditory feedback and inquired to obtain some. Therefore, auditory feedback for targeting attention could be explored further.

The AR system could be developed further to support the tablet-based instructions while maintaining an awareness of the big picture. The study suggested using symbols or other indicators to notify the user of several components:

- Because the view through the tablet is limited, a symbol could be used to indicate that a larger view is needed to show the whole work area and the corresponding AR guidance. In the setup used, it was possible for items to remain hidden outside the display
- Symbols could also indicate the need to use two hands, when the tablet should be set aside on a surface and the instructions could be “frozen” on the screen,
- Symbols indicating the need to listen to or inspect the physical machine. This could also support the transfer of tacit knowledge and serve a training purpose, so that the user does not get too focussed on the AR guidance and forget about the actual machine.

Answers to Research Question 2

RQ2a: Would the emerging technologies be useful and suitable for the context of work?

Regarding the suitability of the AR system for maintenance work, there was a concern of the device having to be hand-held during the maintenance task; putting the tablet onto a desk meant that the user could not get any visual feedback while not holding it. Using the virtual rock crusher in the background showed that although auditory feedback was masked by the background noise so that participants reported not having heard any beeps, the beeps shifted their attention nonetheless.

Answers to Research Question 3

RQ3: What aspects should be considered in the evaluation of emerging technologies?

Video analysis was practical for observing the participants in the laboratory experiment. However, the positioning of the side camera—focussed on the working area and not the user—was not optimal for observing the participant. The whole user should be included in the view. Additionally, gaze tracking technologies would provide more detailed data. To evaluate the AR guidance, a larger variety of actions could be used, for example, the manipulation of heavy or tightly attached objects, continuous adjustments and pauses for object or tool retrieval. Finally, although the participants did not use the virtual rock crusher for guiding their maintenance task, the background noise took the experiment one step closer to more realistic working conditions.

3.4 Study IV: Space telerobotics

This study, "Multimodality Evaluation Metrics for Human-Robot Interaction Needed: A Case Study in Immersive Telerobotics", describes a user experiment where a teleoperated robot-rover system was teleoperated using a wearable, multimodal control system.

3.4.1 Methods

The test participants' task was to teleoperate a mobile four-wheeled robot and collect a sample from the ground using the robot's arm and gripper. The test took place in a mixed-reality laboratory, depicting the setting of a space mission on Mars. Nine volunteers (aged 29–57, five male, four female) participated in the user test. A detailed description of the test can be found in the case study article (Study IV).

Equipment

The multimodal, wearable control system included an HMD and a data glove with gesture control (Figure 17):

- The HMD showed a mono-camera feed (Figure 4d) from the camera carried by the robot. The tracking position of the HMD controlled the pan-tilt of the camera.
- A data glove (worn on the user's right hand) enabled the user to perform hand gestures, which were used to control the four modes of the robot: rover wheels, arm, gripper and idle. The person's arm position was tracked using Kinect. The arm position defined the robot's action in the selected mode. For example, an arm stretched forward in the rover mode would drive the robot forward.

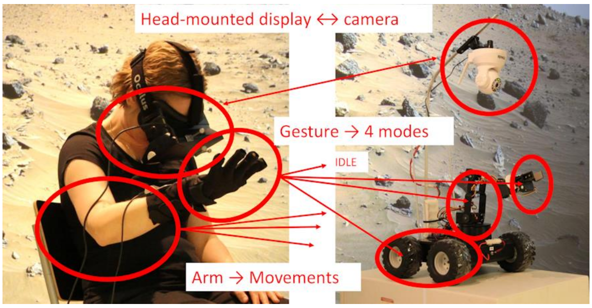


Figure 17. Wearable control system (left) and the teleoperated robot (right) in Study III.

Evaluation methods
The participant's performance was video-recorded using three cameras placed at different angles, and the HMD view was also saved. Four questionnaires followed the test: the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993), NASA-TLX, bodymap and usability questionnaires. Each participant was also interviewed, covering training, task performance, user interfaces, and the control concept. Additionally, two researchers did a heuristic usability evaluation of the system.

3.4.2 Results

The participants had the freedom to try out all control modes and phases of the task. However, the control system was not very stable due to its low maturity, and therefore the participants had to cope with the system not recognising all of their gestures, which caused frustration. The results are mainly based on the physical devices and the conceptual idea of using the system. Additionally, the interfaces, especially the gestures and the visual view, affected the results. The results were based on actual usage experiences. The control system and its parts are listed and characterised in Table 6.

Table 6. Technologies used in Study IV and their characteristics (MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange).

Technology	MM	W	AR	EIE
Control system	✓	✓	✓	✓
Data glove and gestures		✓		
HMD		✓	✓	

Answers to Research Question 1

RQ1a: What benefits did the users experience or expect from emerging technologies?

The wearable devices, which were commercial products, were found to have good wearability characteristics: the HMD was comfortable, it fit nicely and was not considered heavy, and the data glove was lightweight and soft. The HMD provided an adequate resolution, a clear view to surroundings and the transmission delay was considered realistic for a space mission.

The wearable interface offered a natural way to operate the robot without a medium (cf. a joystick or a keyboard). The ability to move the camera using head movements and orienting it with respect to the user's body was emphasised. The participants also liked the feelings of presence and immersion during the task.

RQ1b: What concerns or problems did the users experience or expect from emerging technologies?

Many of the positively experienced aspects had drawbacks as well. The participants commented on missing depth vision, poor image quality and perspective, small field of view, and a long image delay. It was also felt that the HMD was not securely attached. The control modes were difficult to remember.

The HMD view was problematic. Position estimation was difficult because the robot's arm was not visible on the screen at all times. Furthermore, there was a mental mismatch between the image shown in the centre of the HMD and the robot's actual heading (e.g., the robot's camera could be facing toward the right while the rover was being steered straight forward), which caused misguided navigation. Additionally, the participants' head and arm movements seemed to be coupled, and they turned their head toward the direction of the arm movement.

Issues on the physical ergonomics were also raised. The arm gestures were uncomfortable and too wide, and there was no elbow support. Neck pain due to the HMD was also reported. Part of the discomfort originated from awkward postures with head and arm: because of the limited field of view and the wide movement trajectories, the participant's head could be positioned in their "right armpit".

All participants were able to get a feel of the wearable control system. The usability of the system suffered from technical difficulties, and therefore the usability questionnaire results are secondary to the comments and observations from the viewpoint of assessing the wearability and multimodality.

Answers to Research Question 3

RQ3: What aspects should be considered in the evaluation of emerging technologies?

Originally, the focus of this user test was to perform an ordinary usability analysis for a newly developed technical system. Although the system proved to be at a rather immature stage for a thorough usability analysis, important findings regarding the analysis of such systems in the future were identified. Interviews and videos proved valuable in the evaluation, because they showed the user's actual activity and how the users experienced the wearable interface.

Especially in the robotics context, the user aspects are often neglected, and it seems that the complex nature of multimodal interaction needs more attention. In the article, two new evaluation metrics for immersive telerobotics were suggested: type of multimodal interaction and wearability.

"Type of multimodal interaction" refers to both defining how the interaction is planned to happen from the user perspective and the interaction the system is capable of (see, e.g., categories in Nigay and Coutaz, 1993). The evaluation should show whether the users can and will use the modalities offered by the system, and how they use them—and if they use them intuitively in a simultaneous manner without bias caused by too detailed instructions or training (Lisowska et al., 2007). In addition, the experiment should be designed, if possible, so that the user can use the modalities both individually and in parallel. A combination of several methods should be used to evaluate multimodality:

- Questionnaires; including, e.g., statements such as those described in MMQQ (Wechsung, 2014)
- Interviews; naturalness of interaction, strategies to use the modalities sequentially or in parallel
- Observations and videos; actual use, disuse or mistakes, speed of interaction, etc.
- Performance measures and log files, if available, to complement the above-mentioned items

"Wearability" covers multiple aspects: comfort, ergonomics, freedom of movement, and intuitiveness of learning and using the system. Additionally, wearable displays such as the HMDs, involve aspects related to simulation sickness, immersion, sense of direction, situational awareness and quality of display. Because a combination of an immersive HMD and another control device can lead to unpredicted effects, e.g., awkward body postures that go unnoticed by the user as the HMD blocks the users' physical body from their view, it may be mandatory to also consider the multimodality aspects in conjunction with HMDs. The evaluation of wearability aspects can include

- customised usability questionnaires; see wearability aspects above, and those in (Gemperle et al., 1998; Knight et al., 2006)
- user comments
- observations, especially with HMDs.

3.5 Study V: Robotic surgery

This study, "Envisioning robotic surgery: surgeons' needs and views on interacting with future technologies and interfaces", describes a future workshop studying surgeons' views on the future of robotic surgery from three perspectives: good operation outcome, user experience, and learning and training robotic surgery.

3.5.1 Methods

This study consisted of a preparations component and the future workshop. A detailed description of the preparations and the workshop can be found in the case study article (Study V). The current robotic system used by the surgeons who participated in the workshop is shown in Figures 11 and 18.

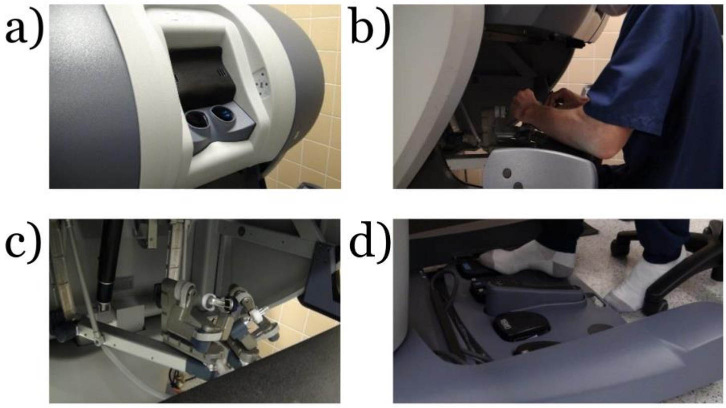


Figure 18. The surgical console of the da Vinci S System that the participants of Study V use in their work. a) Stereo display. b) A surgeon sitting at the console. c) A close-up of the hand controls. d) Foot pedals used to switch between functions.

