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

DOCTORAL
DISSERTATIONS

Aalto University

Errata

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Usability of emerging technologies: user studies with wearable, multimodal and augmented reality solutions
School of Science
Aalto University publication series DOCTORAL DISSERTATIONS 139/2018
Date of Errata: August 9, 2018

Preface, page 2, line 6

The names should read as follows: Mika Hakkarainen, Petri Honkamaa, and Charles Woodward.

Aalto University publication series
DOCTORAL DISSERTATIONS 139/2018
VTT SCIENCE 181

Usability of emerging technologies

User studies with wearable, multimodal and augmented reality solutions

Iina Aaltonen

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Science, at a public examination held at the auditorium F239a of the school on 17 August 2018 at 12.

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Aalto University publication series
DOCTORAL DISSERTATIONS 139/2018

VTT SCIENCE 181

ISBN 978-952-60-8102-1 (printed)
ISBN 978-952-60-8103-8 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-8103-8

ISBN 978-951-38-8658-5 (printed)
ISBN 978-951-38-8657-8 (pdf)
ISSN 2242-119X (printed)
ISSN 2242-1203 (pdf)
http://urn.fi/URN:ISBN:978-951-38-8657-8

Unigrafia Oy
Helsinki 2018

Finland

NORDIC ECOLABEL
441 697
Printed matter

A? Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Iina Aaltonen

Name of the doctoral dissertation
Usability of emerging technologies: user studies with wearable, multimodal and augmented reality solutions

Publisher School of Science

Unit Department of Neuroscience and Biomedical Engineering

Series Aalto University publication series DOCTORAL DISSERTATIONS 139/2018

Field of research Cognitive Science

Manuscript submitted 2 March 2018 **Date of the defence** 17 August 2018

Permission to publish granted (date) 12 June 2018 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

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

ISBN (printed) 978-952-60-8102-1 **ISBN (pdf)** 978-952-60-8103-8

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2018

Pages 181 **urn** http://urn.fi/URN:ISBN:978-952-60-8103-8

A! Aalto-yliopisto

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Iina Aaltonen

Väitöskirjan nimi
Tulevaisuuden teknologioiden käytettävyys: käyttäjätutkimuksia puettavien, multimodaalisten ja lisätyn todellisuuden sovellusten kanssa

Julkaisija Perustieteiden korkeakoulu

Yksikkö Neurotieteen ja lääketieteellisen tekniikan laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 139/2018

Tutkimusala Kognitiivinen tiede

Käsikirjoituksen pvm 02.03.2018 **Väitöspäivä** 17.08.2018

Julkaisuluvan myöntämispäivä 12.06.2018 **Kieli** Englanti

☐ **Monografia** ☒ **Artikkeliväitöskirja** ☐ **Esseeväitöskirja**

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

ISBN (painettu) 978-952-60-8102-1 **ISBN (pdf)** 978-952-60-8103-8

ISSN (painettu) 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2018

Sivumäärä 181 **urn** http://urn.fi/URN:ISBN:978-952-60-8103-8

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.

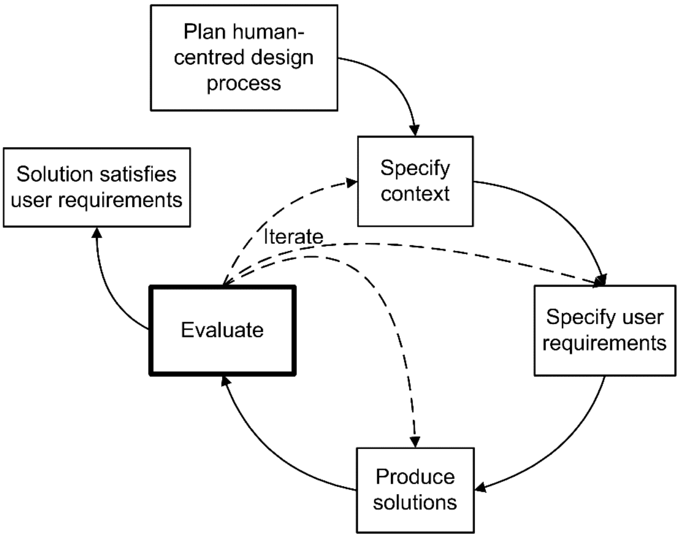


Figure 1. Phases of human-centred design activities showing the iterative nature of design and development (ISO, 2010). The evaluation box is highlighted to show the focus of this thesis.

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.

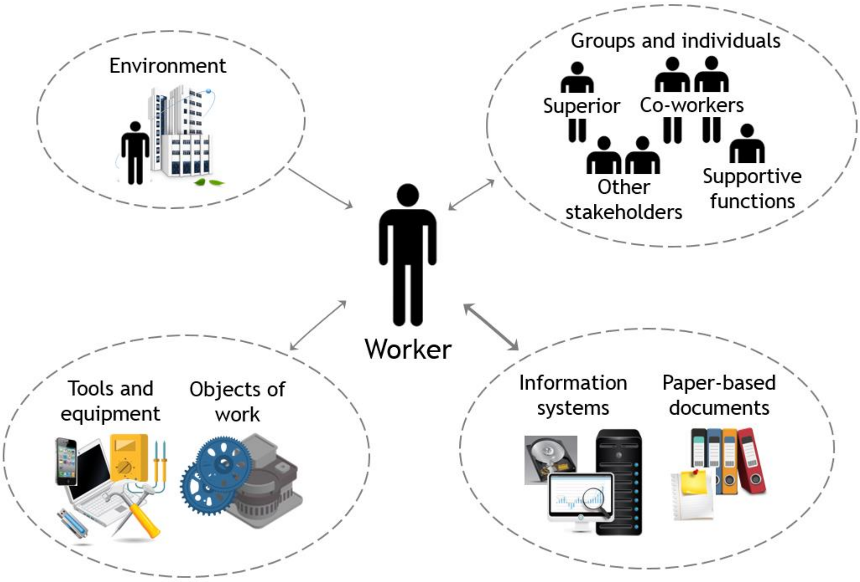


Figure 2. A generic view of information flow (arrows) to and from worker, adapted and modified after (Aromaa et al., 2015). The human agents include groups and individuals with various roles. The environment and other non-human agents are also shown to visualize the information that flows between the 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).

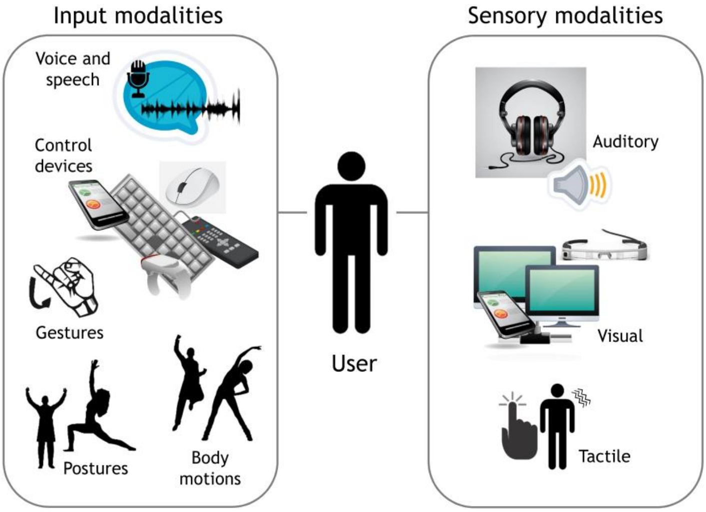


Figure 3. Multimodal interaction. The user can receive stimuli through multiple senses: visual, auditory and tactile. The user can also use combinations of different input modalities for control: speech and various devices and body motions.

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).

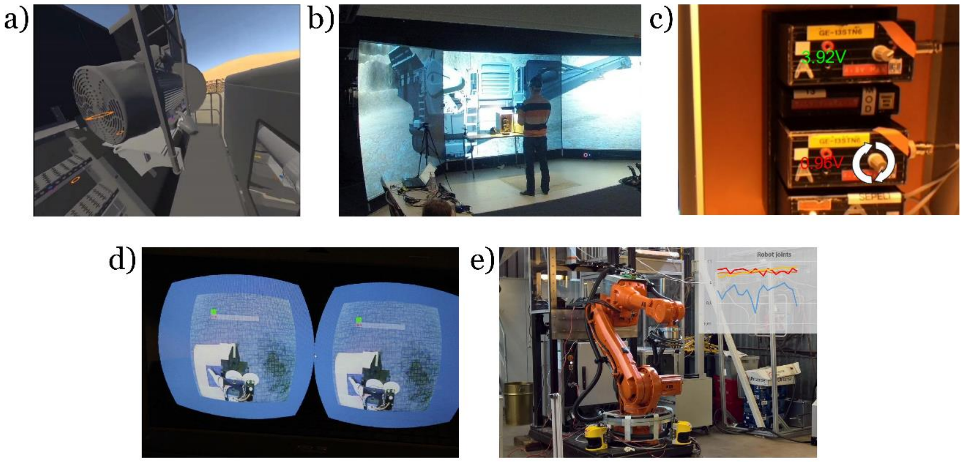


Figure 4. Examples of different forms of virtuality. a) Virtual reality, b) Mixed reality, c) Augmented reality (the red and green numbers and the white arrow are augmented onto the control modules), d) Telepresence (a view of remote video displayed on a virtual reality-set head-mounted display), e)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

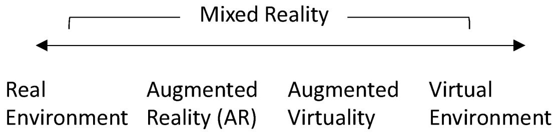


Figure 5. Virtuality continuum showing the position of AR with respect to real and virtual environments, adapted from (Milgram and Kishino, 1994).

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.

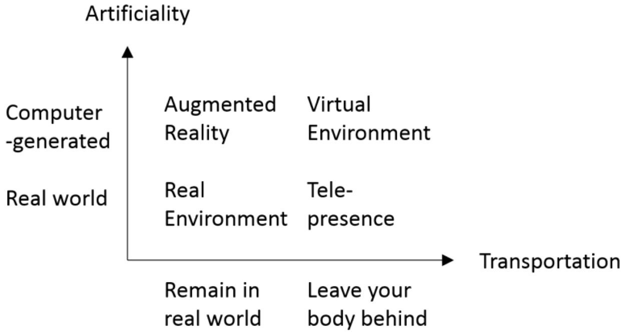


Figure 6. AR positioned on the artificiality and transportation axes, adapted and simplified from (Benford et al., 1998).

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).

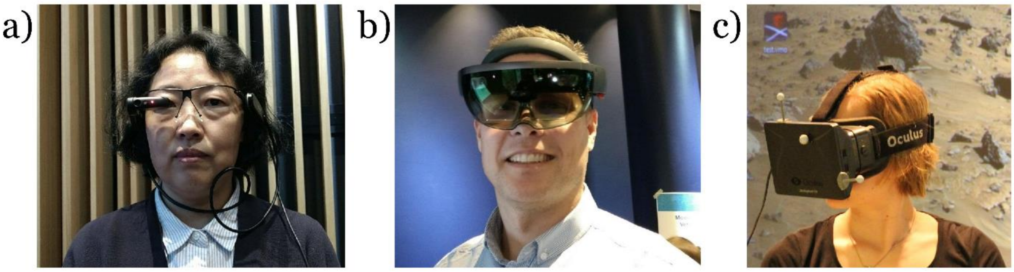


Figure 7. Head-mounted displays. a) Smartglasses with a display over the right eye (Vuzix M300). b) A head-mounted display with a visor onto which the image is projected (Microsoft Hololens). c) Virtual reality headset (Oculus Rift DK1).

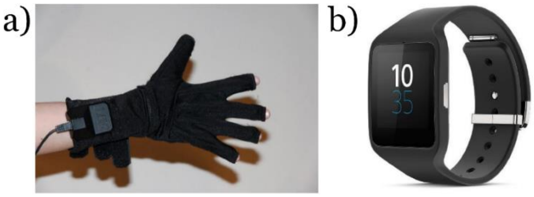


Figure 8. Hand/arm-worn devices. a) Data glove (5DT-5 Ultra). b) Smartwatch (Sony SmartWatch 3 SWR50, source: https://www.sonymobile.com/global-en/products/smart-products/smartwatch-3-swr50/#black, downloaded 22 Nov 2017, with permission).

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).

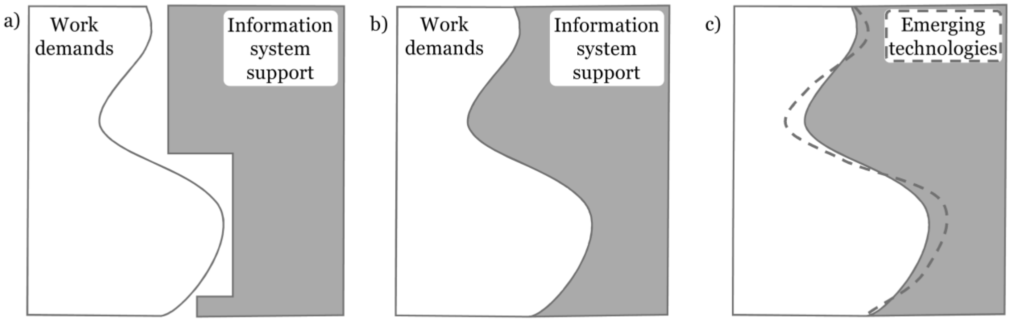


Figure 9. Relationship between work demands and system support. a) An information system that supports the work poorly: there is a gap between the work demands and the support offered by the system (adapted from (Vicente, 1999)). b) An information system tailored to suit the work demands (adapted from 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.

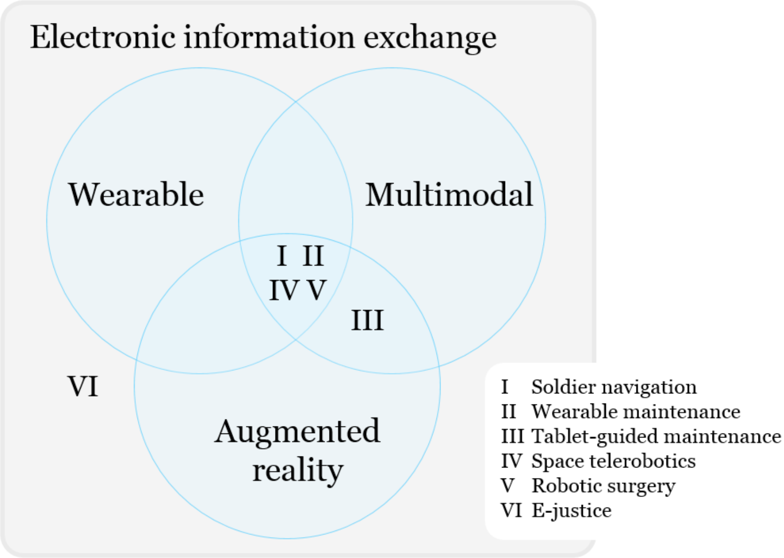


Figure 10. Case studies and their relation to the technology aspects considered in this thesis: electronic information exchange and wearable, multimodal, and augmented reality solutions.

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).

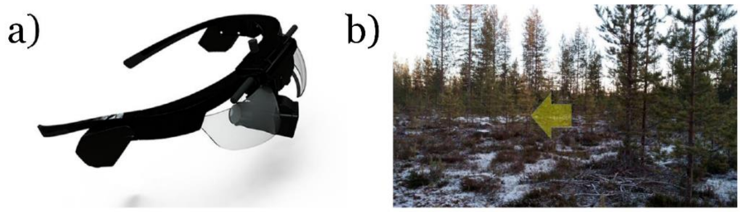


Figure 12. Visual modality in Study I. a) Penny C Wear Interactive Glasses Basic (source: http://www.penny.se/company-media.html, with permission), b) An illustration of a hovering arrow seen via the smartglasses in Sub-study 1. The arrow indicates that the user should turn leftward.

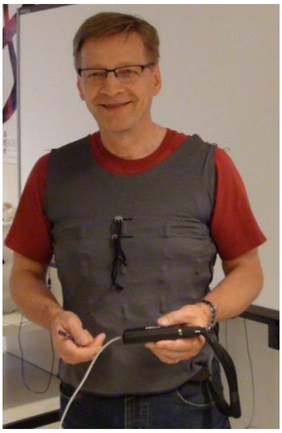


Figure 13. Tactile modality in Study I: A vest with tactors, or tactile elements.