Preparations for workshop

The main method of this study was a future workshop. The workshop was preceded by several preparatory steps:

- Acquisition of a thorough understanding of the surgeons' work in the operating theatre (core-task analysis (Norros et al., 2015), including interviews, ethnography and a literature review)
- An initial list of potential emerging technological solutions was drawn following recent trends
- The list was pruned to 26 technologies belonging to 12 different categories (e.g., haptics, navigation, tissue identification)
- Presentation material for introducing the technologies was prepared using slides, images and videos.

The technologies selected to the workshop that concern the technology characteristics discussed in this thesis are briefly explained below (the numbers in parentheses (#) refer to the numbering of the technologies in Table 2 in the article):

- Head-mounted display (#4): Instead of a fixed stereo-display on the console, the robot video would be shown on a wearable head-mounted display and the endoscopic camera would be moved by head movements.
- Haptic feedback to motion controls (#7) or to a body part (#8): Transmitting feedback from the robot or its instruments to the hand controls or the surgeon's body.
- Virtual "no-go" zones (#11): The surgeon can set virtual zones within the patient's body, where the robot's arms or instruments cannot enter.
- Leaving landmarks on image (#19): Leaving landmarks (e.g., an 'X' shape) on the robot video, the markings are fixed to the site even if the camera is moved.
- Drawing on the video image (telestration; #15): Drawing lines or other shapes on the robot video, the markings are fixed to the site even if the camera is moved.
- General 3-D model of internal organs (rotatable, overlayed on video image; #21): Displaying a 3-D textbook model of the organs on the robot video; the model can be used as a reference of the human anatomy.

- Displaying a patient’s pre-imaged anatomy and nerves (#22, #23, #26): Displaying an image of the patient’s anatomy augmented on the robot video (#22). Displaying the tissue characteristics and their edges augmented on the robot video (#23). The nerve pathways are located by stimulating the tissue and showing the responses augmented on the robot video (#26).
- Comparison data and advice during operation (#12): The robot could offer advice or information about the ongoing operation based on comparison with an “average” operation.
- Rewind (#17): Rewinding the robot's video during surgery, e.g., to check where tissue was penetrated
- Imperceptible motion amplification (computational; #25): Utilising the robot video so that earlier footage can be used to calculate subtle differences between pixels and can be augmented on the robot video.

Future workshop

The future workshop method was used to elicit opinions of the surgeons regarding the effect of emerging technologies on their work. The workshop was inspired by several methods, including Future Workshop (Jungk and Müllert, 1987), Future Technology Workshop (Vavoula and Sharples, 2007) and Anticipation Dialogue Method (Laarni and Aaltonen, 2013). Five surgeons (aged 35–52, four male, one female) participated in the workshop.

The workshop included four phases:

- Envisioning phase: introduction of the technologies to the surgeons to inspire them to envision their work; giving initial ratings for the technologies
- Filtering phase: individual selections of five of the most important technologies
- Discussion phase: presentation of arguments for each of the selected technologies one at a time; a option to comment on others
- Reflection phase: discussion and reflection on future expectations and concerns.

Evaluation methods

The workshop material was analysed using qualitative content analysis (Elo and Kyngäs, 2008). Technologies discussed in the two latter stages of the workshop were analysed based on their support for improving the operation outcome, user experience and learning. Human factors and other practical matters related to the technologies were collected.

3.5.2 Results

All surgeons participated actively in discussing the future technologies and their effects on the surgeons’ work. The results are primarily based on the surgeons' professional estimates of the conceptual ideas of the systems and their suitability for the surgery context. The technologies relevant for this thesis are characterised in Table 7.

Table 7. Selected technologies and solutions discussed in Study V and their characteristics (MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange). The numbers in parentheses (#) refer to the numbering of the technologies in Table 2 in the article.

Technology	MM	W	AR	EIE
Wearable, haptic interaction technologies	✓	✓	✓	(✓)
Head-mounted display (#4)	✓	✓	✓	
Haptic feedback to motion controls (#7) or to a body part (#8)	✓	✓		
Augmented and overlaid images on the robot's video feed			✓	(✓)
Virtual "no-go" zones (#11)			✓	
Leaving landmarks on an image (#19)			✓	
Drawing on the video image (telestration) (#15)			✓	
General 3-D model of internal organs (rotatable, overlayed on video image; #21)			✓	(✓)
Displaying patient’s pre-imaged anatomy and nerves (#22, #23, #26)			✓	
Computational methods for supporting surgery		✓	✓	✓
Comparison data and advice during operation (#12)				✓
Rewind (#17)			(✓)	✓
Imperceptible motion amplification (computational; #25)			✓	✓

Answers to Research Question 1

RQ1a: What benefits did the users experience or expect from the emerging technologies?

Regarding the three aspects considered in the study, improved operation outcome, user experience and learning hands-on robotic surgery, several of the solutions presented at the workshop were thought to benefit them.

The technologies that would mainly support improving the operation outcome were those with which the patient’s pre-imaged anatomy and nerves could be augmented onto the patient’s organs visible in the robot’s video feed. In addition to helping to cope with the individual anatomical differences of the patients, the technologies could improve safety in other ways as well: support for tissue identification leading to faster operations and fewer complications, and the visualisation of the location of nerves could facilitate the operation in sensitive areas. The latter point would also be helped by leaving augmented landmarks and setting up virtual no-go zones. Other overlaid information, such as drawing onto the image or displaying a 3-D anatomical model, could have their uses in learning and teaching.

The addition of haptic feedback could have similar benefits: improving tissue identification and safety, and learning how various tissues behave. Additionally, it was thought that haptic feedback could also aid in learning how to operate the robot. A head-mounted display would support the robot control as well, as the camera follows natural head movements.

The surgeons could also benefit from utilising the robot’s video more extensively using computational methods. In the simplest form, the video could be rewound to show, for example, where a certain tissue was penetrated, supporting learning and teaching, and the patient’s safety. The pulsatile motions behind cell walls could be amplified and augmented, also supporting the patient’s safety as the surgeon could avoid blood loss. Analysing the video footage and the robot’s motions further, the surgeon could get support for learning to suture or perform other procedures with a minimum amount of movements and be alerted if an ongoing operation proceeds in a radically different manner than a computationally average operation. The surgeons also suggested that the comparison of performance to earlier operations could act as a motivational factor for improving performance (cf. “Sports Tracker application”), and the sharing of information could support a communal function.

RQ1b: What concerns or problems did the users experience or expect from emerging technologies?

Because the surgeon relies completely on the robot’s video image while operating, several of the solutions could compromise the patient’s safety by blocking the real-time view of the patient’s body. For example, if computational methods are used to amplify imperceptible motions (such as pulsating veins), the surgeon needs to be notified that the display is not showing the real-time situation, or the real-time situation needs to be displayed and monitored in other ways. The patient’s safety could also be compromised because of data security and hacking issues related to electronic data.

When drawing on the video image, there are two practical problems with the currently implemented (but rarely employed) system: the drawing surface is not sterile and the lines drawn on the image are not mapped onto the tissue and therefore moving the camera view renders the drawings meaningless.

Although haptic feedback would be a very welcome addition, there were three concerns related to it: the appropriate level of realism of the feedback that could be achievable in the near future, potential conflicts between the visual and haptic feedback, and possible malfunctions of the haptic feedback and its consequences. Using an HMD, the ergonomics need to be considered: simulation sickness issues, and the stationary support provided by the current stereo display that the HMDs lack. The HMD and immersion could also affect the team’s awareness and work practices.

Answers to Research question 2

RQ2a: Would the emerging technologies be useful and suitable for the work context?

The study participants had varying opinions on the potential usefulness of the technologies presented at the workshop (see Table 2 in the article). As some of the solutions have not been implemented in the surgery context and others are still in an early development phase, the participants’ estimates of the usefulness were only used for facilitating the discussion at the workshop. In estimating the suitability of the solutions in the surgery context—in addition to considering the patient outcomes—issues of acceptance, trust, safety and security, ergonomics, quality of implementation and team-level interaction need to be considered in the future.

RQ2b: With the adoption of these technologies,
how would everyday work change?

Work practices would undergo several changes with the adoption of the technologies introduced in this study. Although the use of some of the solutions (e.g., nerve imaging) could extend the operating time, other solutions, such as haptic feedback and augmented images, could reduce it by helping the surgeon with the challenging task of tissue identification. AR and computational solutions could change the way and the extent to which the visual display are utilised, and also provide access to previously unavailable data. The more extensive utilisation of the data could open up possibilities for sharing expertise in the surgical community.

In the future, the operating experience could be more immersive: the movements of the surgeon's hands could be directly mapped to the robot instruments and electronic discharges could be transmitted to the surgeon when encountering a nerve. Immersion (a surgeon wearing an HMD, receiving haptic feedback, possibly being blocked from outside stimuli) affects team interaction, which would need to be rethought. Learning and adapting to seamlessly utilising both the haptic and the visual sense would also mean that in the rare yet plausible situations when the haptic feedback should malfunction during an operation, the surgeon could face considerable challenges coping with the loss of one sense.

3.6 Study VI: E-justice

This study, "Envisioning e-Justice for Criminal Justice Chain in Finland", describes a future workshop using the anticipation dialogue method and discusses how future technologies and electronic data exchange could aid workflow in the justice system.

3.6.1 Methods

The study included a preliminary segment and a future workshop. In the preliminary segment, the researchers acquainted themselves with the ways of working in judicial administration agencies, including twelve interviews with prosecutors, judges, and office staff such as assistants. Additionally, courtrooms were visited to get an understanding of the most recent technology available in Finnish courtrooms. A detailed description of the preparations and the workshop can be found in the case study article (Study VI).

Future workshop — anticipation dialogue method

In the future workshop, the Anticipation Design Dialogue method (Laarni and Aaltonen, 2013) was employed to explore how the criminal case workflow could be aided by technical and inter-agency communication (see illustration of the workflow in Figure 19). The workshop had three stages (the workshop took place in 2011):

- Stage 1: "It's the year 2015." The participants explained their thoughts about an ideal workflow
- Stage 2: "Recall back from the year 2015, …" The participants pictured the changes that need to happen before the ideal situation can be reached.
- Stage 3: "New ways of working, new equipment." State-of-the-art technology was presented to the participants so that they could envision how the technology could aid their work.

The third stage was preceded by finding state-of-the-art technology using different sources: research literature and websites on earlier e-government projects that were considered relevant based on the preliminary interviews and the gained understanding of the Finnish case. The technologies included electronic judicial literature; IT-supported decision-making; video conferencing systems; video hearing equipment and possibilities for remote interpretation and subtitling; touch displays and audio commands for controlling audio-visual evidence displays and adjustment of lighting and positioning of video screens in courtrooms; pop-up displays from courtroom desks; holographic displays; laptops and tablets; and flexible workspaces. There were nine participants in the workshop including prosecutors, district and appellate court judges, and assistive staff from three different counties.

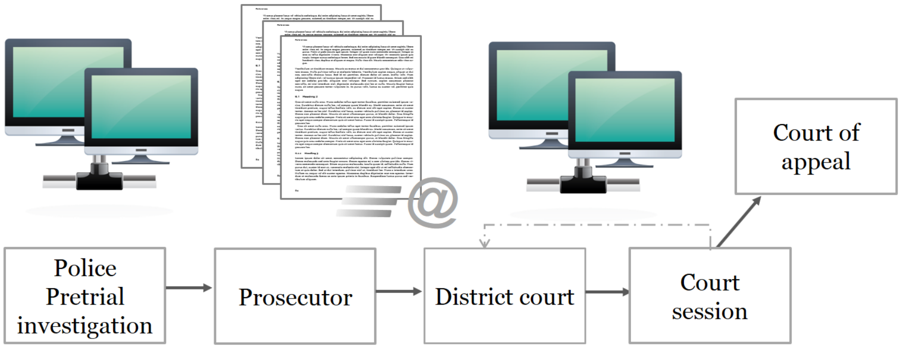


Figure 19. An illustration of the criminal justice chain and electronic information exchange in Study VI.

3.6.2 Results

In the future workshop, the participants created a vision of the smooth workflow in the criminal justice chain. The technologies the participants included in the vision were mainly traditional ICT. The results are primarily based on the participants' professional estimates of the conceptual ideas of the systems and their suitability for their context of work. The participants had varied experiences of using electronic materials and videoconferencing although the experiences were with less advanced technologies than those envisioned in the future workshop. The enabling technologies are listed and characterised in Table 8.

Table 8. Technologies and solutions discussed in Study VI and their characteristics (MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange).

Technology	MM	W	AR	EIE
Information systems, case management systems				✓
Electronic documents				✓
Electronic calendars				✓
Electronic information exchange, e.g., e-mail				✓
Video conferencing	(✓)		(✓)	✓
Courtroom technology	(✓)			✓

Answers to Research Question 1

RQ1a: What benefits did the users experience or expect from emerging technologies?

The benefits of electronic documents and information systems include faster information flow and easier access to cases and related documents. The documents could be interlinked and several plaints concerning one person could be combined using document templates.

Electronic information exchange would enable time savings on several accounts, especially when contacting the parties. The use of shared electronic calendars would reduce the amount of manual work because checking the availability of parties and facilities could be done simultaneously.

Using automated case distribution instead of delivering cases manually to prosecutors could automatically take into account the prosecutor's task load. Video conferencing and remote participation could eliminate some need for travel by interpreters, experts and even procecutors.

RQ1b: What concerns or problems did the users experience or expect from emerging technologies?

The concerns raised by the workshop participants mainly reflected experiences with previous IT systems and reforms. For example, the existing electronic calendars were largely disused because there was only local access to them. Moreover, separate calendar systems for rooms and personnel caused extra work for the assistants. The transfer from paper-based documents is also likely to be challenging, because the independence of the judiciary is strong—meaning that each judge has settled on their own way of doing things—and the structure of the electronic documents likely does not please all parties. Technology itself was not the focus of the discussion, but remote access, wireless networks, power outlets and cabling, a sufficient number of displays for working on multiple documents simultaneously, and the quality of video conferencing were brought up when discussing the mandatory enablers for using the electronic systems.

Answers to Research Question 2

RQ2a: Would the emerging technologies be useful and suitable for the context of work?

There is a clear need for digitalising the judicial administration, as the current information systems and software do not offer the functionalities and usability expected of modern ICT. On the other hand, the judicial administration is somewhat old-fashioned in their work practices, and there is resistance against shifting from paper-based documents to digitalised systems, and even to using computers among the older generations.

Technology, and especially high-tech, is expensive and was of secondary importance to the workshop participants in comparison to achieving a smooth workflow. Electronic systems can enable a smoother workflow, but the systems would likely be accessible only within the judicial administration, therefore leaving out the defendant's counsel, who would have to be contacted manually. Furthermore, because the slowest party in the courtroom determines the pace of the trial, all parties should have equal access to the systems. For some technologies, such as video conferencing for remote hearing, there are legislative barriers delimiting their use. Moreover, concerns were raised whether the judges are able to reliably evaluate the defendant's statements remotely through videoconferencing systems.

RQ2b: With the adoption of these technologies, how would everyday work change?

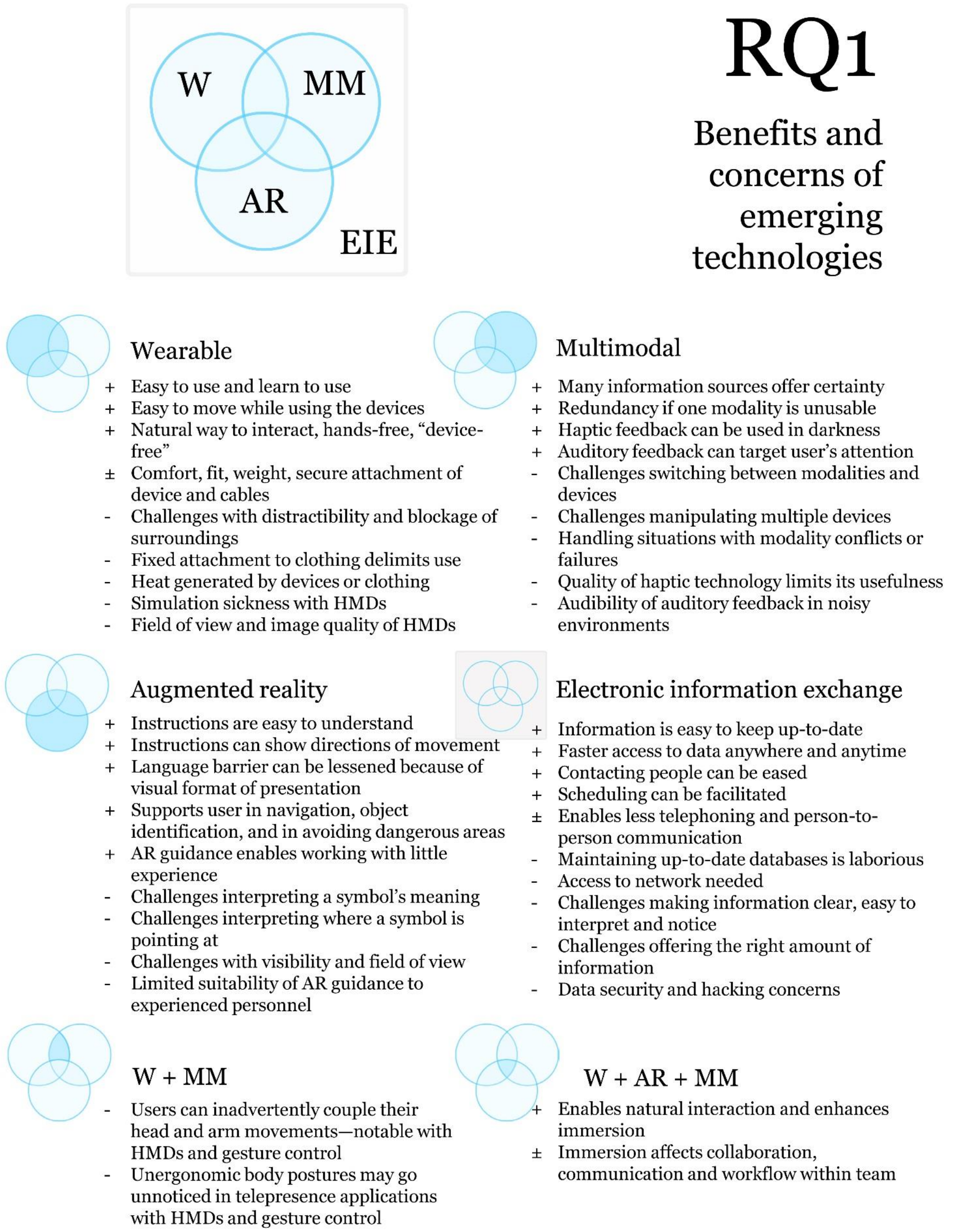
The core task in the judicial administration was not expected to change. On the other hand, there would be a change in where the work takes place: work could be done remotely (outside the workplace, enabled by online information systems) or in an office room instead of a courtroom (video-conferencing systems). For some parties, such as prosecutors and interpreters, this could mean less travel. Additionally, working with electronic documents would require a new way of handling the documents: taking notes, linking the documents and especially coping with the different syntax of electronic documents as to which each party has been accustomed.

The amount of manual work and handling of paper-based materials would be affected by the electronic systems and calendars. The work of the assistants would undergo a significant change, and they believed their professional role would shift towards handling and assisting with the ICT and the courtroom technology.

3.7 Summary of results

3.7.1 Benefits and concerns of emerging technologies

Research question 1 considered the users' benefits and concerns of the emerging technologies. Figure 20 summarises these issues and generalises them above the individual case studies to emphasise the usability and user interaction with wearable, multimodal, and AR technologies. Many of the issues are not related to only one aspect of technology. However, the findings are unavoidably related to their use contexts and the generalisability is therefore limited. Further, some of the results arose in the future workshops, and therefore only reflect the technologies' potential. Detailed findings are shown in Appendix A.