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).

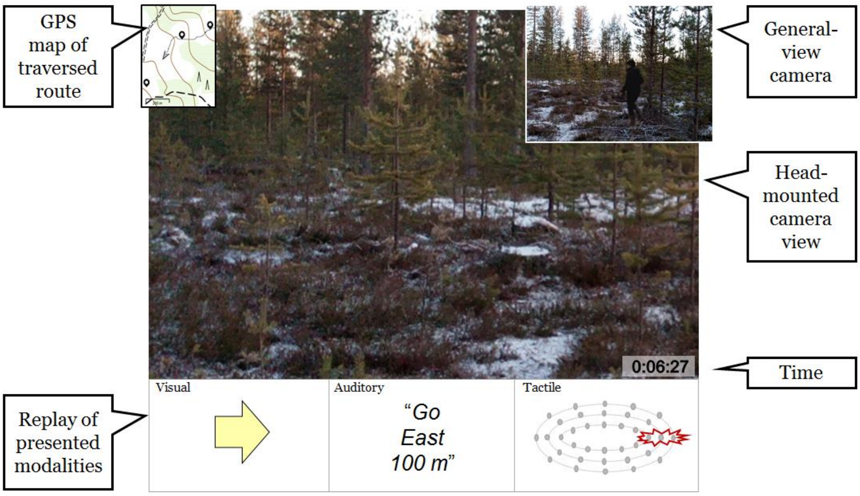


Figure 14. Post-trial replay of multimodal interaction—annotated illustration of the data analysis station described in Study I, showing two camera views, time stamp, and a replay of the presented modalities.

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.

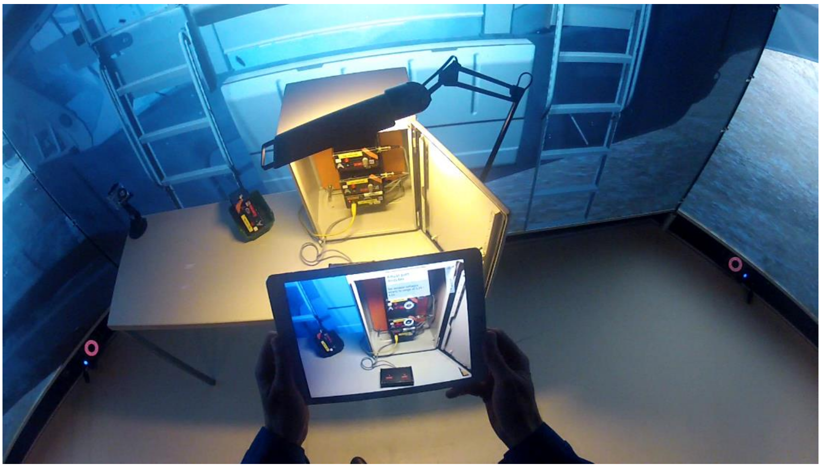


Figure 16. A participant holding a tablet with augmented instructions shown on the screen in Study III. A virtual model of the rock crusher is shown in the background (mixed reality).

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.

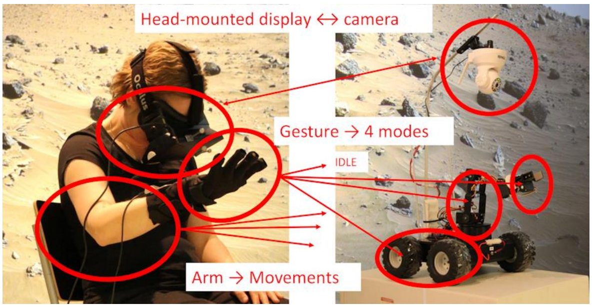


Figure 17. Wearable control system (left) and the teleoperated robot (right) in Study III.

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.

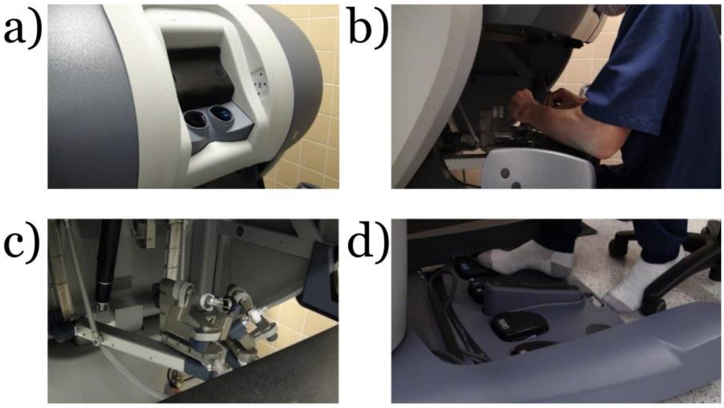


Figure 18. The surgical console of the da Vinci S System that the participants of Study V use in their work. a) Stereo display. b) A surgeon sitting at the console. c) A close-up of the hand controls. d) Foot pedals used to switch between functions.

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.

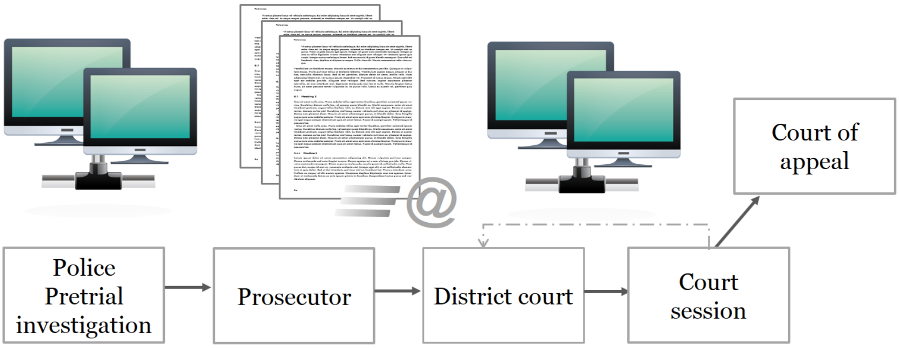


Figure 19. An illustration of the criminal justice chain and electronic information exchange in Study VI.

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?

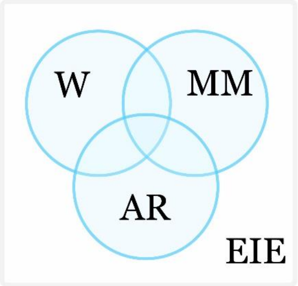
The core task in the judicial administration was not expected to change. On the other hand, there would be a change in where the work takes place: work could be done remotely (outside the workplace, enabled by online information systems) or in an office room instead of a courtroom (video-conferencing 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.

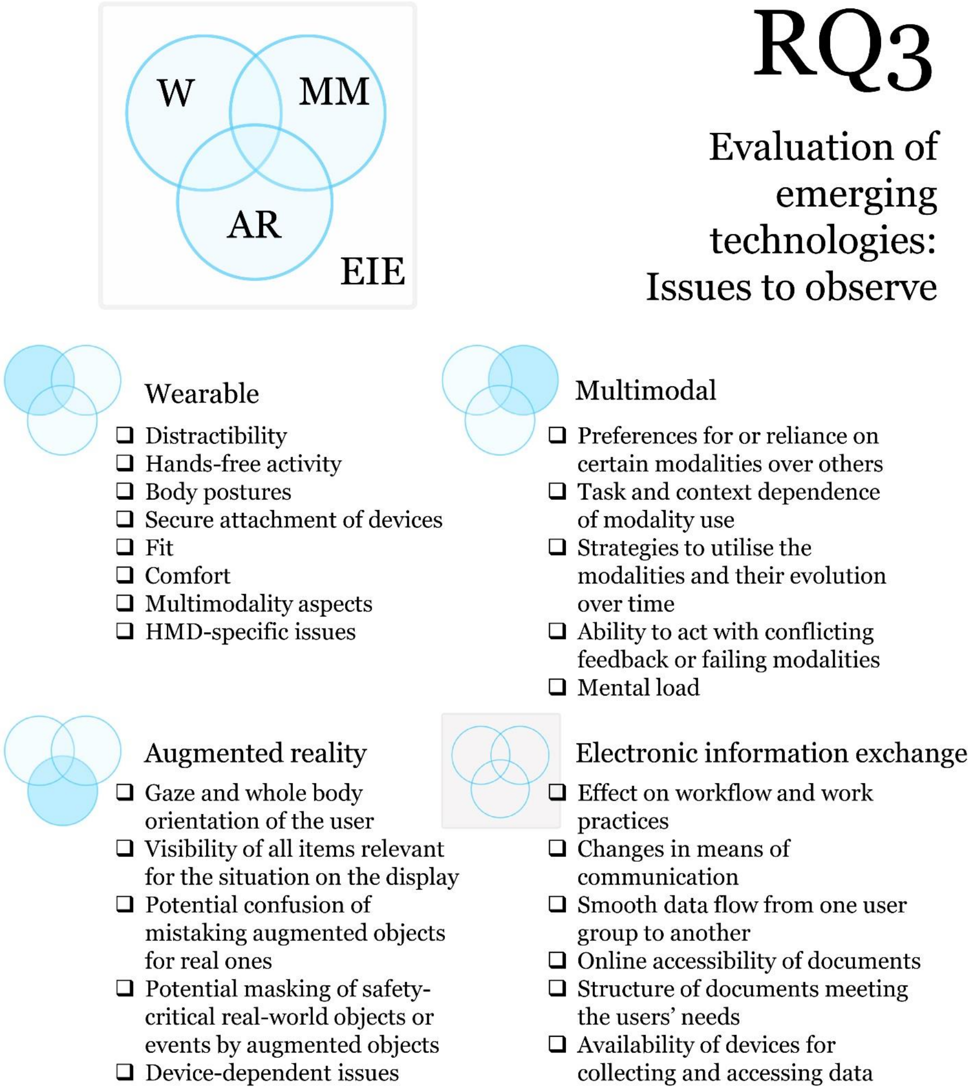
Regarding the suitability, there were issues with embedding the devices to the existing working conditions. For example, in the maintenance case, the existing protective gear, such as gloves and a helmet, and the confined environment, cause limitations. The cabling of the devices needs to be fitted unobtrusively 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				(✓)

Publication I

Aaltonen, Iina; Laarni, Jari. 2017. Field evaluation of a wearable multimodal soldier navigation system. Applied Ergonomics, volume 63, pages 79–90, 2017. http://doi.org/10.1016/j.apergo.2017.04.005

Applied Ergonomics 63 (2017) 79–90

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Field evaluation of a wearable multimodal soldier navigation system

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ARTICLE INFO

Article history:
Received 28 June 2016
Received in revised form
31 March 2017
Accepted 7 April 2017

Keywords:
Navigation
Multimodal
Wearable

ABSTRACT

Challenging environments pose difficulties for terrain navigation, and therefore wearable and multimodal navigation systems have been proposed to overcome these difficulties. Few such navigation systems, however, have been evaluated in field conditions. We evaluated how a multimodal system can aid in navigating in a forest in the context of a military exercise. The system included a head-mounted display, headphones, and a tactile vibrating vest. Visual, auditory, and tactile modalities were tested and evaluated using unimodal, bimodal, and trimodal conditions. Questionnaires, interviews and observations were used to evaluate the advantages and disadvantages of each modality and their multimodal use. The guidance was considered easy to interpret and helpful in navigation. Simplicity of the displayed information was required, which was partially conflicting with the request for having both distance and directional information available.

1. Introduction

In recent years, navigation systems have been developed for many user groups, such as those driving vehicles (Murata et al., 2013; Reagan and Baldwin, 2006; Szczerba et al., 2015), pedestrians (May et al., 2003; Münzer et al., 2006; Pielot et al., 2009; van Erp et al., 2005), and people with visual (Johnson and Higgins, 2006; Lewis et al., 2015; Wilson et al., 2007) or cognitive (Fickas et al., 2008) impairments. In addition, navigation systems for safety-critical domains have been suggested, for example, for firefighters (Streefkerk et al., 2012), first responders (Smets et al., 2008), and infantry soldiers (Elliott et al., 2010; Eriksson et al., 2008; Kumagai et al., 2005).

Challenging environments pose difficulties for navigation systems. A visual display may be useless in dense smoke or muddy water (van Erp et al., 2005). Similarly, terrain navigation is challenging when the environmental conditions are bad, for instance, when there is poor visibility due to darkness, heavy rain, snow, or thick vegetation, or when it is dangerous to walk there. In these conditions, the use of compass and map, or even a hand-held GPS (Global Positioning System) device, may be slow and cumbersome. Furthermore, the disadvantage of using traditional navigation means is that there is high mental workload required to pace count and detour around obstacles (Kumagai et al., 2005).

To cope with these challenges, the use of wearable systems have been suggested. For example, tactile displays, or vibrating tactors placed around the user's torso, have been studied on their own (Jones et al., 2006; Pielot et al., 2009; Srikulwong and O'Neill, 2010; van Erp et al., 2005), and in combination with electronic maps (Smets et al., 2008), head-mounted displays (HMDs) (Elliott et al., 2010; Kumagai et al., 2005; Streefkerk et al., 2012), and speakers or headphones (Calvo et al., 2014; Eriksson et al., 2008; Garcia et al., 2012; Kumagai et al., 2005). Many benefits of using wearable systems were found, including the selection of shorter routes and lower probability for disorienting (Pielot et al., 2009), faster performance (Srikulwong and O'Neill, 2010), less error in night-time navigation (Kumagai et al., 2005), and short familiarization time with the devices (van Erp et al., 2005). Additionally, in outdoor environments under high cognitive and visual workload, tactile displays were found useful (Elliott et al., 2010). Wearable devices can also improve users' situation awareness, i.e., perception and integration of surrounding information with respect to the situation at hand (Laarni et al., 2009).

1.1. Multimodal systems

In a multimodal system, as framed by Möller et al. (2009) and Dumas et al. (2009), human-machine interaction takes place via a number of media and utilizes different sensory and communication channels. Typically, the sensory channels refer to the visual (V), auditory (A) or tactile (T) senses. A common view in cognitive

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http://dx.doi.org/10.1016/j.apergo.2017.04.005
0003-6870/

psychology is that humans process modalities partially independently, and human performance can be improved by multimodal interaction (see, e.g., Dumas et al., 2009). For example, multisensory integration may make the stimulus more salient, and thus improve performance in selective attention tasks (Van der Burg et al., 2008). Wickens' Multiple Resource Theory (Wickens, 2008) can be used for modelling the mental resources available: information coming from a single stimulus can be processed in parallel, if different sensory resources are required. It has been shown that multimodal cues can shorten response times in complex environments (Ferris and Sarter, 2008). Similarly, tactile and auditory cues can facilitate visual target search (Hancock et al., 2013).

1.2. User evaluations in navigation and military contexts

Challenging environments pose difficulties also for user evaluations. In many contexts researchers are unable to go near the activity, for example in firefighting and military tasks. Sometimes, the conditions may be so challenging that the researchers are be forced to take the tests to a laboratory (e.g., Andersson and Lundberg, 2004), where the context of intended use can be only partially simulated.

In order to get an overview of user evaluations of multimodal systems, a table was prepared listing methods used in the evaluation of multimodal systems especially in navigation tasks and in military contexts (Table 1). Most evaluations were performed in applied or laboratory conditions, with the exception of a study by Elliott et al. (2010). In most studies, performance measures (PMs, e.g., elapsed time), or observations and user comments are utilized. Statistical significance tests are often carried out with PMs, but also sometimes with questionnaires. Questionnaires typically cover user-related issues such as usability, suitability for task, acceptability, comfort, workload and situation awareness. Physiological measurements (electrocardiogram, ECG) have also been used (Mynttinen, 2010).

1.3. Aim and scope of study

We studied a wearable, multimodal navigation system with users in a controlled outdoors environment and in the context of a military exercise in demanding outdoor conditions. Our demonstrator system is capable of tri-modal output, i.e., feedback to user can be given via three different modalities (visual, auditory, and tactile). In the two studies we carried out, we used unimodal (one), bimodal (two) and trimodal (three modalities) output.

This paper addresses two research questions: Does the demonstrator system help in navigation? What are the advantages and disadvantages of each modality, and also of multimodal use? The research questions are contemplated mainly on the basis of data collected using questionnaires, interviews and observations.

Although the navigation system described in this study can be used for several purposes (e.g., within-group communication and warning signals), in this paper, only the navigation support provided by the system is considered. Participants were encouraged not to use a hand-held device (with GPS capability), which was a part of the navigation system. In the analysis, only the wearable devices of the system are considered. This paper focuses on the evaluation phase of the navigation system; phases such as task analysis and system design are not covered (see e.g., Laarni et al., 2009; Lemmelä et al., 2008).

In this paper, Section 2 reports two studies in which the system was tested in outdoor conditions. Section 3 discusses the study findings regarding unimodal and multimodal use of the navigation system and provides some considerations to support the future design and evaluation of wearable multimodal systems.

2. Materials and methods

The multimodal navigation system used in this study has been developed in multiple phases, including scenario specification, cognitive task analysis, requirement specification, and concept design. The two studies described in this section concern the evaluation of a demonstrator, where various functionalities, including the multimodal outputs, have been integrated. In Study 1, the system was tested using unimodal and trimodal outputs in a controlled environment, and in Study 2, two bimodal conditions were used (visual + auditory (VA), tactile + auditory (TA)) in the context of a military exercise. The evaluation design was adapted from earlier work in the field, especially from (Elliott et al., 2010; Mynttinen, 2010).

2.1. Navigation system and multimodal outputs

The navigation system was built on Saab 9Land Soldier system. It included a hand-held unit with a 3.7″ display and computer, and terminals for voice and data. The display showed a non-rotating, north-up map with zooming possibility. Waypoints could be set to the route using the hand-held device. The navigation was based on GPS: The user's position was transmitted periodically and automatically, and the heading direction was inferred from preceding GPS readings. The system generated output for the visual and auditory modalities at 10 m intervals (corresponding to 7–12 s at walking speed). When the user stepped outside of the navigation corridor (corridor width 25 m, waypoint diameter 10 m), system output was generated for the auditory and tactile modalities. Table 2 summarizes the information presented for the participants.

Visual information was shown via an HMD (Penny C Wear Interactive Glasses (Fig. 1, left)). The glasses are see-through, and near-retina projection is used to display information to the right eye. The perceived image is hovering in front of the user (Fig. 2, right); the opacity of the image depends on the surrounding lighting conditions and its size and position on the physical facial characteristics of the user. In Study 1, left, right and forward arrows instructed the participant the correct direction to turn (Fig. 2, left). A researcher manually controlled the shown arrows from a remote location, because the system integration had not been completed at the time. In Study 2, the system showed the distance and direction to the waypoint in text format (Fig. 2, centre). When the waypoint was reached, a rectangle (Study 1) or an oval shape (Study 2) was shown.

Auditory instructions were speech-based and transmitted via headphones (Fig. 1, left). In TA condition in Study 2, a more robust set of headphones (Peltor™) with a volume knob was used. Examples of phrases spoken by the system were “Go North-West 120 m”, “You are off track, turn left” (prompted when stepping outside of navigation corridor) and “You have reached the destination”.

Tactile vibrations were transmitted using a vest made of stretch fabric. There were 36 tactors, or tactile vibrators, equally spaced in three rings around the torso (Fig. 1, right). The tactors vibrated at 120 Hz. The vibrations were either to the left or right side of the torso (Fig. 3), which indicated the direction where the user should turn to in order to get back to the navigation corridor, or a round-torso circling vibration when a waypoint was reached. The tactile vest was worn over a thin shirt in both studies.

2.2. Study 1: preliminary navigation test

Study 1 was a navigation test in a controlled outdoors environment.

Table 1
Studies evaluating multimodal systems in navigation and military tasks. The modalities (V = visual, A = auditory, T = tactile) listed pairwise (e.g., VA) mean bimodal stimuli, and a triplet (VAT) trimodal stimuli.

Ref.	Category/Setting	Description	Devices	Output modalities	Evaluation methods
(Elliott et al., 2010)	N, Mil, W F (wooded terrain)	A tactile land navigation system	Hand-held GPS (text or arrows), HMD (GPS map), tactile belt, map + compass	Vx3, T, VT	PM: waypoint completion and navigation time, deviation from route, timeliness of responses to radio, detected targets …; Q (pre and post) (scale 1–7): effectiveness of device; Q (scale 1–7): usability, usefulness, workload, situation awareness, moving, accuracy of guidance, rerouting …; Oral questions: best-liked properties, how to use each device.
(Streefkerk et al., 2012)	N, W A (simulated)	Firefighters' staged rescue task	HMD, tactile belt	VT	PM: completion time, walking speed, # victims found, situation awareness (as percentage of located items drawn on map); Q (scale 0–150): Rating Scale Mental Effort; Q (scale 1–7): preferences, ease of tasks; Q (scale 1–10): Added-value of components; Debriefing
(Smets et al., 2008)	N, W L (game environment)	First responder search-and-rescue task	Screen x2, tactile vest; game controller	VT	PM: time required for rescue; Q (pre): spatial ability test; Q (scale 1–5): situation (location) awareness; Q (scale 1–5): satisfaction: usability, usefulness, comfort.
(Garcia et al., 2012)	N, W L (game environment)	Navigating with multimodal interfaces	Screen, stereo headphones, tactile belt; thumb controls	Vx2, A, T, VA, AT, VT, VAT	PM: time to completion, accuracy of route; Q (pre): Sense Of Direction
(Mynttinen, 2010)	Mil, W A (practice firing range)	A close combat cued shooting task	See-through goggles (led lights), in-ear headphones, a tactile belt	V, A, T, VAT, mixed {V,A,T}	PM: reaction time and shooting accuracy; ECG measurement; Observations using video camera; I: first impressions (three positive and negative issues); Q: NASA-TLX; Q (scale 1–7, each modality separately): modality ranking, suitability, usability, obtrusiveness …; I: modality comparison, easiness …
(Andersson and Lundberg, 2004)	Mil, W L, A (mock-up)	A moving and weapon handling task	Wrist-mounted visual display, tactile vest	T, VT	PM: correct/false action; Video camera; Q (slider scale): comfort, utility, perceptivity of signals and their combinations, effect on movements …
(Oskarsson et al., 2012)	Mil, W, L (simulated vehicle)	Cueing of direction to threat	Head-down/up display, tactile belt, 3-D headphones	Exp.1: V, A, T, VAT Exp.2: VA, TA, VAT	PM: localization error, response time, correct radio calls Q (scale 1–7): mental workload, effort of driving, perception of threat direction, degree of using 3D audio sound for threat localization.
(Ferris and Sarter, 2008)	Mil, W L (game environment)	Cross-modal links between cues and targets	Screen, speakers, tactors on wrists; joystick	VA, AV, TA, AT, VT, TV (cue-target pairs)	PM: target detection, reaction time (variable factors: cue modality and spatial relationship); Video analysis.

Abbreviations: N = navigation, Mil = military, W = wearable, L = laboratory, F = field, A = applied; PM = performance measure, Q = questionnaire, I = interview, pre = prior to test, post = after test. Measures are post-test by default.

Table 2
Summary of information presented for the participants with each modality in each of the two studies (V = visual, A = auditory, T = tactile). Information was automatically updated at 10 m intervals and/or when stepping outside the navigation corridor. In Study 1, the visual instructions were manually controlled.

Mod.	On the move	Waypoint reached
V	Study 1: A left, right, or forward arrow Study 2: Distance and cardinal directions to waypoint in text format inside a rectangle	Study 1: A blank rectangle Study 2: An oval shape
A	Verbal commands:Distance and cardinal directions; Outside corridor: Turn right/left	"You have reached the destination"
T	[No stimulus within corridor]; Outside corridor: Vibrations to the left or right side of the torso	A round-torso circling vibration

Fig. 1. Wearable devices. Left: HMD for presenting visual modality. The light-weight headphones were used in Study 1 and in the bimodal VA condition in Study 2. Right: Tactile vest showing three rings of tactors.

2.2.1. Participants

Four civilian volunteers, aged 20–35 (2 male, 2 female), participated in the study. One participant reported having very good orienteering skills. All participants had experience with smart phones, tablets, and navigators, and one had some prior experience with a wearable device, but not with HMDs.

2.2.2. Task

The study took place in a sports field (length appr. 100 m) surrounded by wooden area and a passing road. The weather was cloudy and cool, and the participants wore coats over the tactile vest. Each route consisted of three waypoints located on different sides of the sports field. The visually unidentifiable waypoints (GPS coordinates) were set in seven different positions and numbered consecutively: three on each side of the field, one starting/ending point (waypoint 1) at the end of the field. The triangular routes were the same for all participants, but different for each condition. The waypoints for the routes were as follows: auditory condition waypoints 1-4-7-1, tactile 1-3-5-1, visual 1-2-6-1, and trimodal 1-3-6-1. Unimodal outputs were first tested individually in the order A-T-V, followed by trimodal output (Fig. 4). Each participant performed the study in the same order with the same pre-set routes.

The participant was instructed to find three waypoints with the help of the system. They were told to turn about 45°, when a vibration (T) or an arrow (V) was perceived. For example, a vibration on the left side of the torso or an arrow pointing left indicated the participant should change the course leftward. The participant could use a compass for the cardinal directions (A), but prior the task, they were also told and indicated by hand gestures that the passing road was almost parallel to north-south direction. Otherwise the participants relied only on the guidance from the wearable devices. They were not shown the map or the waypoints pre-set in the hand-held device. No special training was given besides testing each signal and ensuring the participant could follow the instructions.

2.2.3. Data collection procedure

Prior to test, the participant filled a consent and background information form, which included demographics, orienteering skills and experience with different technologies. During the test, researchers observed the participant from a short distance away.

After testing each modality, a researcher used a first impressions interview: self-evaluated performance ("In your opinion, how well did you perform in the navigation task with the help of the device?", scale 1–5, min-max) and attention to surroundings ("How well were you able to pay attention to the surroundings while you moved?", scale 1–5, min-max), and three pros and cons ("Please mention three plusses and three minuses of the device(s) you used"). After testing all modalities, the participant was interviewed again. The interview considered the participants' opinion on the whole (multimodal) system, their preferred choice of devices/modalities for navigating in terrain, and suggestions for improvement.

2.2.4. Results

All participants completed all routes successfully. The self-evaluated performance was best for the visual modality (manually controlled) and worst for the tactile modality (A 3.5 ± 0.6, T 2.8 ± 0.5, V 4.5 ± 0.6, VAT 3.5 ± 0.6, mean and standard deviation, scale 1–5). On the other hand, the participants' attention for surroundings was best for tactile and worst for the trimodal condition (A 3.0 ± 0.8, T 4.0 ± 0.8, V 2.3 ± 0.5, VAT 1.5 ± 0.6).

For navigating in terrain, the participants were asked about their

Fig. 2. Left: Visual instructions used in Study 1. Centre: Visual instructions in Study 2, according to which the distance to the waypoint is 80 m south-west. Right: A hovering arrow as seen via the HMD—an illustration only. [span 1.5–2 columns, colour in print].

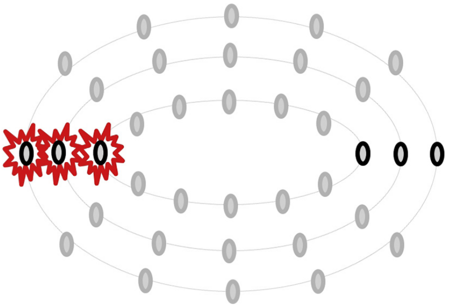

Fig. 3. Tactor configuration of the tactile vest. Only the left- and rightmost tactors were used. When the participant was instructed to turn left to return to the navigation corridor, the three tactors located on the left side of the vest vibrated.

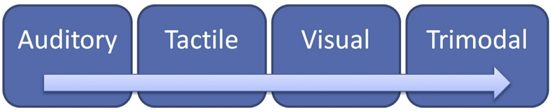

Fig. 4. Modalities tested in Study 1. Each participant used the system four times: first using individual modalities, and finally with all modalities.

preferred modalities. One participant preferred tactile as the primary choice. Another participant answered auditory or visual. The last two participants chose the visual modality as the most preferred one, but they spontaneously added secondary choices, one of them selecting the bimodal VA and the other participant the trimodal VAT. Most of the comments given concerned individual modalities and devices, and there were relatively few comments on trimodal use (Table 3). The comments regarding the slowness of the GPS and consequent buffering of auditory instructions are not included.

2.2.4.1. Technical and other challenges. The slow GPS signal caused several difficulties. The researchers needed to verbally instruct the participants to change direction if they walked too much outside of the sports field, and tell the participant when a waypoint had been reached if the destination reached signal was not delivered due to GPS delays. The visual modality was controlled manually and remotely by a researcher and it was not affected by the slow GPS. This resulted in information conflicts between different sensory channels in the multimodal condition. The interviews revealed that the conflicting information was interpreted in different ways: The participants used either the most reliable or the last perceived output, or an average of tactile and visual modalities (auditory was mentioned to require too much processing; the instructions required processing cardinal directions in a foreign language).

2.3. *Study 2: navigation test in a forest*

Study 2 lasted for three days and took place in the context of a military exercise in a forest.

2.3.1. *Participants*

Nine military conscripts (all male, aged 19–20, time served one year or less) participated in the study. All had normal or corrected to normal (contact lenses) vision. Eight participants had right eye dominance, one reported “undetermined”. One participant was left-handed. The participants were very familiar with hand-held and GPS devices, but most had little or no experience with wearable and virtual technologies. They had not used the wearable navigation system before. In addition, all participants self-reported having good orienteering skills, serving as a baseline for the navigation task.

2.3.2. *Task*

The study took place in a forest in daylight conditions. The weather was sunny and the temperature varied from −5 °C to 0 °C, which felt chilly due to the wind. A thin layer of snow covered the ground. The participants used the system for navigating while they performed a reconnaissance task in the context of a larger military exercise including two opponent sides. The objective was to visit each waypoint (a selection of GPS coordinates supporting the exercise) and return to the starting point after the reconnaissance task was finished. The route for each participant was different, and the participants had the freedom to change the waypoints or step outside of the route if the situation demanded.

The system was tested bimodally (Fig. 5). Five participants were included in the TA condition only, one participant in the VA, and three were included in both conditions separately starting with the TA. In the TA condition, the users wore the tactile vest and a robust set of headphones with a volume knob. In the VA condition, the users wore the HMD and light-weight headphones (Fig. 1, left). In both conditions, the participants carried the hand-held device in a pocket or integrated to a tactical vest. The participants were allowed to use a compass, but in daylight it was not necessary for determining the cardinal directions. The map on the hand-held device could be used as support, but otherwise the participants relied only on the guidance from the wearable devices.

Before starting the test, the participants were shown a short introductory video of the different wearable devices and a slide show on setting up a route using the hand-held device. The participants were informed that the system is a demonstration system

Table 3
Comments on different modalities derived from first impressions interviews in Study 1 (V = visual, A = auditory, T = tactile, VAT = trimodal). The number of participants is given in parentheses if a comment was given by more than one.

Mod.	Pros	Cons	Suggestions
V	Accurate (3) Simple	Arrow disappeared from field of view (3) Non-ergonomic fit (3) Limited visual field due to glasses	Slanted arrow A compass shown on display
A	Distance information provided (3) Clear voice	Not in users' native language (2) Cardinal directions (2)	Message needs to be shorter and simpler to interpret (e.g. left-right) (3)
T	Clear vibrations (3) Easy to follow (2) Surroundings can be monitored (2)	Difficulty in knowing how much to turn (3) The vibrations came too rarely	Support for confirmation on right direction (2) Forward, backward, stop -signals are needed
VAT	Many information sources gives certainty (2) Navigation was smoother than with unimodal	Easier to focus on one device at a time Unsuitable for moving in terrain	–

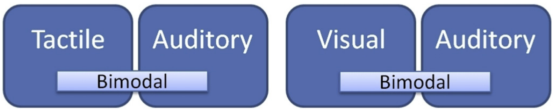

Fig. 5. Tested modality combinations in Study 2.

and that there could be a lag in the GPS signal. All signals were tested before starting, and researchers ensured the participants could perceive them.

2.3.3. Data collection procedure

Prior to test, each participant filled a consent form. A researcher helped each participant to insert waypoints into the hand-held device. The route selection was based on the participant's task in the military exercise. During the task, the participant navigated the route on his own or accompanied by other draftees and, when the task allowed, a researcher. When in the vicinity, the researchers observed and took notes either in writing or using hand-held videocameras. In the TA condition, the participant also wore a head-mounted video camera (manufacturer V.I.O., model POV.1.5 or POV. HD). A separate Android smartphone GPS application was used for tracking the navigated route; this device was placed in the participant's pocket by the researchers. Immediately after the task, the participant was briefly interviewed on their first impressions (self-rated performance and three pros and cons, as in Study 1). In addition to audio-recording the interviews, a pre-filled form was used for notes.