RQ1

Benefits and concerns of emerging technologies

Wearable

+ Easy to use and learn to use
+ Easy to move while using the devices
+ Natural way to interact, hands-free, “device-free”
± Comfort, fit, weight, secure attachment of device and cables
- Challenges with distractibility and blockage of surroundings
- Fixed attachment to clothing delimits use
- Heat generated by devices or clothing
- Simulation sickness with HMDs
- Field of view and image quality of HMDs

Multimodal

+ Many information sources offer certainty
+ Redundancy if one modality is unusable
+ Haptic feedback can be used in darkness
+ Auditory feedback can target user’s attention
- Challenges switching between modalities and devices
- Challenges manipulating multiple devices
- Handling situations with modality conflicts or failures
- Quality of haptic technology limits its usefulness
- Audibility of auditory feedback in noisy environments

Augmented reality

+ Instructions are easy to understand
+ Instructions can show directions of movement
+ Language barrier can be lessened because of visual format of presentation
+ Supports user in navigation, object identification, and in avoiding dangerous areas
+ AR guidance enables working with little experience
- Challenges interpreting a symbol’s meaning
- Challenges interpreting where a symbol is pointing at
- Challenges with visibility and field of view
- Limited suitability of AR guidance to experienced personnel

Electronic information exchange

+ Information is easy to keep up-to-date
+ Faster access to data anywhere and anytime
+ Contacting people can be eased
+ Scheduling can be facilitated
± Enables less telephoning and person-to-person communication
- Maintaining up-to-date databases is laborious
- Access to network needed
- Challenges making information clear, easy to interpret and notice
- Challenges offering the right amount of information
- Data security and hacking concerns

W + MM

- Users can inadvertently couple their head and arm movements—notable with HMDs and gesture control
- Unergonomic body postures may go unnoticed in telepresence applications with HMDs and gesture control

W + AR + MM

+ Enables natural interaction and enhances immersion
± Immersion affects collaboration, communication and workflow within team

Figure 20. Generalised findings regarding user interaction with wearable, multimodal, and AR technologies examined in Research Question 1 (W=wearable, MM=multimodal, AR=augmented reality, EIE=electronic information exchange).

3.7.2 Technologies in the working context

Research Question 2 considered the work perspective of the adoption of the emerging technologies. The use contexts in the case studies were different, and therefore straightforward summaries cannot be drawn on the technologies' suitability and the change in work. There were some similarities, though, and many aspects are generalisable to other contexts as well.

In most of the case studies, the technologies were believed to be useful in the context of work. They could bring time savings, make work smoother, reduce the amount of manual work, facilitate work in both local and remote places, enable access to up-to-date information, and provide support for the workers. The AR guidance in maintenance, however, needs more consideration of its utility: novice users cannot be expected to completely rely on the system-provided guidance, whereas for experienced technicians, the guidance may be unneeded unless the maintenance cycle is long.

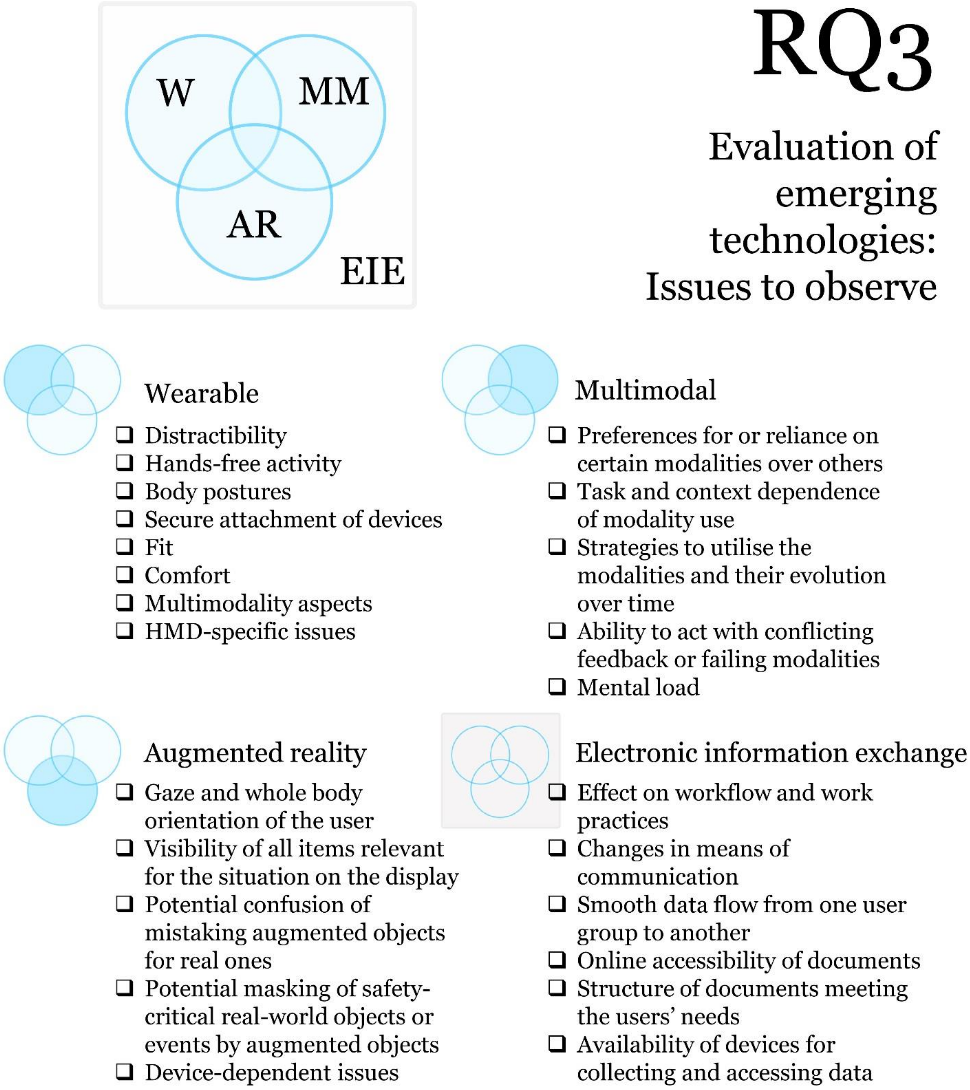
Regarding the suitability, there were issues with embedding the devices to the existing working conditions. For example, in the maintenance case, the existing protective gear, such as gloves and a helmet, and the confined environment, cause limitations. The cabling of the devices needs to be fitted unobtrusively to clothing. In a similar vein, the devices need to be robust enough to survive the usage environment: rough handling and varying indoor and outdoor conditions. The cleanliness of the environment and surfaces (e.g., touching displays and setting aside tablets or other devices) is a concern both in the context of maintenance and of surgery. Furthermore, the addition of technology can contradict the original intended benefit. For example, wearable technologies are often praised for its hands-free nature, but the addition of several wearable technologies may in fact increase the need to use hands to manipulate the devices.

In the studied cases, the work practices could also undergo a change although the core tasks are likely to remain the same. The digitalisation of the information and the electronic information exchange are the enablers for new work practices to emerge. Data can be accessed and updated faster and also forwarded to others, in which case there is less need to rely on paper-based materials. On the other hand, this requires that all stakeholders are committed to using the systems—and have equal access to it. For example, in the e-justice case, the information flow is disrupted if one party refuses to use the electronic systems, and in the maintenance case, somebody has to make sure that the AR guidance systems are up-to-date as the machines undergo changes. Moreover, with electronic information exchange, data security and hacking can become concerns.

The ways to communicate and the amount of communication can also change. In the maintenance case, the workers felt that communication with people would decrease as the information can be communicated directly via an information system. In the surgery case, sharing progress data on how a surgeon is operating a certain procedure could support a communal function among surgeons; on the other hand, bringing immersive technologies to the operating surgeon could block the surgeon from the rest of the operating staff in the operating theatre and change the communication and workflow. Finally, a change in the work practices takes some adaptation and will likely raise issues of acceptance.

3.7.3 Evaluation of emerging technologies

Research Question 3 considered the user evaluation aspects of the emerging technologies. Based on the methodological considerations elaborated in Studies I, III and IV, and the user issues collected in RQ1 and RQ2, a number of findings could be made. When examining interaction with wearable, multimodal, and AR technologies, and the underlying electronic information exchange, there are several issues that should be specifically observed, and these are collected in Figure 21. Additionally, some device-spesific issues and existing guidelines and relevant literature are presented below.



RQ3

Evaluation of emerging technologies: Issues to observe

Wearable
- ☐ Distractibility
- ☐ Hands-free activity
- ☐ Body postures
- ☐ Secure attachment of devices
- ☐ Fit
- ☐ Comfort
- ☐ Multimodality aspects
- ☐ HMD-specific issues

Multimodal
- ☐ Preferences for or reliance on certain modalities over others
- ☐ Task and context dependence of modality use
- ☐ Strategies to utilise the modalities and their evolution over time
- ☐ Ability to act with conflicting feedback or failing modalities
- ☐ Mental load

Augmented reality
- ☐ Gaze and whole body orientation of the user
- ☐ Visibility of all items relevant for the situation on the display
- ☐ Potential confusion of mistaking augmented objects for real ones
- ☐ Potential masking of safety-critical real-world objects or events by augmented objects
- ☐ Device-dependent issues

Electronic information exchange
- ☐ Effect on workflow and work practices
- ☐ Changes in means of communication
- ☐ Smooth data flow from one user group to another
- ☐ Online accessibility of documents
- ☐ Structure of documents meeting the users' needs
- ☐ Availability of devices for collecting and accessing data

Figure 21. Issues to observe in the evaluation of user interaction with wearable, multimodal, and AR technologies examined in Research Question 3 (W=wearable, MM=multimodal, AR=augmented reality, EIE=electronic information exchange).