Then each participant was given a multipage questionnaire (Likert scale 1–7, disagree-agree). It included demographics and prior experience with technology (Part 1 of questionnaire), and statements concerning individual modalities (Parts 2–4, 10–12 statements for each modality) and the hand-held device (Part 5) and the whole system (Part 6, 31 statements). The statements in Parts 2–4 regarded the format and interpretability of information, and wearability, usability and usefulness of the device. In Part 6, there were statements regarding the functioning of the whole system, usability and learning aspects, wearability and physical strain, information display, situation awareness, and suitability for field tasks and navigation. There were also open field questions after each part. The three participants who tried both bimodal conditions answered the whole questionnaire (with the exception of the visual modality) after the TA condition, and filled only the part concerning visual modality after the VA condition.

The questionnaire items were mostly adapted from System Usability Scale (SUS) (Brooke, 1996), Questionnaire for User Interface Satisfaction (QUIS) (Chin et al., 1988), systems usability framework (Savioja et al., 2014; Savioja and Norros, 2013), and Situational awareness rating technique (SART) (Taylor, 1989). NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988) was not included in its original format, but the questionnaire contained items regarding mental workload related to each modality and the experienced stress in general. After all participants had completed the task, the following themes were discussed in a focus group: usefulness and autonomous adaptation of different modalities, situation awareness, ergonomics and suitability for military use.

All interview data was transcribed from audio-recordings and analysed. Data from head-mounted and other video cameras were watched and analysed by systematically coding findings and themes that emerged from the data; these included any comments regarding the usability of the devices (mostly the hand-held device), problems in reading instructions from the wearables, and finding the exact location of the waypoint. Questionnaire data was analysed in a spreadsheet program by descriptive statistics and qualitative analysis.

2.3.4. Results

All participants were able to get a feel of how the system worked and use it in navigating in the terrain. Based on the Android phone tracking (separate from the hand-held device containing the waypoints), the routes traversed by the participants were approximately 300 m–1.5 km long and lasted 20–40 min. The routes were not followed directly from waypoint to waypoint, because of terrain features or the enemy situation and reconnaissance needs in the military exercise. Fig. 6 shows two examples of pre-planned waypoints that could be retrieved from the system and the actual routes traversed.

2.3.4.1. First impressions interview and questionnaire results. In the first impressions interview, the participants self-evaluated their performance with the help of the system slightly better in the TA condition (TA 3.5 ± 0.5, $n = 8$; VA 3.2 ± 0.8, $n = 3$; mean and standard deviation, scale 1–5). Fig. 7 shows the questionnaire

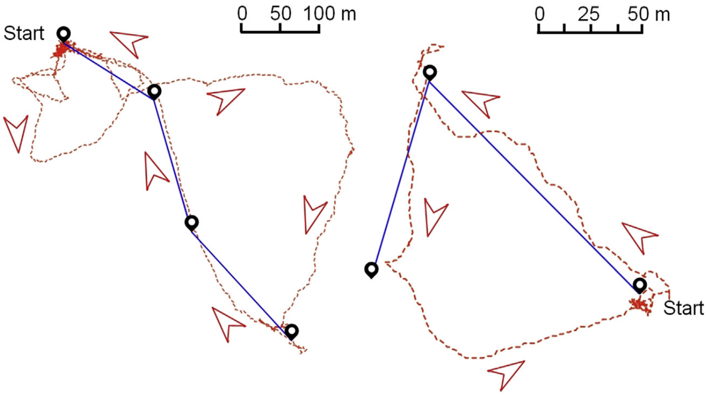

Fig. 6. Two examples of traversed routes. The straight lines indicate the planned route with black waypoints. The dashes indicate the actually traversed and tracked routes. Arrowheads show the direction of walking; in the left figure the preplanned route was navigated “backwards” toward the starting point. The loops near the waypoints indicate that the participants walked in circles searching for the exact location. Note the different distance scales.

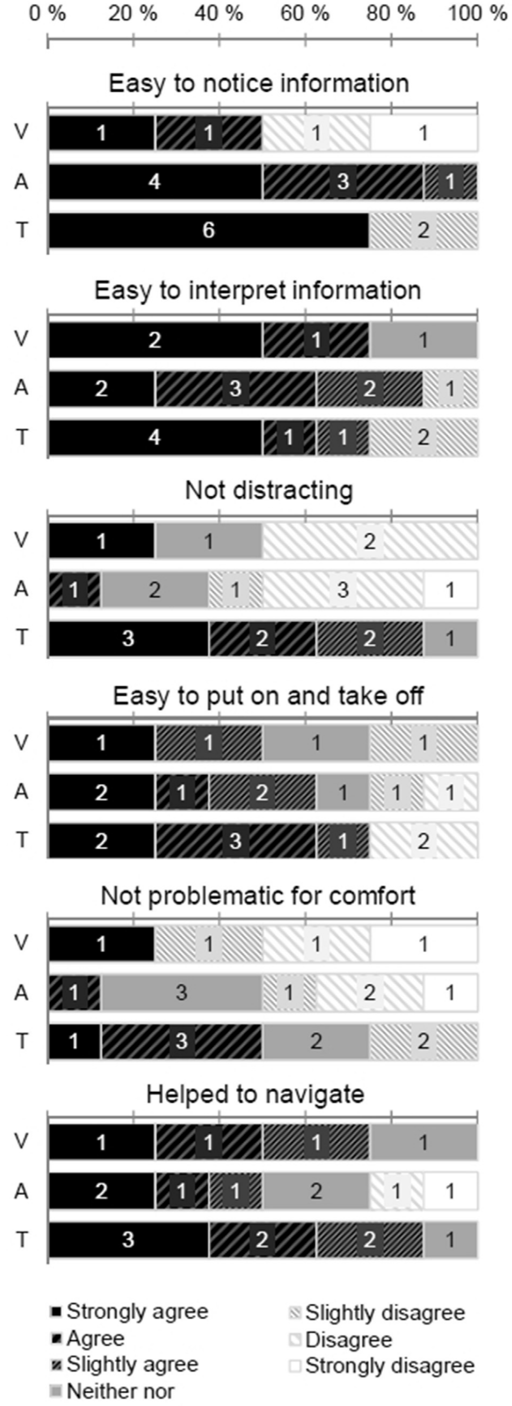

Fig. 7. Participants' responses to questionnaire statements in Study 2 depicted relatively to each modality. Darker colours indicate stronger agreement with the statements whereas lighter colours indicate disagreement. The data labels show the number of respondents. (V = visual, A = auditory, T = tactile. Total number of participants $n_V = 4$, $n_A = 8$, $n_T = 8$. Auditory modality data is reported only in TA condition. The statements in the questionnaire were formulated in more detail, and the formulations of the statements "Not distracting" and "Not problematic for comfort" were reversed.)

results for individual modalities regarding statements common for all modalities (Parts 2–4 of the questionnaire). The data on the auditory modality are from the TA condition (see Section 2.3.3).

All modalities helped in navigating ("The [device] helped me to navigate in the test", Fig. 7), which was supported by comments to the open questions and the first impressions interview. Table 4 summarizes the comments given in the interviews, questionnaires and the focus group. It was frequently mentioned that the system would support navigation especially in the dark. On the negative side, several comments were made on the attachment of the cables.

The questionnaire results and comments regarding the visual modality reflect the problem with the physical fit of the HMD, which limited the visual field (Table 4) and affected the visibility of the presented information (Fig. 7, top-most chart; see also Fig. 2, right). The researchers' observations during the signal testing also support this finding. Although the ease of interpretation of the auditory information was estimated to be at about the same level as the other modalities, there were several comments that the guidance needs to be made clearer. Comments were also made on the slowness of the GPS and resulting buffering of audio messages. The tactile vest was rated least distracting of the wearable devices, and many positive comments were given regarding its use especially while moving, and in the dark. The vibrations were, however, hoped to indicate the correct direction more accurately.

The mental workload when navigating in terrain was asked in the context of each modality and was evaluated low (V 1.3 ± 0.5, $n = 4$; A 1.8 ± 1.4, $n = 8$; T 1.4 ± 0.5, $n = 8$; scale 1–7). Kruskal-Wallis (KW) test was used to test differences between modalities. The KW analysis was not significant ($p > 0.05$). According to questionnaire results (TA 5.3 ± 1.9, $n = 8$; VA 6.0 ± 0.0, $n = 1$; average of four learning statements concerning the whole system) and written comments, the system was considered easy to learn, and sufficient information on how the system works was given (5.9 ± 1.5; all participants).

2.3.4.2. Focus group. The focus group discussion considered the potential of the whole wearable system. Although all participants did not try all modalities, they had seen the initial introduction video and seen others put on and take off the devices. In general, the system was thought to be more useful in dark conditions (see also Table 4). The concept of multimodality was not covered in the discussions per se. Because the participants had different preferences on the individual modalities, there was no consensus on an optimal setup. The system should, however, be easily put on because the clothing worn depends on the mission. Additionally, all cables should be securely attached and hidden to support moving in all postures.

The effect of the system on situation awareness was also discussed in the focus group. The HMD was thought to force the users to divide their attention among multiple things. The auditory instructions should not come too often, because environmental sounds would be blocked, which is undesired in reconnaissance missions. Additionally, the optimal frequency of repeating the auditory instructions would depend on the speed of traverse and the length of route.

2.3.4.3. Technical and other challenges. The testing conditions were challenging. In addition to coping with the demands of the military exercise and therefore lack of experimental control, the researchers had to troubleshoot disconnected cables and drained batteries, which was partly due to cold weather. Further, during the study, the GPS was slow and it caused buffering of the auditory instructions.

The participants were instructed to select a few waypoints (GPS coordinates) suitable for their reconnaissance task. They were very adept in using the hand-held device, and even with very little training, able to modify their routes by themselves. They initially inserted 2–4 waypoints, but changed or skipped some of them when the situation in the military exercise required them to do so. This resulted in a drawback: most of the inserted waypoint coordinates were not saved in the system or were overridden by new waypoints. Therefore, we cannot state an exact number for the waypoints found.

The head-mounted cameras were used to estimate if the waypoints were reached with the help of the tactile vest and auditory instructions in the TA condition. Two participants found all the waypoints they sought (one and two waypoints, other waypoints were skipped manually due to non-system related reasons), confirmed by their comments on feeling the round-torso circling vibration. One participant verbally commented that the instructions were making him go in circles (similar to loops in Fig. 6); all three waypoints were found in this manner. For one participant the GPS was so slow that the waypoints could not be found, and for another, based on the video material, it was not possible to say for certain if the waypoints were found. Three participants were noticed to frequently check on the map shown on the hand-held device, and therefore the contribution of the wearable devices on their navigation was undetermined. In the VA condition, only one participant could be followed by researchers, and based on the hand-held camera footage and the participant verbally observing the instructions were guiding him in circles, both two waypoints were found.

3. Discussion

Next we will summarize the findings regarding the navigation with the system. Because the evaluated system was a demonstrator, the results need to be interpreted in how the users foresee its potentials and challenges. Table 5 shows a literature overview regarding the results found in the use of multiple modalities in field navigation and offers a reference for further discussion.

3.1. Navigation with the system

The demonstrator system helped in navigation with all tested modality combinations although there were technical issues with the slow GPS. The wearable navigation system was considered easy to learn with minimal training, which has been also noted by others (Elliott et al., 2010; Eriksson et al., 2008; Kumagai et al., 2005; van Erp et al., 2005). In Study 2, the mental workload was considered low for all modalities evaluated individually, which is typical for wearable devices in the navigation context (see Table 5). In the study by Elliott et al. (2010), the workload was found lower for a multimodal (VT) condition than for individual modalities.

3.2. Unimodal use

In the literature, diverse preferences for individual modalities have been mentioned (Table 5). In a study by Kumagai et al. (2005), the auditory was found preferable over visual for target detection, whereas tactile was liked while moving because it enabled simultaneous tasks using other senses. Another study found tactile the best, followed by visual (Eriksson et al., 2008). Our findings in Study 1 differ from these as there was a preference for visual for terrain travel and self-evaluated performance. However, the visual modality was manually input and therefore very accurate, and the

Table 4
Summary of comments given by participants regarding the system and individual modalities in Study 2 (V = visual, A = auditory, T = tactile). The source of each comment is mentioned in the column on the right, including the number of participants supporting the comment and the related bimodal condition. The comments are from the first impressions interviews (I), questionnaire (Q) and focus group (FG). E.g., “5 in TA I; FG” means that five participants in TA condition gave the comment during their interviews and the issue was also brought up in the focus group.

Mod.	Comments	Source
System	Supports navigation,	6 in TA I, 2 in VA I
System	Supports navigation esp. in the dark	2 in TA I; FG
System	Guides to the right place	3 in TA I
System	Makes navigation easier	2 in TA I; 1 in VA I
System	No need to read paper map	2 in TA I; 1 in TA Q
System	Easy to learn	3 in TA Q
System	Distance information provided	2 in TA I; 2 in VA I
System	Should be easily put on and taken off	100. FG
System	Should be functional also when it's snowing or raining	103. FG
System	Attachment of the cables (e.g., due to vegetation and crawling)	5 in TA I; FG
V	HMD was too big	2 in VA I
V	Limited visual field due to glasses	1 in VA I, 1 in VA Q
V	It should be possible to flip away the see-through HMD	FG
V	HMD forces users to divide attention among multiple things	FG
V	Abundance of information can hamper environment monitoring	1 in VA I
V	Difficulties with moving while wearing the HMD	1 in VA Q
A	Guidance should be simpler	1 in TA I
A	Cardinal directions were confusing	2 in TA Q
A	Auditory instructions need clarification	1 in TA Q
A	Environmental sounds should not be blocked	1 in TA I; FG
A	Guidance should be audible over the sound of running steps	1 in TA I
T	Useful	2 in TA I
T	Convenient, also in the dark	2 in TA Q
T	Light-weight	1 in TA Q
T	Easy-to-use	11 in TA Q
T	Vibration should indicate the correct direction more accurately	1 in TA Q
T	Suitable when moving	1 in TA Q
T	Cables should be attached firmly to support moving in all terrain	1 in TA Q

Table 5
Summary of findings from field navigation studies with multiple modalities reported in literature. Both unimodal and multimodal studies in field and applied conditions are included. The modalities (V = visual, A = auditory, T = tactile) listed pairwise (e.g., VA) mean bimodal stimuli.

Ref.	Category/ Setting	Description	Devices	Output modalities	Results
(Elliott et al., 2010)	N, Mil, W, F (wooded terrain)	Waypoint navigation + secondary tasks	Hand-held GPS (text or arrows), HMD (GPS map), tactile belt, map + compass	Vx3, T, VT	Waypoints were found. Navigation times were significantly lower for V than for T or the multimodal VT (hand-held V with arrows) for speeded traverse. The mean workload was lower for VT than either device used alone. With wearables (T and V-HMD), rerouting obstacles and situation awareness were rated better than with a hand-held GPS. Tactile requires less training and visual attention, and is easy to use. Hands-free was appreciated. Tactile was preferred for travel and visual map/GPS for confirming location.
(Streefkerk et al., 2012)	N, W, A (simulated)	Firefighters' staged rescue task	HMD, tactile belt	VT	The search task took longer to perform and the workload was slightly higher with the multimodal system compared with baseline (difference not significant). 75% of users preferred the tested system over the baseline. The users commented on information overload, and the interface presented inaccurate or irrelevant information for the task.
(Kumagai et al., 2005)	N, Mil, W, F (wooded terrain)	Waypoint navigation + secondary tasks	Helmet-mounted display, mono sound speakers, tactile belt	V, A, T (unimodal)	Waypoints were found; no significant differences between modalities for distance travelled or performance. The devices were easy to learn. Low overall mental workload for the wearables. High acceptance rate for all modalities for terrain traverse. For object detection, A was more acceptable than V. Tactile was liked while moving because visual search and listening were possible. Otherwise no overall preference of any one modality. Visual display needed position adjustment, and users stopped their movement to use it. Tactile was uncomfortable (esp. thermal) and restricted mobility. Direction of A was difficult to determine.
(Eriksson et al., 2008)	N, Mil, W, F (semi-open terrain)	Waypoint navigation + secondary tasks	Hand-held GPS, stereo headphones, tactile belt	Vx2, A, T (unimodal)	Waypoints were reached. With visual (arrows + distance), navigation speed was higher than with T or A (continuous pulsating ringing). Self-rated mental workload was higher for A than T. Two thirds of users preferred T and the rest V. Auditory was not liked due to blocked sounds and the delimiting effect on attention. Tactile directed attention away from terrain less than A or V. Tactile could be improved on usability and integration to equipment.
(Calvo et al., 2014)	N, W, F (open field)	Waypoint navigation	Hand-held mobile phone, stereo headphones, tactile belt	Vx3, A, T (unimodal)	Waypoints were found in all conditions. Egocentric map condition (V) was rated most usable. Comparing V (arrows), A (audio tones), and T conditions, A was faster than V, but A was considered less usable than V or T conditions. Usability of the eyes-free conditions (i.e., A and T) was considered high and perceived mental workload low, supporting the intuitiveness of these displays. Tactors suffered from misalignment.