The evaluation aspects related to wearable devices are very practical although multimodality can complicate the evaluation of the whole, because wearable devices are often used with other devices. Wearability guidelines including fit and comfort are described in Section 1.2.4. HMD-specific issues are important both in the context of wearable devices and augmented reality solutions. With augmented reality, tablets are often used. Device-specific issues are listed below.

HMD-specific issues:

- ☐ Visibility of information in different conditions
- ☐ Adequate quality of visual feed
- ☐ Field-of-view
- ☐ Simulation sickness and immersion issues (see Section 1.2.3) and their imposed changes to team interaction
- ☐ Physical ergonomics and body movements related to the users not being able to see their own body.

Tablet-specific issues:

- ☐ How do the users hold (see also Hoober, 2017) and tap the tablet while using AR or perform tasks
- ☐ Where do users place the tablet
- ☐ Can the tablet be used with gloves.

The task design of AR user studies can also support bringing forth the above-mentioned issues, for example, by including a variety of actions to be done while viewing the augmented information, e.g., manipulation of heavy or tightly attached objects, continuous adjustments and pauses for object or tool retrieval. Additionally, existing guidelines should support the design (Section 1.2.3).

The starting point to evaluate multimodality lies in recognising that a system is multimodal and accounting for it as early as the design of the user study. A user study can benefit from the following guidelines:

- Include a baseline, unimodal and multimodal conditions; the option for individual or parallel use of modalities; usage in a real use context
  - The literature in Section 1.2.2 aids in categorising the multimodal interaction
  - The evaluation of the multimodal functionality of a system instead of considering each modality separately can be challenging
- Questionnaires or items from existing literature can be used
  - Multimodality aspects, e.g., “The different input modalities are blocking/complementing each other.” and “The different input modalities are working poorly/well together.” described in MMQQ (Wechsung, 2014)
  - Logic on the system level (utility for task, concept of operation), e.g., “The system was operated in a way I would expect it to be operated.” (Savioja and Norros, 2013)
- Video data can be used for replaying the usage situation and performing post-trial analysis (see the data analysis station in Section 3.1.2, Figure 14).

4. Discussion

This section discusses the findings of this thesis. The discussion starts by considering the use of the emerging technologies in various work contexts, followed by the contributions of the case studies to research knowledge. Then, the limitations of the research methodology are considered. Finally, future research directions are outlined.

4.1 Technologies in work context

This thesis complements and builds on earlier findings on what we know about user interaction with emerging technologies. The issues addressed in this thesis are practical in nature and they are focussed on the technologies' expected everyday use. Specifically, this thesis brings the context of work to the table in good time as the technologies are emerging to the market (McWilliams, 2016; Sinha, 2016). There are still relatively few user evaluations of the emerging technologies in work contexts, and the design guidelines for these technologies are still evolving. Therefore, it is important to add to the understanding of the user aspects with these technologies in order to design suitable systems for workers. A thorough understanding also facilitates the system evaluation already in the early design stages so that at least the most disruptive problems can be eliminated before adoption into workplaces.

This thesis addressed several aspects of usability, including ease-of-use, usefulness, practicality and learnability. Acceptance and motivation to use the technologies, which are closely related to usability, were also brought up. Regarding work practices, issues of workflow, work culture, communication and team interaction were addressed as well. Issues regarding the use of wearable devices, such as fit, comfort, and aspects related to taking off and putting on a device and moving while wearing them were considered. Furthermore, image quality, field of view and camera orientation have an impact on the user, especially with the AR technologies and HMDs. Finally, with multimodal, wearable, and AR technologies, information presentation is a significant element, because it affects the ease of data interpretation as well as the mental load and disctractability of the technologies experienced by the user. Additionally, because the use of the technologies is based on electronic information exchange, safety and security cannot be neglected.

The technologies' usability and other user aspects influence the work in many ways. If the technologies suffer from poor usability, their benefits can be negated by the reluctance of the workers to take them into use, which can lead to their disuse. In the context of work, however, poor usability can sometimes be tolerated if the added value is sufficient. Especially in professional use, training can be used to mitigate some of the effects of poor usability, and if the workers use the technologies on a regular basis, they can adapt to the technologies' peculiarities. Obviously, these are not ideal solutions.

On the other hand, the work context also places other demands on the technologies besides its immediate usability. The workers need to be able to trust the systems and their functioning especially in safety-critical work contexts. For example, in military tasks such as reconnaissance, the users need to trust and rely on the system-provided information and its security—exposing the user to the opponent is unacceptable. Similarly, the use of the system should not add to the user's cognitive load as it can cause serious consequences.

Regarding the changes in the nature of work, the emerging technologies can unintentionally create more secondary tasks related to operating the technology itself, taking extra time although the intended benefit is typically to speed up work. Eventually, the technologies can change the way workers perform their main task, but this is difficult to estimate because the technologies are still developing. Following this line of thought, a future concern related to the ability of the emerging technologies to provide access to information everywhere may be the workers' dependency and reliance on the technologies in performing the work tasks. Related concerns include the skill degradation of traditional skills and the workers' ability to cope with situations when the technology fails.

Most of the findings presented in this thesis are practical in nature as they are grounded in user studies. Several groups of people can benefit from these results. Firstly, the future workers who may eventually be using these technologies in their everyday work will benefit from solutions that are easy to use and support their work tasks. Secondly, the findings can help employers understand the technologies' opportunities and estimate their suitability for work, and also raise awareness of the concerns related to their use. Thirdly, the findings exemplify the current state of these technologies from the user perspective and give an impression of what can be expected in the future, which can be of interest to the public and to society in general. Finally, the results will support researchers working on user interaction and technical development. The summary of results in Section 3.7 offers a good starting point for the familiarisition of the user aspects related to these emerging technologies. The results influence several research areas, including AR and robotics, and especially the design and evaluation of user interfaces and usability.

4.2 Contributions to research knowledge

This section describes the contributions this thesis makes to the existing research regarding the user interaction with emerging technologies and the evaluation of the user's perspective. New issues were raised especially concerning multimodal interaction, both in terms of using multiple sensory modalities and handling devices while simultaneously operating on other objects. In general, the novelty of these user studies is the evaluation of the technologies in the context of work. The contributions of the case studies are positioned under the three research themes reviewed in Section 2: digitalisation of information flow, guidance using wearable and AR systems, and robot teleoperation. A detailed discussion of the results can be found in the case study articles.

4.2.1 Research on digitalisation of information flow

Digitalised information and electronic information exchange are prerequisites for sharing information and using emerging technologies. In this thesis, digitalisation and knowledge transfer were examined especially in Study VI: E-justice, but they were also clearly the enablers for the concepts researched in Study II: Wearable maintenance.

The domain of Study VI, judicial administration, was the most conservative one included in this thesis. At the time the study was done, the domain was—and seemingly still is—struggling with digitalisation and the use of electronic documents. For the judicial domain, video conferencing was still considered an emerging technology. Therefore, it is not surprising that the state-of-the-art technologies presented to the study participants were of secondary importance to functioning electronic information exchange. Although the work itself was not expected to change, electronic documents and videoconferencing would enable working anywhere—similar to the promises of using wearables in other domains (Study II). With videoconferencing in the judicial administration, however, there are concerns about the video quality and the ability to reliably evaluate person's statemets via video (cf. sense of presence mentioned by Wiggins, 2006).

One of the important findings of this thesis is the understanding that the electronic information exchange—regardless of the technologies and interfaces that make if available—is a requisite for enabling work to take place anywhere and anytime. In addition, to enable that, the needs of all stakeholders using the system have to be taken into account in the technology development, as acknowledged in the research domains of e-justice (Gole and Shinsky, 2013; Lupo and Bailey, 2014; The European Commission for the Efficiency of Justice (CEPEJ), 2016) and maintenance (Anastassova et al., 2005; Lukowicz et al., 2007; Bottecchia et al., 2009; Aromaa et al., 2015; Wang et al., 2016).

4.2.2 Research on guidance using wearable and AR systems

An appealing application area of wearable devices and AR systems is guidance. In this thesis, guidance was examined in navigation support (Study I: Soldier navigation), and in maintenance work (Study II: Wearable maintenance and Study III: Tablet-guided maintenance).

The use of wearables in navigation support is appealing because it frees the user's hands and can offer advantages in cognitively demanding situations. The results of this thesis support earlier findings on using wearables for navigation support, for example, the ease of using the tactile modality (Kumagai et al., 2005; Eriksson et al., 2008; Elliott et al., 2010), the simplicity of visual arrows (Elliott et al., 2010), and low mental workload for wearables (Kumagai et al., 2005; Elliott et al., 2010; Calvo et al., 2014). Additionally, other researchers in this area have also raised the issues of the fit and integration of equipment (Eriksson et al., 2008; Calvo et al., 2014), information overload related to multimodality (Streefkerk et al., 2012), and the issue of the modalities complementing each other (Elliott et al., 2010). New issues regarding user interaction were mainly raised concerning multimodal use: the certainty and smoothness provided by redundant modalities, the possibility for information conflicts, and the difficulty of focusing on multiples devices simultaneously. To the best of my knowledge, Study I is the first report on using trimodal—visual, auditory and tactile—feedback for helping a user navigate in the field. Earlier trimodal studies have been done using simulated or game environments, which is also the case for most of the unimodal and bimodal studies. Therefore, Study I provides an important addition to what is known about the use of wearables in field conditions. Finally, in addition to employing diverse data collection and evaluation methods, the study suggested methodological improvements on how multimodal, wearable systems should be evaluated in the future, building on the work by Elliott et al. (2010), Mynttinen (2010) and Wechsung (2014). The developed data analysis station was illustrated in Section 3.1.2 (Figure 14).

In the maintenance domain, it seems that there exist only a few studies on wearables in industrial work (Lukowicz et al., 2007; Pasher et al., 2010), and there is an acknowledged lack of user studies regarding AR (Nee et al., 2012; Wang et al., 2016). Therefore, the inputs of this thesis regarding maintenance work (Studies II & III) are especially relevant for future work in the maintenance domain.