Abbreviations: N = navigation, Mil = military, W = wearable, F = field, A = applied.

study was done in civilian context. The participants self-reported their attention for surroundings was lowest in the visual condition, which could be a significant factor in military activities, such as in target detection mentioned by Kumagai et al. (2005)). Findings on individual modalities were similar in both studies, and they are elaborated in the following subsections.

3.2.1. *Visual modality*

The visual modality easily suffers from the size and problematic fit of the display, its delimiting effect on the visual field and the difficulty moving while wearing the HMD (Studies 1 & 2; Kumagai et al., 2005). In our system, interpreting distance information and cardinal directions was considered too demanding to focus on. Although providing distance information is important, the advantage of the simplicity of using arrows has been noted (Study 1; Elliott et al., 2010; Eriksson et al., 2008). Future improvements such as slanted arrows or displaying a compass were suggested the participants. Additionally, the (see-through) eye piece could be mounted to a helmet and flipped down (Kumagai et al., 2005) or otherwise flipped away from visual field (Study 2).

3.2.2. *Auditory modality*

Auditory information was evaluated to be easily noticed. The participants requested for the auditory message to be shorter and simpler (instead of spoken distance and cardinal directions), which might be difficult to attain while preserving the well-liked distance information. Kumagai et al. (2005) have tested stereo sounds, but some users had difficulties in detecting from which side the sound was coming from. In general, the volume level should be adjustable to accommodate different individuals (Kumagai et al., 2005) and to match the environmental sounds (Study 2) as the environmental sounds are easily blocked (Study 2; Eriksson et al., 2008). In addition, the optimal repetition frequency of the instructions would depend on the speed of traverse and the length of route.

3.2.3. *Tactile modality*

The tactile modality was liked on many accounts: it is easy to follow, and convenient while moving and observing the environment, also in the dark (similar to Kumagai et al., 2005). The tactile modality has been also praised on its hands-free and “eyes-free” operation (Calvo et al., 2014; Elliott et al., 2010). Although Elliott et al. (2010) reported tactile cues were not perceived as strongly when running uphill, our participants thought the information was easy to notice also in the field conditions. In our studies, the coding scheme was very simple (left and right vibrations), and the participants wished for more accurate directions. Kumagai et al. (2005) and Jones et al. (2006) have used a directional coding scheme successfully. However, distance coding has been found more difficult to interpret and it did not improve performance compared to a control condition (van Erp et al., 2005).

3.3. *Multimodal use*

There was a smaller number of findings on the multimodal use, partially because of the participants’ tendency to elaborate on the modalities separately and the format of the questionnaire used in Study 2. In Study 1, the participants had a chance to compare both unimodal and trimodal use, and they had a better basis for commenting on multimodal use against a “unimodal baseline”. In both studies, there were individual preferences on modality combinations.

For wearable navigation systems, the direction of and the distance to the next waypoint, and the simplicity of interpreting the displayed information, have been noted as important (Elliott et al., 2010; Kumagai et al., 2005; van Erp et al., 2005), which was also supported by our findings. Added to that, in the military context, there is a need to be able to observe the environment and act (e.g., run, crawl, aim, shoot) without interference from the devices.

This raises an interesting question of whether to use one device with multiple functionalities, or several devices with simple—and possibly redundant—information. Redundancy may diminish user's concern about not noticing the information and against the breakage of devices. Issues that require consideration include battery life, cabling, wearability (see guidelines by Gemperle et al., 1998; Knight et al., 2006), learning, and ease-of-use. Wearability is especially important with tactile displays, because continuous contact with the skin needs to be maintained (Calvo et al., 2014; Jones and Sarter, 2008). Furthermore, the time of day affects the experienced mental effort (Kumagai et al., 2005). Multisensory cues can be advantageous under perceptual load (Spence and Santangelo, 2009). An example of a successful modality combination was suggested by Elliott et al. (2010), who concluded that a visual display supports where the user is with respect to waypoints and a tactile display supports staying on course. Alternatively, automatic modality adaptation (i.e., adapting a multimodal interface to different interaction contexts) could be considered (Kong et al., 2011).

3.4. *Methodological considerations*

The data collection methods used in our study gave us quite a comprehensive understanding of the various user aspects of the system. Feedback on individual modalities, as well as on the combination of them, was received. A limitation of this study was the lack of objective performance measures (e.g., completion time and deviation from the route, see Tables 1 and 5). Objective measures were not calculated because the system was a demonstrator and, in Study 2, the navigation speed and accuracy were of secondary priority to complying with the objectives of the military exercise. In this respect, the qualitative approach used in this study offers more valuable insights to the use of the wearable multimodal system.

Additionally, we realized that more attention needs to be given to *how* the modalities were used by the participants in the multimodal conditions, e.g., reliance on one or more modalities, conflict handling between information sources, and dependence on task and context. To facilitate the analysis of multimodal interaction, we drafted a suggestion for viewing multimodal data collected in the field (Fig. 8). This kind of presentation of the data could work as a post-trial video analysis tool for researchers, or act as material for “think aloud” interviews or as stimulus for workshops with potential users and system developers (cf. Buur et al., 2010).

In general, a controlled study (cf. Study 1) is useful for comparing individual modalities and their combinations and for determining whether a user can succeed in navigation using that modality alone. Field trials (cf. Study 2) can concentrate more on performance, workload, situation awareness, preferences, and strategies of how different modalities were used in certain tasks (see also context of use by Bristow et al. (2004)) and whether this strategy changed during the study. In addition to measuring the usability of individual modalities, the usability of the system as a whole (e.g., Savioja and Norros, 2013) and the use of multiple modalities simultaneously (see Beringer et al., 2002; Kühnel et al., 2010; Ramsay et al., 2010; Turunen et al., 2009; Wechsung, 2014) should be covered.

3.5. *Conclusions*

All three modalities evaluated in these two studies were found helpful in navigation and were very easy to learn. Although each modality has its weaknesses, in a multimodal system their

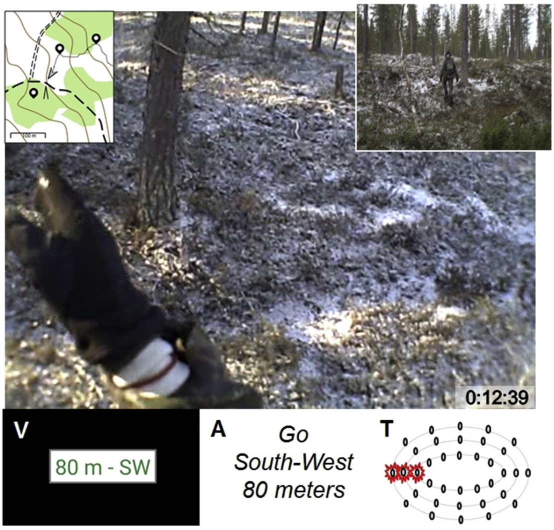

Fig. 8. Suggested data analysis station for post-trial replay of data collected using cameras and log data. In the main screen, video from the head-mounted camera shows what the user was looking at. Multimodal system output is replayed under the main screen, and insets show—on secondary screen if available—a map of the traversed route and video stream from a general-view (e.g., hand-held by a researcher) or a 360-degree camera. Gaze tracking data and physiological measurements (e.g., pulse) could also be shown.

strengths can be employed and built on. A simple visual arrow can integrate seamlessly to the constantly monitored surrounding view while traversing in terrain in daylight conditions. Additionally, visual information can be constantly displayed (vs. sequential data presentation). The auditory modality, i.e., speech, is an intuitive way for presenting distance information to a target. The tactile modality is especially convenient for supporting navigation in the dark, because it does not strain other perceptual modalities, and also very intuitive for immediate reactions (cf. a person tapping another on the shoulder). Multimodal use is complicated to evaluate because both the devices themselves and the type of information relayed affect the user experience, and it is easier for users to elaborate on individual modalities. Redundant information through multimodal systems, however, can increase users' confidence in the correctness of the information.

However, while acknowledging the benefits of the modalities, we could identify some general user requirements for wearable multimodal systems for field conditions; each of these requirements are critical in that if some of them are not met, the users may be reluctant to use the system:

- The user has to be able to use the system in all weather and lighting conditions
- The devices should not block the user from ambient events
- The tactile patterns should be detectable in different postures
- The wearable system should fit well and offer mobility
- The system should be easily put on and taken off
- The system should not transfer heat to the user
- The user should be periodically informed of the status of the system and its modalities
- The relayed messages should be simple to interpret.

These results can guide the future design and evaluation of multimodal systems in the field. In addition to finding an optimal modality combination for each task and context, there are several open possibilities left for future research: what type of information is displayed through each modality, how to construct a simple but efficient stimulus coding for both distance and direction, how do the individual modalities contribute to the perception of the whole in field conditions, and how do users deal with conflicting information.

Acknowledgements

Multimodal Soldier Interface System (MUMSIS) project was one of nine projects run under the Combat Equipment for Dismounted Soldier Feasibility Study Programme (CEDS-FSP). The study was financed by project member states—Austria, Finland, France, Germany, Portugal, Romania, Spain, and Sweden—under the responsibility of European Defence Agency (EDA). Iina Aaltonen has received a grant from Wihuri Foundation for writing her PhD.

We thank all project participants who worked together to integrate the system. Special thanks to Antti Väätänen, Juhani Heinilä, Jari Matikainen, and the Finnish Defence Forces, who enabled us to carry out the field work. We also thank Britta Levin and Jonathan Svensson for co-working with the questionnaires and reports. Special thanks to the reviewers for their suggestions.

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Publication II

Aromaa, Susanna; Aaltonen, Iina, Kaasinen, Eija; Elo, Joona; Parkkinen, Ilari. 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. AcademicMindtrek ’16. Pages 235–242. 2016. http://doi.org/10.1145/2994310.2994321

Use of Wearable and Augmented Reality Technologies in Industrial Maintenance Work

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ABSTRACT

Industrial maintenance is an increasingly complex and knowledge intensive field. Although new technologies in maintenance have been studied extensively, their usage is still lacking in the industry. We have studied knowledge-sharing solutions using augmented reality (AR) and wearable technologies in actual industry cases to find out if maintenance technicians find them useful and usable in their everyday work. Two test cases were included: the use of a wearable system consisting of three devices in the crane industry, and the use of AR guidance in the marine industry. In both cases two maintenance technicians tested the technologies and data were collected using questionnaires, interviews and observation. The maintenance technicians were positive towards the use of these technologies in their work. However, some practical issues were raised concerning the simultaneous use of multiple devices and the placement of the devices. A more system-level approach to designing wearable and AR technologies could be applied to ensure their utility in the field. Findings from this study can be used when designing and implementing wearable and AR technologies in maintenance, but also in other industry domains like the manufacturing industry.

CCS Concepts

• Human-centered computing~Field studies • Human-centered computing~Mixed / augmented reality • Human-centered computing~Ubiquitous and mobile computing systems and tools • Human-centered computing~Smartphones • Human-centered computing~Mobile devices • Human-centered computing~Tablet computers

Keywords

Maintenance; wearables.

AcademicMindtrek'16, October 17-18, 2016, Tampere, Finland
© 2016 ACM. ISBN 978-1-4503-4367-1/16/10…$15.00
DOI: http://dx.doi.org/10.1145/2994310.2994321

1. INTRODUCTION

In global industry, companies are starting to invest more on their service business. They want to increase productivity and provide good quality services for their customers. However, managing the maintenance process can be challenging due to its complexity and knowledge intensiveness [1]. Maintenance work can be described as a 'combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function' [2]. According to Reason [3], maintenance activities can be defined as (1) unscheduled operations, including corrective maintenance, and disturbance- and failure-preventive operations (opportunity-based maintenance); (2) scheduled disturbance- and failure-preventive operations; (3) inspections; and (4) calibration and testing.

Franssila [4] has identified challenges in knowledge management in service business, such as the inadequacy of formal documentation, unreliable networks, information on new products (e.g. new updates) being difficult to share to the field, and tacit knowledge from the field being difficult to channel to other members in the organisation. In addition, the working environment may present challenges, as the maintenance location may vary day-to-day and include safety critical tasks, such as working in high places. Maintenance tasks may also require working in obstructed places and being careful of other nearby traffic (e.g., automatic vehicles and pedestrians). In addition, noise, poor lighting, dust, grease and/or hot temperatures may make the working environment more challenging.

The possibilities of using wearable and AR technologies have been studied in many industrial domains. A wearable computer can be characterized as being body-worn, mobile, ready-to-use, and adaptive to the user's changing environment [5, 6]; it is often a combination of devices, such as a head-mounted display (HMD) and a separate input device [7]. Augmented reality technologies supplement the real world with overlaid virtual objects [8]. The fundamentals of wearable computers and AR are addressed in [9]. Lukowicz et al. [10] have summarised the research of industrial wearable applications in four different domains: aircraft maintenance, car production, healthcare, and emergency response. In addition, in the military domain, various wearable solutions have been developed in future soldier projects [11, 12]. Wang et al. [13] recently compiled an overview of the use of AR technology in assembly, while Nee et al. [14] and Ong et al. [15] have made a survey of AR applications in design and manufacturing.

The knowledge sharing issues of maintenance have previously been introduced and discussed in detail [1], and three technology concepts for knowledge sharing have previously been proposed [16]. In this study, we have focused on the user experience and usefulness of two proposed technologies (wearable and AR technology) to support knowledge sharing in maintenance. The paper is organised as follows. Section 2 describes related research, while Section 3 presents the field studies on wearable and AR based knowledge sharing systems. First, the data collection methods used in both cases are described. For the first case 'wearable system for data collection and reporting', the technology description and study design are presented alongside the results. The same steps are also used for the second case with an 'AR system for task guidance'. Section 4 discusses the results and summarises the outcomes.

2. RELATED RESEARCH

The main application areas of wearable and AR technologies in maintenance are in providing information/guidance/instructions (e.g., manuals), documenting maintenance (e.g., pictures) and collaborating with other people (e.g., novice vs. expert) [10]. Nee et al. [14] have summarized AR-assisted maintenance systems. Several studies have compared AR technologies with more traditional ways of providing instructions and guidance [17–25]. Studies show that AR technologies are feasible in providing instructions since they are often faster to use, errors occur less frequently, and operators approve of the use of the technology. In a study of long-term use of industrial AR systems, it was found that an AR system does not increase users' overall strain but may increase eye discomfort. [25]. There are also studies about the use of AR for remote collaboration where maintenance experts can discuss and share knowledge with each other [26–28]. In addition, Funk et al. [24, 29] have studied a projection-based AR assembly system developed for context-aware assistance.

Ziegler et al. [30] have discussed the potential of smartwatches to support maintenance tasks by providing six different typical usage scenarios. Zheng et al. [31] 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. Zheng et al. [32] also compared different technologies (two eye-wears, a tablet and a paper) to provide instructions in maintenance. According to [33, 34], the mobile multiple-display environments are not understood well at the moment. Therefore, the authors highlight challenges in the design of multi-display ecosystems and request better guidelines to tackle challenges.

However, much of the published research related to this topic lacks an industrial context and only describes the developed technology, provides scenarios and concepts, and/or demonstrates technologies tested in laboratory settings (e.g., [30, 35–37]). According to Navab [38], many research groups produce only demonstration prototypes. Zheng et al. [32] tested in a realistic environment, but the test persons were not real maintenance technicians. However, there have been some descriptions of real life experiences; for example, Siegel and Bauer [39] studied the use of wearables with aircraft maintenance technicians, while Mynttinen [40] studied wearables used by the military in the field. It is difficult to evaluate the developed technologies in a real context (due to safety, cost, etc.) and in many cases, researchers choose to do the test in a laboratory environment to obtain better repeatability (see [41]). In our study we wanted to collect real-life experiences from actual maintenance technicians.

3. THE FIELD STUDIES

Two field studies of knowledge sharing in maintenance were performed: first with wearables, and second with AR technology. The same data collection procedure was used in both studies. The results described here are based on qualitative analysis of data from questionnaires, discussions of questionnaire answers (participants elaborated on their selection in more detail) and also observations. Comment authors are not made identifiable due to the small number of participants; comments were made by only one or by both participants.

3.1 Data Collection Methods

Participant demographics and consent forms were first collected. Additionally, the maintenance technicians' familiarity with wearable and augmented and virtual reality technologies was elicited. The use of the systems was observed during the task performance. In the second case, the test was video recorded. After the test, participants completed a questionnaire measuring usability, technology acceptance, and user experience. The questionnaire was based on the System Usability Scale (SUS) [42] and the technology acceptance model (TAM) [43]. A 7-point Likert-scale was used (ranging from strongly agree (7) to strongly disagree (1)). In both cases, the questionnaire was used to evaluate systems as a whole. The small number of participants allowed for selections in the questionnaire to be elaborated on through a follow-up discussion (e.g., 'why did you strongly agree that the system improved your work performance?'). The items were selected for the follow-up discussions if the Likert-scale answer deviated from the middle-range. This qualitative way of using the SUS and TAM questionnaires supported the evaluation of the potential of these prototype technologies in actual maintenance work. In addition, the interview included open questions regarding user experience, acceptance, collaboration, and other implementation possibilities. The interviews were audio recorded.

3.2 Wearable System for Data Collection and Reporting

This case is related to a crane company's service activities in their customer's facilities. The crane company's service team is located on-site in a large steel factory, where the team performs planned and preventive services and on-demand corrective maintenance work 1. Their goal is to maximize the uptime and minimize the downtime as much as possible. The working environment in the factory is noisy, dark, sometimes very warm and the surfaces are greasy. In addition, there is lot of automatic vehicle and pedestrian traffic in the large indoor factory area. Maintenance technicians communicate with their factory personnel daily, as the good timing of maintenance tasks is very important for the steel company. Mobile and Wi-Fi networks are available.

Currently maintenance technicians will check the necessary information before going to the crane or call a colleague via mobile phone if extra information is needed during the maintenance. Reporting is done at the office with a PC after the maintenance. They share photographs via multimedia messages or from the office via email. Sometimes they have taken videos instead of photographs.

3.2.1 Technology Description

This wearable system was developed to improve communication between the information systems and a maintenance technician.

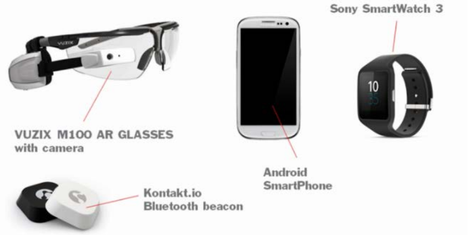


Figure 1. Wearable system

The system was proposed in order to make on-site reporting easier and to shorten the reporting time afterwards.

A feasibility demo application for the wearable system was implemented using Android smartphone (Samsung Galaxy S5), a Sony Smartwatch 3, and M100 Smart Glasses / head-up display (VUZIX) (See Figure 1). Kontakt-io Bluetooth beacons were tested for optimal location on the factory premises. With the demo application setup, technicians were able to document and report service findings.

3.2.2 Study Design

Two maintenance technicians (aged 23 and 54 years, with 4 and 24 years work experience respectively) took part in the field study. Both operate machines several times during working hours. Both maintenance technicians were active users of smartphones, a tablet PC, a desktop PC and navigator. Both knew the terms 'head mounted display', 'wearable technologies' and 'virtual environment'. The younger technician also knew the term 'gesture-based control system'. Neither knew the term 'augmented reality'.

First, there was an introduction for the participants and a brief training in how to use the system, with a hands-on demonstration. Their goal in the test was to perform maintenance procedures for a predefined target. During the maintenance the wearable devices were used as follows: start the process with the smart phone, check the information from the smart glasses, select the target from the smartwatch, take pictures and report (by using all three devices), and finally, check the document from the smartphone (See Figure 2).

Figure 2. A maintenance technician using a wearable system for data collection and reporting.

The functions of the wearable system could have been chosen in many different ways. This specific configuration was selected to examine the benefits of the wearable systems. The emphasis was on the hands-free and gloves-on operations. The user interface of the smart glasses was not very intuitive and clear to use especially with gloves, and therefore, the smart glasses were used for taking photographs with the smartwatch used as a shutter. For this study it was also easy to mount the smart glasses on the helmet because wearing a helmet is mandatory. In addition, with the helmet mounting it was easier to get a suitable viewing position, and it was easy and fast to turn smart glasses aside when not needed.

3.2.3 Results

3.2.3.1 Usefulness and User Experience of the System

In the maintenance technicians' opinion, the smartwatch was easy to use and it was easy to recover from mistakes. Sometimes the smartwatch slid under the work glove and the glove needed to be moved by the technician to make the screen visible. Sometimes it was difficult to remember which direction (up/down or right/left) to swipe the screen.

The smart glasses were easy to use and the user experience of gesture-based interaction was positive. In addition, the ability to take photographs was evaluated to be good. It would have been better if the smart glasses could be more easily moved into and out of the field of view. The technicians did not always remember the position of the buttons on the smart glasses. The maintenance technicians sometimes took their helmet off and the smart glasses were thereby also removed. Taking photographs was difficult since two devices had to be used simultaneously: pressing the camera button on the smartwatch and keeping the target visible in the smart glasses. Additionally, the photograph stayed visible in the smart glasses for too brief a time to be able to check its quality. It was commented that it was sometimes too dark to take good photographs. It might be sometimes impossible to take photographs in small confined spaces, since the camera was attached to a helmet.

The smartphone was evaluated as being easy to use. It was easy to insert short comments on reports and read them from the smartphone afterwards. However, it was laborious to frequently take out the smartphone from a pocket. Furthermore, the maintenance technicians needed to take their gloves off when using the smartphone.

It was easy to learn to use the complete wearable system ("Learning to operate the system would be easy for me" M=6, SD=0.0). The role and linkages between each device were easy to understand. However, sometimes it was difficult to remember whether to use the smartwatch or the smartphone. Therefore, the maintenance technicians would prefer to use only one of them. Due to the number of devices, the use of the system was a little bit too complicated and interfered with working (e.g., "Using the system would enhance my effectiveness on the job" M=2.5, SD=2.1). The system decreased hands-free working and it could be a safety issue in this environment. However, the maintenance technicians reported that they would tolerate their hands being occupied more if the reporting time was thereby made shorter.

3.2.3.2 Work Perspective

The maintenance technicians thought that the adaptation of the wearable system could have a positive impact on their work and could ease their work. The evaluated system, however, slowed down their work because the technicians needed to change between devices during the maintenance task ("Using the system in my job would enable me to accomplish tasks more quickly" M=3, SD=2.8). Nevertheless, they felt that the use of the wearable system would not change the actual work much. The maintenance technicians felt that an experienced maintenance technician does not need instructions on how to do the maintenance. They also felt that novice maintenance technicians could not rely solely on a wearable system for guidance. They would use the system in the future if it was developed further and was workable. The maintenance technicians felt that their colleagues might be interested in using such a system, but that some resistance might emerge. If all information is available in the system, communication with other people might decrease.

3.3 Augmented Reality System for Task Guidance

This case was related to solutions in the marine industry 1. In this case the focus was on a planned and preventive field service related to engines in a mid-sized oil tanker. Typically, in tankers, the working environment is dark, noisy, greasy and hot, and it includes a lot of working in confined spaces. The workers use mainly hand tools, power tools and special measuring instruments. There are no reliable mobile networks on ships and wireless local area networks are only provided on some vessels. Marine engine service workers must communicate with other people in their company and with technical personnel on ships. This study, however, did not take place on-board, but rather in the company's laboratory environment, which was a big hall with a real engine.

Current maintenance instructions are mostly available in paper format. Maintenance technicians receive information from their supervisor, from instruction manuals or from designers. The maintenance technicians learn by doing and trying, for example, how to disassembly something. A computer that enabled searching for information and reporting is typically located far away from the site of maintenance work. Manuals are not always up to date and some may have errors, for example, due to translation. The maintenance technicians felt that they did not need much help while working but they would communicate via telephone if they need it. If they needed more information, it was typically related to the assembly phase than disassembly.

3.3.1 Technology Description

The purpose of this AR system is to give more comprehensive and interactive guidance to the maintenance technician. The system was built on an iPad Air tablet using Metaio Creator. The user interface was Junaio. The maintenance technician receives help that is available in information systems via a tablet and an AR application (See Figure 3).

Figure 3. Maintenance technician using augmented reality system for task guidance.

The maintenance technician was given a list of maintenance steps and visual guidance on what to do in the subsequent steps. Visual guidance could be given via 2D drawings, 3D models, or symbols (See Figure 4). The 3D models and symbols (e.g., arrows) were animated to show the correct operating direction. The system allowed the maintenance technicians to proceed at their own pace and acknowledge when a maintenance step is completed. At each step, the system informs about the required tools, spare parts, and the technical information needed to execute the maintenance work successfully. The system ensures that all necessary maintenance procedures are performed, and enables the information to be updated in the customer's system.

3.3.2 Study Design

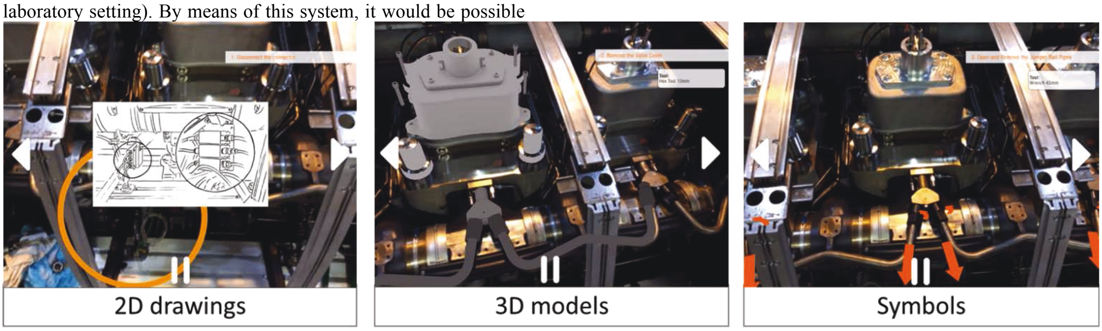
Two maintenance technicians (aged 34 and 49 years, with the work experience of 11 and 29 years respectively) took part in the test. The younger technician worked with machines several times during the work days. The older technician did maintenance tasks on a weekly basis. Both maintenance technicians were active users of smartphones and PCs. In addition, the younger technician was an active user of a tablet PC and navigator but did not know the term 'AR'. The older technician had some experience of using a navigator. He had also heard the term 'tablet PC' and 'AR'. Neither of them knew the terms 'head-mounted display', 'wearable technologies', 'gesture-based control system', and 'virtual environment'.

Participants were given a brief introduction and demonstration in how to use the system. The task description in the case was: check the machine condition from the tablet, open the maintenance order from the tablet, select the operation, walk to the target, put on the AR guidance, perform a disassembly using AR guidance, and finally, accept the task performed. After performing maintenance activities, participants completed the questionnaire, discussed the questionnaire results, and answered the interview questions.

3.3.3 *Results*

3.3.3.1 *Usefulness and User Experience of the System*

The maintenance technicians thought that the use of the AR system could be beneficial and have a positive effect on maintenance work. The system could be useful especially when certain maintenance tasks are done for the first time. Therefore, it could be useful in early stages of work experience, but the maintenance technicians did not feel that they would use or need the system later. However, it could also be useful to an experienced maintenance technician when the maintenance cycle is long. Despite the system intruding on their traditional working process, the participants felt that they were able to focus on their work. They thought that this system could be most beneficial in the field (compared to this current laboratory setting). By means of this system, it would be possible to decrease the amount of work that needs to be done before an actual maintenance task. The use of the system could also change the work in a way that there would be less telephoning and communication between people. It could also decrease the amount of errors/mistakes. On the negative side, it disturbed their work flow, since they were not used to using that kind of system in their everyday work.


2D drawings

3D models

Symbols

Figure 4. Screenshots from the tablet. Task guidance is given by using additional information, such as with 2D drawings, 3D models and symbols.

The user experience for the AR system was positive. The participants felt that the system was easy to use (I thought the system was easy to use" M=6, SD=0.0) and they would like to use it again ("I think that I would like to use this system again" M=7, SD=0.0). The symbols used were easy to understand, it was clear what to do, the system instructed well, and the task sequence was explicit. In addition, it showed in which direction to do things, for example, when twisting a screw or taking a part off. 3D pictures were also considered to be good. The participants did not feel any physical strain and they did not mind that they needed to use both hands and to stop the work when holding the AR system. Participants felt that AR instructions were better than instructions on paper, since it might be easier to keep AR instructions up-to-date and there was no language barrier as the instructions were more visual. The participants felt that it was easy to learn to use the system after some initial training ("Learning to operate the system would be easy for me" M=6.5, SD=0.7). User experience issues that need to be improved were related to the tracking system: participants were sometimes confused about how to hold the tablet in their hands. They also thought that the system might be too 'sensitive' for this environment and were questioning its robustness. The participants also found a mistake in the task instructions. Even though they mentioned before that this system might be easier to keep up-to-date, they had questioned this ability in their laboratory environment, because the parts change rapidly in the engine. After checking the step from the tablet they put the tablet aside. In addition, the maintenance technicians needed to take off their gloves every time they used the AR system.

3.3.3.2 *Work Perspective*

The maintenance technicians felt that the AR system supports knowledge sharing. All the necessary information could be found and it was near and available. However, they were concerned about whether they could trust the information that the AR system provided.

The maintenance technicians felt that the attitudes towards accepting this technology in their workplace would be positive. Maintenance technicians might have fears about new technology since they are afraid that anyone could then be seen to be capable of doing maintenance work and their skills would not be valued. They thought that this system could serve both novices and experts.

The maintenance technicians felt that it would be useful to develop this technology further. However, they reported that the battery lifespan needs to be long enough to last in the field. This AR system could be used also for photographs and video recording. The tablet could be machine-related so that information on the current maintenance target would be rapidly and easily available.

4. DISCUSSION

The purpose of this study was to find out if maintenance technicians find AR and wearable technologies useful and usable in their everyday work. This study was carried out in industrial settings with actual maintenance technicians. Even though there were only four test users, their feedback was valuable, as they have an understanding of the tasks and of how the solutions would really be used. Focusing on actual users is challenging, as enlisting several participants is difficult because of the nature of maintenance work: it is economically and time intensive and study participation can interfere with normal work. Therefore, a qualitative study approach was adopted.

In general, the user experience and usefulness of both systems was positive. However, the main problem with the wearable system was the number of different devices, since switching devices during use was perceived as challenging [34, 44]. In the augmented guidance case, during the work tasks, the users had to put the tablet aside quite a few times—which does not necessarily mean the work takes longer: Zheng et al. [32] showed in a Wizard-of-Oz study that a tablet is not slower to use than eyewear technologies in a maintenance task.

Novice maintenance technicians would benefit of the systems when using them for instructions and guidance. That said, maintenance tasks can be safety-critical, and it may not be possible to let novices to work by themselves and relying only on the guidance of technical systems. Experienced maintenance technicians wanted to use the guidance mainly when learning new things or doing maintenance tasks that occur rarely. It has been suggested that the assistance system could be adaptive so that different instructions are given to beginners, advanced and expert assembly workers [45]. Nevertheless, it is still challenging to adapt systems to users' needs and performances.