Study II targets the gap of field user studies concerning the use of wearables and AR in industrial maintenance. The findings of the study supported those of others regarding the wearability, ergonomics and field of view of HMDs (see review in Wang et al., 2016), robustness of devices for work (Pasher et al., 2010; Zheng et al., 2015a), the intuitiveness of AR guidance (e.g., Henderson and Feiner, 2011), and the enabled access to up-to-date documents (Siegel and Bauer, 1997). On the other hand, new aspects were brought up regarding the multimodal use of wearable technologies actually requiring the users to use their hands more for manipulating the devices (wearables are typically assumed to enable hands-free work (Bottecchia et al., 2009; Chimienti et al., 2010; Zheng et al., 2015a, 2015b)); the capability to use the devices while wearing gloves; the question of the usefulness of AR guidance for experienced technicians (cf. adaptive instructions in Funk et al., 2015); the potential of AR to lower the language barrier; and the effects of everywhere-access to information on team interaction and communication.

Study III confirmed others' findings that AR guidance enables inexperienced users to perform maintenance tasks (Ong et al., 2008; e.g., Henderson and Feiner, 2011; Zheng et al., 2015a). However, very few studies have reported on the qualitative aspects of how tablets are used in AR guidance tasks. It seems that the few existing user studies have focussed on comparisons between various displays for AR guidance, or they are primarily technical in nature. Taking a very practical approach, Study III reported how a user holds a tablet while simultaneously performing a maintenance task and how the tablet affects the user's visual view of the task, complementing and adding to the work of several authors (Grasset et al., 2007; Henrysson et al., 2007; Hoober, 2017; Veas and Kruijff, 2008; Zheng et al., 2015a). In Study III, suggestions for using auditory cueing and symbols to support the work were made. Additionally, suggestions for improving the user study design and evaluation were given, extending the work by Dünser et al. (2007), Ko et al. (2013), Re and Bordegoni (2014), and Santos et al. (2015).

4.2.3 Research on robot teleoperation

In telerobotics, a lot of effort is currently being put into the technical development of the robots and their interfaces. Despite the efforts to improve individual aspects of interaction such as haptic feedback, it seems that the user experience and the whole interaction that happens between the human and the robot have not been the focus of research. This thesis tackled the human factors related to robot teleoperation in two different setups: teleoperation of a mobile robot (Study IV: Space telerobotics) and a surgical robot (Study V: Robotic surgery).

In the teleoperation of mobile robots, the results of Study IV support earlier findings on the intuitiveness and ease of using wearables (Boudoin et al., 2008; Fernandes et al., 2014; Jankowski and Grabowski, 2015) and gestures (Brice et al., 2010). Although Boudoin et al. (2008) briefly mentioned that natural interaction could be supported by combining multiple interfaces, it seems that this is the first study that brings forth the issue of the multimodal nature of interaction using HMDs and wearables for teleoperation. Overall, earlier studies using wearables for teleoperation are mainly technology-oriented and few studies have reported and elaborated on the user aspects at all—with the exception of four studies (Kechavarzi et al., 2012; Fernandes et al., 2014; Livatino et al., 2015; Zareinia et al., 2015). The results of Study IV suggested that the sensitivity of the data glove should be improved—as is the case of the haptic feedback reported in (Randelli et al., 2011; Livatino et al., 2015)—and that the field of view was small as mentioned by Livatino et al. (2015). New findings reported in Study IV included practical observations regarding the difficulty of determining the steering direction while wearing the HMD (cf. usability guidelines to display the robot's body in the interface by Adamides et al., 2015), and the inadvertent coupling of the user's arm and the head movements (cf. holding gaze at target by Brice et al., 2010). Regarding the robotics research community, the findings raise awareness of the user aspects related to wearability and multimodality and offers practical methods for examining and evaluating them.

To the best of my knowledge, Study V is the only study examining human factors related to a range of future technologies in robotic surgery. In robotic surgery, the discussion of future technologies is mainly focussed on technological development, economic and feasibility-related issues, and the possibilities for improving the operation outcome. In general, user experience has not attracted much attention in the research field, although a multidisciplinary approach has been called for by several experts (Camarillo et al., 2004; Taylor, 2007; Marcus et al., 2013; Marescaux and Diana, 2015). Regarding user interaction, Study V raised issues similar to those suggested by others, such as ergonomics (e.g., Van Der Schatte Olivier et al., 2009) and haptic feedback (e.g., Okamura, 2004), but this study also positioned these and other issues into the operating theatre of the future. Therefore, the findings of this thesis support the whole robotic surgery community in understanding the user needs and the potential of the emerging technologies to support surgeons in their future work.

4.3 Limitations of research

This section discusses the methods and research settings of the case studies and this thesis. The research methods of the case studies are widely used in qualitative user research. However, the methods used in human-centred design each have their problems, affecting the reliability and validity of the results through a number of biases. Reliability refers to the consistency of how well the same results can be reproduced. Validity relates to the method used for obtaining results being appropriate for its task.

Questionnaire answers can be rushed or reserved (Stanton et al., 2013). They can also suffer from social desirability, meaning that the participants answer in a way that they expect to be pleasing to the researchers. The validity of interview results is difficult to determine, and the quality depends on the skill of the interviewer and the quality of the interviewee (Stanton et al., 2013). The interviewers may influence the interviewees, for instance, using a certain tone of voice or phrasing of the questions (Sharp et al., 2007). Similarly, observations can suffer from analyst bias or participant bias (Stanton et al., 2013). The analyst can interpret the results in a biased way, or the participant's actions may be affected because they know they are being observed. Similar biases affect the analysis of focus groups and future workshops. The methods and research settings of the case studies are each discussed in further detail in the articles and also partially in the case studies' contribution regarding the third research question.

The results of this thesis are not meant to be a comprehensive list of issues that concern these emerging technologies, but as they are collected in several studies both in the laboratory and in the field, they offer a strong and varied starting point and extend existing knowledge. On one hand, the benefit of the laboratory studies of this thesis is that they are easier to reproduce, and therefore they offer better reliability than field studies. On the other hand, the field studies have better ecological validity (i.e., how the test environment influences the results (Sharp et al., 2007)) and they have raised many issues that might have gone unnoticed in laboratory conditions. The field studies also show the real need for the technologies studied in the actual usage environment.

The small number of participants in the case studies affects the generalisability of the results negatively. However, as has also been mentioned by others (Pasher et al., 2010), getting hold of the real users is challenging because their effort is required in the workplace. Furthermore, most of the technologies included in the studies have been either demonstrators, prototypes or even concept-level ideas, and therefore adding a larger sample of participants might not have added more information at this level of technological maturity. The low level of maturity also means that the evaluations of the suitability of the technologies to work are based mainly on brief trials with prototypes, or purely concept-level ideas, instead of fully functional tools and also on the workers' estimates reflected against their knowledge of the work requirements. The data collected in the form of questionnaires—which could have carried more weight at higher technology-readiness levels and with larger numbers of participants—were interpreted mostly in a qualitative manner, and refined and complemented by data collected with other methods such as interviews. On the other hand, the underside of collecting qualitative data from long-term studies with large numbers of participants is that the data processing becomes labourious and time-consuming.

In general, the user studies concentrated on the evaluation part of the iterative cycle of human-centred design (ISO, 2010) as was shown in Figure 1. As is the case with many studies where emerging technologies are used, a lot of the research effort goes to tackling the technologies themselves, and therefore, at this level of technological maturity, the user aspects have unfortunately been secondary to those of hardware development. Ideally, the technology development would go hand-in-hand with the user needs, starting already in the early stages. In order to make final solutions that meet the users or workers' demands, the human-centred design cycle also needs to be iterated several times.

Finally, the decision to classify many different technologies under the wearable, multimodal, and AR aspects in this thesis deserves a word of explanation. There were three main reasons for this approach. Firstly, there were the obvious characteristics, such as some devices being wearable or implemented using AR technologies. Secondly, these three aspects emerged naturally during the analysis of the case studies. In a way, they describe different approaches to enriching and adding to the experienced reality through technology. Another person could have chosen them differently, for example, by considering the types of feedback or interfaces, or mobility. The chosen selection, however, supported the evaluation aspect as well as the usability aspects. Thirdly, many technologies were "lumped together" for the sake of simplicity. For example, "AR" is only a narrow strip of the virtual reality continuum (Figure 5), but the term was used rather broadly here, although with a focus on the visually displayed information. Similarly, "multimodality" can also be distinguished in at least two ways depending on the types of inputs and outputs. It would have been tedious to write (and read) long explanations at every turn. Overall, the three aspects provided a framework under which it was easier to discuss the evaluation methods needed for these emerging technologies.

4.4 Opportunities for future research

Emerging technologies are, by definition, on the verge of being adopted into general use. Before that can happen, however, there is still work to be done in making sure the technologies answer the users' and future workers' needs, for which more user studies—using human-centred design principles—will be required. In determining the usefulness and suitability of the emerging technologies in various contexts of work, more research is needed in the long term, because the work itself evolves as new technology is taken into use.

Regarding the technology discussed in this thesis, multimodality is an aspect that will be encountered almost inevitably when considering wearables and AR technologies. Therefore, it would be important to recognise if a system has multimodal characteristics—already in the early design phases—so that it does not come as a surprise when the users interact with the system, and so that these characteristics can be optimally benefited from. The adaptation of multimodal systems to the use context (Dumas et al., 2009; Kong et al., 2011) is an intriguing research direction both from the technological and the user perspective.

With wearable technologies, finding the optimal combination of several devices and the integration of the technology into clothing are questions for the future. The HMDs studied in this thesis are still somewhat clumsy, but the newest models (such as the Hololens in Figure 7b) can improve the possibilities of using AR in the context of work. More user research on AR is needed in general, and in the context of work, in determining for whom the AR guidance should be targeted. Furthermore, AR and immersion can also affect workers other than those using the technology, which is why effects on team interaction need to be taken into account as well.