Based on the field studies, a more comprehensive and user-driven approach needs to be adopted during the design of wearable and AR systems. In the first study case, the smart glasses were attached to a helmet, which was an easy and useful solution. Unfortunately, a maintenance technician needs to take the helmet off occasionally and is not able to take photographs when doing so. Therefore, the goals and tasks of the user need to be known well. Work environments also need to be considered since they can be too harsh for certain types of technologies [46]. In both cases, the work environments were among other things greasy and dirty, which entails new requirements regarding, for example, touch screens. In the study of Zheng et al. [32], participants were worried about dropping a tablet or get it dirty. It is also important to consider the whole tool entity. In the wearable system case, there were several wearable devices functioning together. The participants would have preferred fewer devices, although the problems faced could perhaps be solved with smoother switching between devices. Maintenance technicians were wearing gloves, carrying things and using other tools. It is important to consider this as a whole from the system point of view to be able to provide devices that fit to the tool in its entirety and the working conditions. The information provided has to be contextually relevant, i.e. it has to be exactly the kind of information that is needed in the current work situation [45], and moreover, the information should be provided in a contextually relevant form and device. In the augmented reality case, there was an error in the disassembly procedure and in industrial settings, wrong information may have severe consequences. The user should be able to trust the information provided, and also understand the information. That is why it is important to consider how the information is presented (e.g., text, symbols) and in what language.

Based on these findings we suggest that when designing wearables and AR systems in industrial maintenance, more detailed consideration is given to (1) the goals and tasks of the user; (2) the usage environment; (3) the whole system of tools and devices, and (4) contextual information. These are additional to the more technology-driven or otherwise single-topic-related design guidelines, such as in wearable computing [36, 47–50] and in AR technology [51, 52]. Kourouthanassis et al. [53] have also proposed a set of more comprehensive interaction design principles for the development of mobile AR applications in a travel context.

As the number of test users was small and the tested systems were prototypes, the results indicate that these kinds of knowledge sharing systems are promising in industrial maintenance. More studies are required to obtain more comprehensive results, which would include more test users and more test environments. For instance, this study did not cover the typical situation where maintenance technicians have to travel to their maintenance site. In addition, the accuracy and transfer of information should be developed further to be able to test long-term use. In long-term use the technology's durability and robustness are key factors and therefore should also be studied further.

5. ACKNOWLEDGEMENTS

This study was funded by Tekes – the Finnish Funding Agency for Innovation – and was carried out as part of the S-STEP research project under FIMECC (Finnish Metals and Engineering Competence Cluster). The authors are grateful to all the researchers and company representatives who contributed to and supported the work presented in this publication.

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Publication III

Aaltonen, Iina; Kuula, Timo; Helin, Kaj; Karjalainen, Jaakko. 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. Pages 1–6. 2016.

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

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Abstract
Augmented reality has been pictured as one of the solutions for assembly and maintenance through the use of augmented guidance. We performed a video analysis on how users interacted with a tablet in a tabled-based AR-guided maintenance task. The setup included a virtual model of a rock crusher run in the background of a physical maintenance cabinet. In the analysis, attention was paid on whether the tablet was placed on a table and whether the maintenance tasks were done viewing past or through the tablet. The analysis showed that the tablet was mostly held in the left hand and actions were performed using the right. In most subtasks, participants viewed the objects past the tablet. However, when voltage had to be adjusted using a physical knob, many participants fumbled for the knob looking through the tablet. The users largely ignored the virtual model. The model, however, added to the realism of the task by masking the auditory feedback that the participants reported not hearing but to which they reacted. The study points out practical tips for supporting user interaction of tablet-based AR guidance systems for maintenance tasks. The findings on tablet use are relevant also in other domains where instructions are displayed on handheld devices.

• Human-centered computing~User studies • Human-centered computing~Mixed / augmented reality • Human-centered computing~Tablet computers

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1. Introduction

Augmented reality (AR), i.e., virtual images overlaid on real objects in real-time [Azum97], can be used in many domains, such as in maintenance, assembly and other manufacturing, military training, surgery, entertainment, and product design [OnYN08]. The augmented images can be displayed using head-mounted displays, handheld devices such as tablets and mobile phones, and projectors [NOCM12, ZhDB08]. The real-life objects can be either tracked based on their natural features or using visual markers attached to the objects [NOCM12].

One promising application area in maintenance and assembly is AR guidance; also termed AR instructions [ReBo14], AR-based job aid [ABME05], AR-assisted maintenance system and AR-based assembly guidance [OnYN08]. AR guidance means that instructions are given to the user in textual and/or visual format augmented on the target objects. The benefits of AR guidance in assembly have been noted in several studies: the tasks were easier to handle and they could be done more effectively and with fewer mistakes compared with other instruction formats, and skill transfer could be enhanced (see [OnYN08] for a review).

User studies in AR contexts have regarded human perception, user task performance, and collaboration between multiple collaborating users, and interface or system usability [Düns08]. Users' subjective experiences were most often measured using preference, ease of use, perceived performance and intuitiveness [BaBl12]. The methods in AR user studies have included questionnaires and/or performance measures [BaBl12], although some qualitative measures derived using direct observations, video analysis and interviews have also been mentioned [DüBi11].

In this study, we used video analysis to study user interaction with a tablet during a maintenance task with a tablet-based AR guidance system in virtual laboratory. The analysis considered how the tablet was held and how the participants viewed and acted on their surroundings through and past the tablet in different phases of the task. The purpose of the paper is to draw attention to the tablet use and give practical tips for supporting user interaction design of tablet-based AR guidance systems for maintenance tasks. The results on tablet use are relevant also in other domains where instructions are displayed on handheld devices, including the consumer market. Additionally, we discuss the effect of the virtual model.

2. Related work

There are several studies mentioning details on interaction with mobile handheld devices in AR contexts. These details are typically reported as additional comments, and the focus of research has often been in developing and comparing interaction techniques and devices.

In a study using handheld glasses for viewing and navigating AR content on a table and on a wall, the positioning of the participants' hands on the handle was described in detail, and a few were reported to tilt the device for changing the vertical viewing angle [GrDB07]. In a virtual object positioning and rotation task, mobile phone users were noticed to prefer holding the phone steady with one hand while pressing physical keypad buttons with the other [HeMB07]. Similarly, users of joystick-like handle for an ultra-mobile PC were observed to use a second hand for supporting the device in addition to the one grasping the handle [VeKr08]. In a CD-track selection task based on AR, some participants were observed to hold a phone sideways although the interfaces were designed to be used upright [Henz12]. In a Wizard-of-Oz study of a car maintenance task, participants using a tablet were observed to perform some manipulating tasks, which are usually done using both hands, using only one hand and holding the tablet in the other [ZFSD15].

3. User interaction study

The user tests were performed in a virtual reality laboratory where participants performed a maintenance task of a rock crusher with the help of augmented instructions.

3.1. System description

A virtual rock crusher was visualized in a three-screen system (Figure 1). The participants wore a helmet, which was tracked with Vicon optical tracking system to calculate the correct viewpoint with respect to the rock crusher.

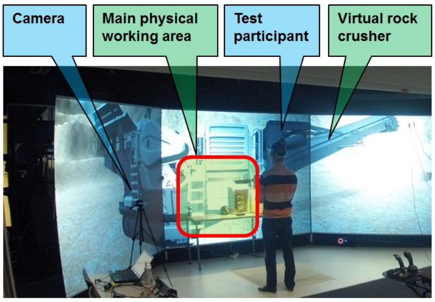


Figure 1. Layout of test set-up.

The main physical working area was located to front of rock crusher. On the desk, there was a maintenance cabinet containing removable modules with potentiometers for controlling the module output voltage (Figure 2, left). One of the modules had been intentionally made faulty. A tablet (iPad Air, iOS 8) was deployed for running the ARgh! system [HKKA15], with the application connected to a server for fetching the data about work task sequences, i.e., the module output voltages and cables connected. The logic of the modules was built with Arduino Uno. All the augmented instructions were visualized on the tablet (Figure 2, right) based on the currently active subtask and the tracked modules. Additionally, the tablet made a beep sound when a subtask was completed. The controller box was tracked in the ARgh! system with image-based tracking (Vuforia), which enables augmenting information (e.g., voltages) in the correct place over the controller box.

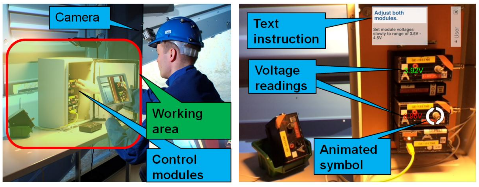


Figure 2. Left: Side camera view of participant. Right: Screenshot of the augmented instructions on tablet.

During the task, the virtual rock crusher acted as if it were a real machine. Depending on the modules' output voltages, the machine was "spitting out" a respective flow of rocks, with the corresponding sounds, which could be quite loud.

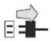
3.2. User experiment

The user experiment consisted of three parts: a training phase, the maintenance task (reported in this paper), and a teaching phase. The training was either an introductory video (01:38 min) or a short free exploration with the devices (max 5 min). In the teaching phase, the participant explained the basic functions of the AR system to a "novice".

Task The participant's task was to perform maintenance on the rock crusher by following the AR instructions on the tablet. The participant interacted with the real objects in the working area, and the tablet was used for receiving augmented instructions and acknowledging the completion of some subtasks by tapping the screen (see Table 1).

Firstly, after starting the machine, the system instructed the participant to adjust the voltages of the two modules in the cabinet (Figure 2). While being adjusted, one of the modules reported it was malfunctioning, and the participant needed to exchange the broken module with a new one. The test was completed after both modules were working, the voltages adjusted to correct readings and the engine was running. In every other test, either module 1 or module 2 was malfunctioning.

Table 1. AR guidance in each subtask, with corresponding notions of user interaction regarding viewing and acting through or past the tablet. The symbols were animated, and their position over the objects indicated where the actions should take place.

AR guidance		**User interaction**	
Text instruction	**Symbols and example voltages**	**Through or past the tablet**	**Other notions by researchers**
[Test starting -screen]	-	**Through**: walking toward the desk	
Ladies and gentlemen, start your engines! Press and hold start button.	-	**Past**: 3 persons Through: 1 per.	Virtual rock crusher was glanced multiple times.
Adjust the modules. Set voltages to range of 3.5-4.5 V	 4.92V (red) 0.96V (red)	Many fumbled for the knobs **through** the tablet and did the adjustments.	Three participants tilted the tablet for better angle. Two reacted to auditory beeps.
Fault detected in module 2! Turn off the machine by pressing the stop button.	3.92V (green) or 0.96V (red)	Most viewed **past** the tablet.	
Machine is now turned off! Disconnect cable from module [1 or 2].	 3.92V (green) or 0.96V (red)	Most viewed the cables **past** the tablet.	Most participants spent some time on finding a suitable viewing angle. There was some confusion on which cable should be disconnected and how.
Module [1 or 2] disconnected. Now remove module [1 or 2] from the chassis.*Click here once you have removed the module.* 	 3.92V (green) or 0.96V (red)	Mostly **past** the tablet.	Some confusion on where to put the module while acknowledging the task by tapping.
Module [1 or 2] removed. Now pick up new module and place it the chassis. *Click here once you have placed the module.*  		Mostly **past** the tablet.	Some uncertainty on from where to pick the new module.
Module [1 or 2] placed. Connect cable to module [1 or 2].	 3.92V (green) or 0.96V (red)	Mostly **past** the tablet.	Two put the tablet on the desk. Three reacted to auditory beeps. Two relied only on the written instruction; the connect symbol was not shown on screen. Three others took extra care to check the whole instruction with symbols.
Start your engine! Press and hold start button.	[symbols unrelated to start button]  3.92V (green) 0.96V (red)	Two acted **through** the tablet; two others glanced **past** the tablet but pressed the button viewing **through**.	
Engine is running! Now adjust the modules to correct voltage of 3.5-4.5V.	 3.92V (green) 0.96V (red)	Most viewed **through** the tablet; three observed fumbling for the knobs.	One had difficulties with the tracking being blocked by hand, and tried holding the tablet in left, then right hand, and partially adjusting the voltages blindly.
You did it! Both modules are working as they should. So keep it as it is…*Click here to restart.* 	4.42V (green) 4.31V (green)		

Participants Six persons (4 male, 2 female) participated in the user experiment. All participants worked as researchers or senior researchers and they were aged between 30–43 years. All participants had adequate English skills to use the system with English instructions. All other test materials (spoken instructions, questionnaire and interview questions) were provided in the participants' native language, and in English for one person.

The participants' prior experience with technical devices and technologies was asked. At the minimum, all participants understood the terms tablet, virtual reality and augmented reality. One reported being an active user of them, and two others had some experience of AR.

Data collection Prior to experiment, the participants filled a consent form. Data was collected using videos, audio-recordings, and observation notes taken by researchers. Two cameras were used in each part: one docked on the helmet (GoPro2, Figure 2) and one providing a side view (Figure 1). In addition, the participants filled in questionnaires regarding simulation sickness, usability, and learning (not reported in this paper). Lastly, the participants were interviewed.

Video analysis The video material was analysed by transcribing the actions seen in the videos subtask by subtask, using both video views. A special emphasis was paid on the use of hands and the positioning of the tablet. The following notions were made on the participants behaviour:

- Duration of the task
- Mistakes (not following the AR instructions)
- Holding the tablet by hand(s) or putting it on the desk
- Viewing objects through or past the tablet
- Signs of noticing the system-generated beeps of accomplished subtasks
- Signs of noticing the virtual rock crusher
- Moving in the virtual laboratory
- Reading the written instructions on the tablet screen
- Actions based on the AR instruction or by own initiative
- Spoken comments and questions
- Acknowledging the completion of a subtask by tapping a text box.

4. Results

All participants successfully completed the maintenance task in 2–5 minutes (mean 3:10, sd 1:00). Two participants disconnected a wrong cable, but otherwise the task was completed without mistakes. There was very little speaking during the task. On two occasions, the system had to be booted due to a dropped network after which the correct subtask was resumed. The tracking of the modules worked fluently, although participants sometimes had to adjust the viewing angle.

4.1. User interaction with the tablet

The participants mostly used their left hand for holding the tablet, and performed actions using their right hand, either watching through or past the tablet (Table 1). Three participants had a habit of pausing and holding the tablet with both hands for a better view, often accompanied by taking 1–2 steps back or leaning slightly backward. Some commented that putting the tablet on desk was not practical, because all feedback came via the tablet.

The tablet was put on the table by two participants when they had difficulties with the cables. Otherwise the tablet was held by at least one hand, also when it was awkward to tap a text box on screen while holding a module.

All participants viewed both through the tablet and past it in at least one phase of the task, while simultaneously looking at or acting on the physical objects. In some cases, it could not be estimated from the videos when a participant switched from viewing through or past. Nevertheless, most subtasks related to connecting or disconnecting cables and modules were viewed past the tablet (see Table 1). Although most participants completed these subtasks without mistakes, there was confusion on which cable should be disconnected even though the symbol's position indicated the correct cable. On the other hand, when the participant had to reach for the modules' knobs, it was mostly done through the tablet view, resulting in some fumbling for the knob (Figure 3). During the voltage adjustment, most kept the view through the tablet.

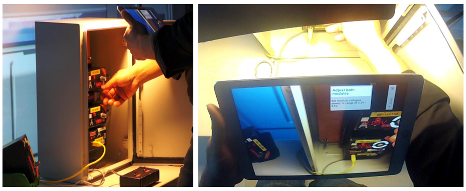


Figure 3. Adjusting voltages. Left: Participant is reaching for the upper module's knob while viewing through the tablet and misses it by a few centimetres. The tablet tilted towards left when the participant started reaching forward, and the hand was not visible on screen. Right: Shortly after, the participant has adjusted the tablet slightly to the right to view the voltage readings (head-mounted view). The fingers are fixed on the knob, but not visible on screen.

4.2. Audio feedback and virtual model

When interviewed, all participants said they had not heard any sounds besides the virtual rock crusher. The video analysis, however, showed that five participants reacted to the feedback beeps. The unnoticed beeps made the participants either stop their current action or look at the tablet. The virtual rock crusher was largely ignored by the participants; the participants looked at the model only when initially walking closer to the desk, where they remained throughout the task, and right after starting the engine.

5. Discussion and conclusions

Handheld devices for AR are attractive to users because they are common, cheap and easily available. Their mobility and light weight also appeal to the users, even though they may have small keypads and screens, limited resolution, bandwidth, and computational resources [ZhDB08]. Compared with wearable devices, however, with handheld devices the interaction may take different forms because the augmented view is not always "on". To study the interaction, we used video analysis to examine how participants used the tablet in an AR-guided maintenance task.

The participants were observed to use the tablet with one and two hands, and they viewed their surroundings both through and past the tablet. One hand activities were also reported in [ZFSD15]. In this study, both hands were used for holding the tablet in order to get a better view of the overall situation, as opposed to maintaining the device still for reducing jitter as in [Henz12]. In addition, the participants were observed to tilt the device for a better angle as also mentioned in [GrDB07].