In general, it seems that in the future, information will be accessible anywhere and anytime, which is supported by wearables and AR technologies. In an unfortunate yet plausible scenario, the technologies can end up offering information that is distracting, or force us to multitask. Alternatively, they can support us by offering just the right amount of relevant, context-sensitive information. Along this line of development, the idea of objects in the environment functioning as a part of the human mind—termed *active externalism* by Clark and Chalmers (1998)—gains ground. As the wearables and gesture interaction were seen in the film *Minority Report*—described in the Introduction—science fiction has also envisioned a future where the mind is divided between the physical environment and the Internet (Stross, 2005). On one hand, technologies offer a huge potential for supporting the data processing humans are capable of, but on the other hand, the further along this coupling with the technology goes, the larger the risks become if the technology fails when we have accustomed ourselves to relying on it. Therefore, in considering the future work and humans' role in it, one of the important aspects to study is how we humans change our way of thinking and acting as the technology evolves.

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Appendix

Appendices A1–A6. Detailed findings of case studies I–VI, respectively. The findings are sorted into pros and cons and characterised using the technological aspects (MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange). The characterisations mainly refer to the findings and their contribution to the whole, not to the technology itself. Additionally, the column “User aspect” suggests how each finding relates to the user perspective.

Appendix A1

Study I: Soldier navigation. Detailed results.
(MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange)

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Navigation system; whole system				✓	✓	✓	✓
	+	The system was considered easy to learn	Learnability		✓	✓	
	+	Navigation was smoother multimodally than unimodally	Information presentation	✓	(✓)		
	+	Many information sources provide certainty	Information presentation	✓			✓
	+	The system provides distance information	Information presentation				✓
	+	No need to read paper map	Information presentation				✓
	±	Should be easily put on and taken off	Wearability		✓		
	-	Attachment of cables is problematic	Wearability		✓		
	-	Unsuitable for moving in terrain	Wearability	(✓)	✓		
	-	Easier to focus on one device at a time	Mental load	✓	✓		
	-	Potential information conflicts if feedback through different modalities is unsynchnorised or input manually	Information presentation	✓			✓
	-	Battery drainage and power supply to devices	Practicability	(✓)	(✓)		
Navigation system; visual modality (Sub-study 1)					✓	✓	
	-	Limited visual field due to glasses	Image & view		✓	✓	
	-	The instructing arrow disappeared from the field of view	Image & view		(✓)	✓	(✓)
	-	Non-ergonomic fit	Wearability		✓		
Navigation system; visual modality (Sub-study 2)					✓	✓	
	+	The device helped with navigation	Practicability		(✓)		✓
	+	Easy to interpret information	Information presentation		(✓)		✓
	+	Low mental workload when navigating in terrain	Mental load	(✓)	(✓)		(✓)
	-	HMD problematic for comfort	Wearability		✓	(✓)	
	-	HMD was too big	Wearability		✓	(✓)	
	-	Difficulties with moving while wearing the HMD	Wearability	(✓)	✓		
	-	Limited visual field due to glasses	Image & view		✓	✓	
	-	The device is distracting	Mental load	(✓)	✓	✓	
	-	HMD forces users to divide attention between multiple things	Mental load	✓	✓		(✓)
	-	Abundance of information can hamper environment monitoring	Information presentation Mental load		(✓)	✓	✓
Navigation system; auditory modality					✓		
	+	Easy-to-interpret information	Information presentation		(✓)		✓
	+	Clear and easy-to-notice voice	Information presentation	(✓)	(✓)		(✓)
	+	Device provides distance information	Information presentation				✓
	+	Low mental workload when navigating in terrain	Mental load	(✓)	(✓)		(✓)
	-	Headphones problematic for comfort	Wearability		✓		

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Navigation system; auditory modality *(cont.)*	-	The device is distracting	Mental load	(✓)	✓		
	-	The device blocks surrounding sounds	Mental load	(✓)	✓		
	-	Cardinal directions were confusing	Information presentation	(✓)			✓
Navigation system; tactile modality					✓		
	+	The device helped with navigation	Practicability		(✓)		✓
	+	Easy-to-use	Usability		✓		
	+	Easy-to-interpret information	Information presentation		(✓)		✓
	+	Easy-to-notice information	Information presentation	(✓)	✓		(✓)
	+	Lightweight	Wearability		✓		
	+	Easy to put on and take off	Wearability		✓		
	+	Device is suitable for use while moving	Wearability Practicability	(✓)	✓		
	+	Convenient, also in the dark	Practicability	✓	✓		
	+	The device is not distracting	Mental load	(✓)	✓		
	+	Low mental workload when navigating in terrain	Mental load	(✓)	(✓)		(✓)
	-	Cables should be attached firmly to support moving in all terrain	Wearability Practicability		✓		
	-	Difficulty in knowing how much to turn	Information presentation		(✓)		✓

Appendix A2

Study II: Wearable maintenance. Detailed results.
(MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange)

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Wearable system for maintenance				✓	✓	✓	✓
	+	Adoption of the wearable system could ease and have a positive impact on work	Practicability		✓		
	+	Easy to learn to use	Learnability	✓	✓		
	+	The role and linkages between each device are easy to understand	Usability	✓	(✓)		(✓)
	-	Novice technicians cannot rely solely on the system-provided guidance	Information presentation Practicality				✓
	-	Instructions are useless for experienced technicians	Practicability			(✓)	✓
	-	Possibility for decreasing amount of communication with other people	Cooperation				(✓)
	-	Switching devices during use is challenging	Usability	✓	✓		
	-	Difficult to remember whether to use the smartwatch or the smartphone	Usability	✓	(✓)		
	-	Due to the number of devices, the use of the system was slightly complicated and interfered with working	Usability Work culture	✓			
	-	Slower work due to the need to change between devices during the task	Practicality Work culture	✓	(✓)		
	-	Amount of hands-free working was decreased; a possible safety issue in the work environment	Practicability Safety	✓	✓		
Smart glasses					✓	(✓)	
	+	Easy to use	Usability		✓		
	+	A positive user experience of the gesture-based interaction	Usability	(✓)	✓		
	+	Ability to take photographs was evaluated to be good	Practicability				✓
	-	Impractical to take off a protective helmet where the smart glasses were attached; display not available without the helmet	Practicability Image & view		✓	(✓)	
	-	Difficulties in taking photographs in small confined spaces due to the camera being attached to a helmet	Practicability Image & view		✓		
	-	Difficulties in taking photographs because of the requirement to use two devices simultaneously; pressing the camera button on the smartwatch and keeping the target visible in the smart glasses	Usability Image & view	✓	✓		
	-	Difficulties in remembering the position of the buttons on the smart glasses	Usability		✓		
Smartwatch					✓		
	+	Easy to use and easy to recover from mistakes	Usability		✓		
	-	The watch easily slid under the work glove concealing the screen	Practicability Image & view		✓		
Smart phone							✓
	+	It was easy to insert short comments on reports and read them from the smartphone afterwards	Usability				(✓)

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Smart phone *(cont.)*	-	Problematic access to device because it had to be taken from a pocket and gloves needed to be removed.	Practicability		(✓)		
Tablet-based AR system for maintenance						✓	✓
	+	Usefulness for early work career	Practicability			(✓)	✓
	+	Usefulness for experienced technicians when the maintenance cycle is long	Practicability			(✓)	✓
	+	The use of the system could have a positive effect on maintenance work	Practicability			✓	(✓)
	+	Electronic AR instructions easier to keep up-to-date than paper-based instructions	Information presentation			✓	✓
	+	Easy to use	Usability			✓	
	+	Easy to learn to use the system after some initial training	Learnability			✓	(✓)
	+	The system gave instructions well; it was clear what the user was required to do	Information presentation			✓	(✓)
	+	The symbols were easy to understand	Information presentation			✓	(✓)
	+	Visual instructions suffer less from language barrier	Information presentation			✓	(✓)
	+	The instructions showed in which direction to do things (e.g., twist a screw); 3-D pictures were also considered good	Practicability			✓	✓
	+	No considerable drawback experienced due to the need to use both hands and to stop work when holding the tablet	Practicability			(✓)	
	±	Electronic data bases easier to keep up-to-date but due to the rapid changing of engine parts, the realisation of updates is questionable	Practicability			(✓)	✓
	±	Change in work practices due to less telephoning and communication	Cooperation Work culture			✓	✓
	-	Reservations for using or needing the system in the future	Practicability			✓	✓
	-	Disturbed workflow due to unfamiliarity of using the system in everyday work	Workflow			(✓)	(✓)
	-	System-provided maintenance instructions contained a mistake	Information presentation			(✓)	✓
	-	Too sensitive for the work environment; questionable robustness	Practicability			(✓)	
	-	Gloves need to be taken off when using the system	Practicability			(✓)	
	-	Confusion over how to hold the tablet	Practicability			(✓)	

Appendix A3

Study III: Tablet-guided maintenance. Detailed results.
(MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange)

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Tablet-based AR guidance; visual instructions						✓	
	+	No prior experience is required for successfully completing a task	Practicability			✓	✓
	-	The device needs to be handheld; putting it on a desk is not practical because feedback is provided through the tablet	Practicability			✓	
	-	Tapping a text box while holding the device is awkward	Practicability			✓	
	-	Manipulation of physical objects awkward while viewing the scene through the tablet	Usability Practicability			✓	
	-	Two hands used for getting a better view of overall situation or a better angle by tilting	Practicability Usability Information presentation			✓	(✓)
	-	Instructions are not always shown in the field of view	Image & view			✓	
	-	Confusion over the visual symbol; interpretation of its meaning or the position it is pointing at	Usability Information presentation			✓	✓
Tablet-based AR guidance; auditory feedback				(✓)			
	+	Audio beeps can target the users' attention even in noisy conditions	Mental load	(✓)			
	-	Environmental noise masks the auditory feedback	Mental load	(✓)			
Virtual rock crusher				✓		✓	
	+	Brings realism to the scenario: the rock crusher masked the auditory feedback (beeps)	Practicability	✓		✓	
	-	Model largely ignored by the (non-professional) participants	Practicability	(✓)		✓	

Appendix A4

Study IV: Space telerobotics. Detailed results.
(MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange)

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Control system				✓	✓	✓	✓
	+	Natural way to operate using the wearable interface	Usability	(✓)	✓		
	+	Feelings of presence and immersion during the task	Usability	(✓)	✓	✓	
	-	Mismatch between the image shown in the centre of the HMD and the robot's heading direction causing misguided navigation	Information presentation Image & view	✓	✓	✓	
	-	Undesired coupling between head and arm movements; users turned their head toward the direction of the arm movement; users' arm is invisible due to HMD	Usability Image & view	✓	✓	✓	
	-	Awkward postures with head and arm; head positioned in the "right armpit" due to view on HMD and control movement	Wearability	✓	✓	(✓)	
Data gloves and gestures					✓		
	+	Operating without a medium	Usability	(✓)	✓		
	+	Easy to move with	Wearability	(✓)	✓		
	+	Lightweight, soft	Wearability		✓		
	-	Control modes are difficult to remember	Usability	✓	✓		
	-	Haptic feedback for object manipulation suggested to improve accuracy	Usability	✓	✓		
	-	Uncomfortable and wide arm trajectory; elbow support not provided	Wearability	(✓)	(✓)		
HMD					✓	✓	
	+	Moving the camera using head movements; orientation with respect to user's body	Image & view	(✓)	✓	✓	
	+	Clear view to surroundings	Image & view		✓	✓	
	+	Adequate resolution	Image & view		✓	(✓)	
	+	Realistic transmission delay	Practicability		✓	(✓)	(✓)
	+	Comfortable, not heavy, nice fit	Wearability		✓		
	-	Difficult position estimation; robot arm is not shown on screen at all times	Image & view	(✓)	✓	✓	
	-	Depth vision missing	Image & view	(✓)	✓	(✓)	
	-	Small FOV and poor perspective	Image & view		✓	✓	
	-	Poor image quality	Image & view		(✓)	(✓)	
	-	Long image delay	Practicability		✓	(✓)	(✓)
	-	Neck pain due to posture	Wearability	✓	✓		
	-	HMD not securely attached	Wearability		✓		

Appendix A5

Study V: Robotic surgery. Detailed results. The numbers in parenthesis (#) refer to the numbering of the technologies in the respective article.
(MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange)

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Wearable, haptic interaction technologies				✓	✓	✓	**(✓)**
Head-mounted display (#4)				✓	✓	✓	
	+	The robot control is improved because the camera follows natural head movements	Usability	✓	✓	(✓)	
	-	Workflow, interaction and communication between staff members need to be rethought if one person is immersed	Workflow Cooperation		✓	✓	
	-	Team awareness is a concern if only one person is immersed	Cooperation		✓	✓	
	-	Simulation sickness is a concern	Wearability		✓	✓	
	-	Potentially compromised ergonomics; the stationary support provided by the stereo display of the currently used robotic console is not available with HMDs	Wearability		✓	(✓)	
Haptic feedback to motion controls (#7) or to a body part (#8)				✓	✓		
	+	Haptic feedback would improve tissue identification and therefore improve patient safety	Safety Practicability	✓			
	+	Haptic feedback could aid in learning about the qualities of different tissues and in learning how to operate the robot	Learnability	✓			(✓)
	+	The movements of the surgeon's hands could be directly mapped to the robotic instruments and electronic discharges could be transmitted to the surgeon when encountering a nerve.	Usability	✓	✓		
	-	Potential conflict between the visual image and haptic feedback problemetic	Information presentation	✓			✓
	-	Problematic if haptic feedback would cease to function during surgery	Practicability	✓			(✓)
	-	Appropriate level of realism likely unachievable in the near future	Practicability	(✓)			
Augmented and overlaid images on the robot's video feed						✓	**(✓)**
Virtual "no-go" zones (#11) Leaving landmarks on image (#19)						✓	
	+	Possibility to block the robot's instruments from entering a zone or visually mark areas where extra precaution is needed; improved safety	Practicability Safety			✓	(✓)
Drawing on the video image (telestration) (#15)						✓	
	+	Telestration could support teaching	Learnability			✓	
	-	The lines drawn over image are not fixed to the site and thus they are meaningless if the camera is moved	Practicability			✓	

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Drawing on the video image (telestration) (#15) *(cont.)*	-	Telestation is impractical in the operating theatre because the drawing surface in nonsterile	Practicability			✓	
General 3D-model of internal organs (rotatable, overlayed on video image) (#21)						✓	(✓)
	+	A 3-D model could support learning	Learnability			✓	(✓)
	-	The 3-D model is not helpful if the patient has atypical anatomy	Practicability			✓	(✓)
Displaying patient's pre-imaged anatomy and nerves (#22, #23, #26)						✓	
	+	Visualisation of the location of nerves could facilitate the operation in sensitive areas	Practicability Safety			✓	
	+	Supports tissue identification, faster operations and less complications; improved safety	Practicability Safety			✓	
	+	Supports improving surgical outcome	Practicability			✓	
	+	Supports coping with individual anatomical differences of the patients	Practicability			✓	
	-	Use of technologies can increase the operating time although it may be worthwhile	Practicability Workflow Safety			✓	
Computational methods for supporting surgery					✓	✓	✓
Comparison data and advice during operation (#12)							✓
	+	Support for learning to suture or perform other procedures with a minimum amount of movements	Learnability				✓
	+	Possibility to alert the surgeon if an ongoing operation proceeds in a radically different manner than a computationally average operation; improved safety	Safety				✓
	+	Comparison of performance to earlier operations could act as a motivational factor for improving performance	Work culture				✓
	+	Sharing information could support a communal function	Cooperation Work culture				✓
Rewind (#17)						**(✓)**	✓
	-	Potential danger if the user does not realise the system is displaying non-real-time video instead of direct video feed	Practicability, Safety			✓	(✓)
Imperceptible motion amplification (computational) (#25)						✓	✓
	+	Visual display of pulsatile motions (veins) can facilitate the prevention of blood loss	Practicability Safety			✓	(✓)
	-	Potential danger in displaying non real-time video if not properly indicated to and comprehended by the surgeon	Practicability Safety			✓	(✓)
Electronic information exchange							✓
	-	Data security and hacking are future concerns	Safety				✓

Appendix A6

Study VI: E-justice. Detailed results.
(MM=multimodal, W=wearable, AR=augmented reality, EIE=electronic information exchange)

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Information systems, case management systems							✓
	+	Enabler for new work practices	Work culture				(✓)
	+	Amount of manual work would be reduced due to electronic information exchange between parties	Workflow Practicability				✓
	+	Automated systems replace some of the assistants' work; Assitants' role shifts to assisting with ICT	Workflow Work culture				✓
	+	Up-to-date contact information in registers saves time and manual work	Workflow Practicability				✓
	+	Clear cases can be forwarded in an accelerated manner	Workflow Practicability				(✓)
	+	Automated forwarding of cases or electronic material to assistants and prosecutors	Workflow Practicability				✓
	+	Swift browsing and easy access between interlinked documents	Workflow Practicability				✓
	±	The databases need to be remotely accessible and online work is required	Practicability				✓
	-	Resistance to adopting new practices; the culture of doing things "my way" is strong in judicial administration	Work culture				(✓)
	-	Refusal and disuse of new systems among older generations	Work culture				(✓)
	-	Cautious expectations due to earlier IT system reforms	Usability Work culture				(✓)
	-	All parties need to have corresponding means to access the systems	Workflow				(✓)
	-	Defendant's counsel does not have access to the database	Workflow				✓
	-	The progress of court sessions is dependent on the most "old-fashioned" party	Workflow Practicability				(✓)
Electronic documents							✓
	+	Documents have clear structure and interactive links for effective work, and could have smart attributes to them	Usability Workflow				✓
	+	Document templates enable handling multiple plaints concerning one defendant	Workflow				✓
	+	Sufficient number of displays enables working on several documents simultaneously	Practicability Workflow				(✓)
	+	Personal notes can be added to personal copies of documents	Practicability				✓
	-	Due to the independence of the judiciary, the structure of the electronic documents likely does not please all parties	Work culture				(✓)
Electronic calendars							✓
	+	Booking rooms and personnel are facilitated by visually displayed availability of each party	Usability Work culture				✓
	+	An overlapping view of several calendars facilitates the assistant's scheduling task	Usability				✓

Technology	+/-	Finding or comment	User aspect	MM	W	AR	EIE
Electronic calendars *(cont.)*	-	Separate calendar systems for rooms and persons cause extra work for assistants	Practicability				(✓)
	-	Only localised access to calendars causes disuse	Practicability				✓
	-	Defendant's counsel is not included in the system and has to be contacted manually	Workflow				✓
Electronic information exchange							**✓**
	+	Assistants can send summons, etc. to parties electronically	Workflow				✓
	+	Automated case distribution takes into account the prosecutor's task load	Mental load Workflow				✓
Video conferencing				**(✓)**		**(✓)**	**✓**
	+	Video conferencing eliminates some need for travel by interpreters, experts or even prosecutors	Practicability			(✓)	✓
	+	Preparation for trial can be done in an office room	Workflow Work culture			(✓)	✓
	-	The evaluation of defendant's statements is difficult via video connection	Image & view Practicability			✓	(✓)
	-	Current legislation does not enable remote participation	Practicability Work culture			(✓)	(✓)
Court room technology				**(✓)**			**✓**
	+	A wireless network ensures access to information systems and paper files are not needed	Practicability				✓
	+	Extra displays enable examining evidence and plaints	Practicability	(✓)			(✓)
	-	High-tech was of secondary importance to the participants	Practicability Work culture				(✓)
	-	The costs of new technology is high	Practicability				(✓)

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Working life is undergoing a gradual change from using computers to devices that enable access to information anywhere and anytime. From the user perspective, however, the introduction of new technologies has often been difficult, and yet we are now facing an abundance of emerging technologies whose suitability for work is not known.

The six user studies of this thesis examine the usability of emerging technologies and their suitability for work in the context of navigation, maintenance, telerobotics, robotic surgery, and e-justice in courts. The emerging technologies cover wearable, multimodal and augmented reality solutions, and the underlying electronic information exchange.

This thesis offers a collection of practical user aspects that need to be considered when designing, developing and adopting these technologies at workplaces. Additionally, suitable user evaluation approaches are suggested for these technologies. The results will facilitate designing future technologies with the user's best interests in mind.

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