The participants were mostly observed to view their surroundings and manipulate the physical objects past the tablet display using their right hand. When the participants needed to turn a physical knob to adjust the voltage, however, many looked through the tablet even when it made them fumbling for the knob. In addition, few put the tablet on the desk at all, because the visual feedback needed to be monitored from the tablet.

The use of the virtual model of the rock crusher in the background had only a small effect on the participants' behaviour. On one hand, the sounds of the rock crusher masked the auditory feedback (beeps), as the participants reported not having heard any auditory signals, but in the video analysis it was apparent that they still reacted to them. Using the virtual model therefore took the experiment one step further from a laboratory.

On the other hand, the participants did not seem to pay attention to the virtual rock crusher after the machine was started, although it was indicated during the initial introduction that the target of maintenance was the rock crusher. There can be several reasons for this. The participants might have thought that the virtual model was there only for decorative purposes. The participants with at least some prior experience with AR seemed to pay even less attention to it, so it is possible the others were looking at the machine only because of its novelty effect. Following the same line of thought, the participants in this study were volunteers and not experienced with maintaining machines, whereas a professional technician used to reacting to the sounds of a machine might have acted differently. In addition, the AR instructions were so detailed that the machine could be effectively ignored, and therefore the lack of interest toward the machine was only slightly surprising.

The main limitation of the research design was the positioning of the side camera. In some instances, the video view from the side camera was sometimes limited and the participants head was not always visible. Using the view from the head-mounted camera – which was mounted atop the helmet about 10 cm above the eyes – and a side camera view centred on the working area, left some uncertainty to estimating whether the participant looked past or through the tablet, and exact percentages for viewing past or through could not be given. Therefore, it is important to make sure the whole user is visible in the camera to see the direction of gaze and the position and angle of the head. Additionally, gaze tracking technologies could be used.

A longer set of experiments would be useful for observing long-term effects on user interaction [Henz12]. The guidance could include repeating elements such as actions related to manipulating heavy or tightly attached objects, performing continuous adjustments, and pausing to fetch tools from a farther place. In addition, the overview of typical handheld AR tasks and characteristics in [VeKr08] can be of use.

Several authors have suggested design guidelines for AR guidance. Chimienti et al. [CIDD10] outlined a "standard procedure" for designing AR guidance for assembly tasks with the help of flow charts and selection charts. In the same line, a framework for supporting remote maintenance has been suggested, including aspects of how to manage the instructions and what kind of textual and visual elements can be used [ReBo14]. Additionally, user-centred requirements for maintenance, e.g., how the system should support diagnostic activity, have been discussed [ABME05]. Some examples for applying HCI design principles in AR contexts have also been given [DGSB07].

Based on our findings on the tablet use, we suggest considering the following in the future design of AR guidance to support user interaction:

- Symbol for indicating the work area

If the whole work area is not visible on display, or the user needs to get a broader view of the situation and take a step back for "zooming out".

- Cueing symbol for listening or inspecting the physical machine

In order not to make the user too immersed by the AR guidance, the instructions cue the user for paying attention to, e.g., a specific sound.

- Symbol for managing a task by one hand only or placing tablet on a surface

An indicator for suggesting the task can be accomplished using one hand, or that both hands are needed and the tablet should be placed aside.

- Surfaces for placing the tablet

In a car maintenance task, the test users were reported to easily find convenient places for placing the device [ZFSD15], but in the industry the working area can be greasy [ArAV16] and finding a surface nearby is harder.

- Instructions displayed on a set-aside tablet

The instructions on a set-aside tablet should be designed so that they can either be “frozen” or user can manually click on different phases without needing to repeatedly pick up the tablet and aim at the objects.

- Auditory feedback

Audio beeps can be used to target the users’ attention, even in rather noisy conditions. In this study, the participants wished to have more (especially audio) feedback on when to proceed.

The findings on tablet use are relevant also in other domains where instructions are displayed on handheld devices. The different ways of interaction can be also taken into account when teaching future maintenance technicians how to use AR systems. It would be beneficial for them to recognize what kind of tasks are most efficiently be done using one or two hands, and develop their own preferred work practices. Finally, an interesting area to explore is to study if a user can benefit from performing some tasks through the tablet display, and how can the design of these systems support that.

Acknowledgements

We thank all test and project participants. This study has been funded by the European Commission’s Seventh Framework Programme FP7 under grant agreement 318329 ‘TellMe-project’. I.A. has received a grant from Wihuri foundation for writing her PhD work.

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Publication IV

Aaltonen, Iina; Aromaa, Susanna; Helin, Kaj. Muhammad, Ali. 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. Advances in Intelligent Systems and Computing, volume 595. Pages 335–347. 2018.

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

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Abstract. Multimodal, wearable technologies have the potential to enable a completely immersive teleoperation experience, which can be beneficial for a number of teleoperated robotic applications. To gain the full benefit of these technologies, understanding the user perspective of human-robot interaction (HRI) is of special relevance for highly advanced telerobotic systems in the future. In telerobotics research, however, the complex nature of multimodal interaction has not attracted much attention. We studied HRI with a wearable multimodal control system used for teleoperating a mobile robot, and recognized a need for evaluation metrics for multimodality. In the case study, questionnaires, interviews, observations and video analysis were used to evaluate usability, ergonomics, immersion, and the nature of multimodal interaction. Although the technical setup was challenging, our findings provide insights to the design and evaluation of user interaction of future immersive teleoperation systems. We propose new HRI evaluation metrics: Type of multimodal interaction and Wearability.

Keywords: Human-robot interaction · Metrics · Multimodal · Wearable · Telerobotics · Immersion · User studies

1 Introduction

Immersive telerobotics, where the user can experience being present at the site of a teleoperated robot, has great potential in many domains, for example, in operating planetary rovers [1] and other tasks in the space [2], mining [3], nuclear power plants [4], high-pressure ocean missions [5], and robotic surgery [6]. From the user perspective, the combination of a teleoperated robot and wearable multimodal interfaces is fascinating. When users are required to interact with the environment via a robot using these interfaces, it is no longer trivial to evaluate and understand the nature and quality of human-robot interaction (HRI).

Many teleoperated systems with wearable, multimodal interfaces have been developed, but most often the user experience is considered very briefly and comprehensive user evaluation methods have not been utilized. Using quantitative performance metrics

J. Chen (ed.), *Advances in Human Factors in Robots and Unmanned Systems*,
Advances in Intelligent Systems and Computing 595, DOI 10.1007/978-3-319-60384-1_32

[7] or established questionnaires (e.g., [8, 9]) alone is not enough to account for the nuances of multimodal interaction and the effects of virtual displays. Qualitative methods, such as interviews and observations, are needed to capture the user experiences and the way the multimodal interfaces are actually used.

In this paper, we suggest two evaluation metrics that should be considered in designing and evaluating HRI of immersive telerobotics systems: Type of multimodal interaction and Wearability. The need for the metrics was recognized in a case study, which is also reported in this paper. Based on existing literature and our findings, we also suggest methods for evaluating them. In Sect. 2, the human aspects of multimodal interaction and existing evaluation methods, and related research in telerobotics, are introduced. Section 3 describes the case study, the used evaluation procedure and results. In Sect. 4, the results are discussed and metrics for evaluating wearable and multimodal interfaces are proposed.

2 Related Work

2.1 Evaluation of Multimodal Interaction

In general, in multimodal interaction, the user interacts with a system using two or more modalities, which can refer to sensory modalities (e.g., visual, auditory, [10]) or input modes (e.g., speech, touch, gesture, [11]). Multimodal displays, and also controls, have been suggested for HRI to decrease task difficulty, promote sense of immersion, and mitigate operator workload (see [12]). Several evaluation methods for multimodal interaction have been used in the human-computer interaction domain.

PROMISE [13] is a framework for multimodal dialogue system evaluation which includes several quality and quantity measures. Although PROMISE was developed for multimodal dialogue systems, some of the measures are applicable to HRI, such as user/ system turns and semantics. SUXES [14] is a method for capturing and comparing both user expectations and user experiences. The statements can be used for evaluating the overall system and for different input and output modalities. Kühnel et al. [15] compared available usability questionnaires and found that methods AttrakDiff, SUS, and USE are suitable for the usability evaluation of systems with multimodal interfaces, but the selection of questionnaire depends on the purpose of the evaluation. Ramsay et al. [16] evaluated a multimodal mobile phone map application using a variety of methods: log data, field notes (recordings and observations), and interviews. Wechsung [17] has developed a taxonomy for describing multimodal quality aspects of interaction and designed a psychometrically validated MultiModal Quality Questionnaire (MMQQ); The basis was in questionnaires designed for unimodal systems, which were found inapplicable for usability evaluation of multimodal systems.

2.2 User Evaluation of HRI

The metrics for evaluating HRI have been divided into human, robot, and system components [18]. The human component includes seven items: accuracy of mental models, degree of mental computation, human reliability, productive time vs. overhead time, situation awareness, trust and workload. In general, five primary methods for user evaluations in HRI have been suggested: self-assessments, interviews, behavioural and psychophysiology measures, and task performance measures (e.g., time to complete a task) [19]. The use of three or more methods is recommended.

2.3 Wearable and Multimodal Interfaces in Telerobotics

A number of studies mention user experiments of telerobotic systems with similar properties to ours: wearable and multimodal control of a field robot [20, 21]; multimodal control of mobile robots [22, 23]; a haptically controlled robot [24, 25], also in robotic surgery [6]; wearable [26, 27], tangible [28] and traditional [29] user interfaces; and head-mounted displays (HMDs) [30, 31]. Typically, the experiments have involved quantitative performance evaluations, whereas user-related measures are mentioned very briefly and methodological details are often omitted. None of the papers found have elaborated on the multimodal interaction from the user perspective. The following user experiments provide, however, a representative sample of diverse methods used in the evaluation of the human component of HRI.

Kechavarzi et al. [29] evaluated three user interfaces for a teleoperated mobile robot. The methods used were a survey of participants' perceptions of robots and immersive tendencies; performance measures (e.g., time to perform); questionnaires (e.g., satisfaction, immersion, intuitiveness, comfort); and an interview. Fernandes et al. [26] tested three interfaces, including a wearable arm-mounted one, for operating a robotic manipulator in a pick-and-place task. Both objective (e.g., outcome of task) and subjective (a survey concerning ease of use) measures were used. Zareinia et al. [6] tested three haptic hand-controllers in a robot-assisted surgical system. Ten performance measures (e.g., operator effort) and a questionnaire (e.g., easiness to learn and use the system, and comfort) were used. Livatino et al. [31] evaluated different screen and display types, including an HMD, in a virtual medical endoscopic teleoperation task. Both quantitative (collision rate etc.), and qualitative variables (questionnaire, e.g., presence and comfort) were used.

3 Case Study

3.1 Setup

Robot System. The robot included three main components: (1) a four-wheel drive remote controlled car, operated by a 12-volt battery, provided forward, backward and turning manoeuvrings, (2) a robotic arm (Lynx al5d) included three main links and actuator (effector), and (3) a non-stereoscopic pan tilt camera (Tenvis JPT3815W), mounted on an aluminium construction 40 cm over the rover (Fig. 1 – Left). Similar systems have been described in [20, 21].

Fig. 1. Left: Robot system. Right: User with HMD and data glove in a mixed reality laboratory. The hand posture is IDLE.

Gesture-Based Control System. The control system was composed of four subsystems. (1) A main computer connected with wireless adapter (Xbee), communicating with the rover. This computer was also connected with (2) an HMD (Oculus Rift DK1) which provided mono-camera feed to users. The tracking position of the HMD was used for the pan tilt camera control. (3) The user also wore a right-handed data glove (5DT-5 Ultra) and (4) the arm of the user was constantly tracked with a Kinect depth camera (Fig. 1 – Right).

The user interacted with the robot system in two ways. First, by tilting the HMD, the user controlled the camera placed on the rover and received visual feed of the robot's surroundings. The same image was displayed for both eyes (Fig. 2 – Left). Second, using the arm with the data glove, the user drove the rover and controlled the robot arm and the gripper. Only one control mode could be active at the time.

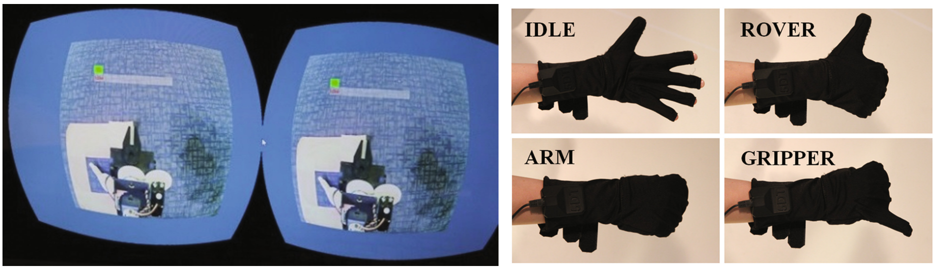

Fig. 2. Left: The HMD view looking down at the gripper and the target. The mode is IDLE, and the tracking is working (*indicated by the green square in the upper left corner*). Right: The data glove and the hand postures for switching the control modes.

The control mode was switched using the glove with different hand postures (Fig. 2 – Right). The modes (postures) were: ROVER (a fist, thumb pointing left), robot ARM (thumb under the fist), and GRIPPER (thumb under fist, 1–4 fingers outstretched, e.g., pinkie, depending on the user). In addition, holding all fingers outstretched put the system to IDLE mode. In the upper left corner of the HMD view, the user was shown which mode was active. A red or green rectangle also indicated if the system could track the user's arm position.

The user's arm position controlled the robot's action. In the ROVER mode, the robot could be moved forward (arm away from torso), backward (towards shoulder), or turn (to either side). In the ARM mode, the position of the user's hand defined the absolute position of the robot's gripper. For example, if the users moved their fist up, the robot lifted its arm/gripper to a corresponding position. In the GRIPPER mode, moving the hand to the right (left) would close (open) the gripper.

3.2 Test Procedure

Participants. Nine volunteers (5 males and 4 females) participated in the final user test, preceded by a debugging session with three testers. The participants were aged 29–57 (average 36) and they were all right-handed. They were recruited via a research organization. Three participants reported using virtual reality technology frequently and four rarely. Two did not have any experience of 3D technologies; others had seen 3D movies or played games. In addition, three participants had prior experience of telerobotics using a haptic control device and a virtual display, and one had teleoperated a farming crane using joysticks.

Task. The task was to teleoperate a robot on Mars to collect a sample ("a rock") while being seated in an orbiter (cf. [32]). The test took place in a mixed reality laboratory where the participant was seated on a chair next to the robot arena. Prior to test, the participant could see the robot's surroundings and practice operating the robot also without mounting the HMD. There were five phases in the task: (1) Drive the robot next to the rock. (2) Move the robot arm next to the rock. (3) Pick up the rock with the gripper. (4) Drive the robot next to a box. (5) Put the rock into the box.

Data Collection. Prior to the test, each participant filled a consent form, a background information form, and two questionnaires: simulation sickness questionnaire (SSQ) and a bodymap. All questionnaires are described in the next subsection. A researcher took notes on how the training phase (duration 10–16 min) went, noting any difficulties in training or technical adjustments.

During the test, the participant's and robot's performance was videoed from three different angles, a side and front view of the participant, and an overall view showing the robot, the rock, the box and the participant in the background; additionally, the view from the HMD was saved. Researchers filled an observation form for each participant and took notes on performance, timing, technical issues, use of control modes, ergonomics, and participants' effort and frustration. Furthermore, researchers noted instructions and other help that were given. The test time was limited to 15 min.

After the test, the participant answered to SSQ, NASA-TLX, bodymap and usability questionnaires, and was interviewed. The audio-recorded interviews were structured to cover themes of training, task performance, user interfaces, and the control concept. In addition to the user evaluations, two human factors researchers used the robot system and made a heuristic evaluation based on Nielsen's heuristics [33].

Questionnaires. An adapted SSQ [9] using 30 items was used to collect simulation sickness symptoms. The experience of discomfort in a certain area of the body was assessed using a bodymap of the upper body (7-point scale: no discomfort–severe discomfort). An unweighted NASA-TLX [8] was used to collect the experience of subjective workload. The usability questionnaire consisted of 40 statements (5-point Likert scale: completely disagree–completely agree). The statements were formulated using a combination of several approaches: systems usability framework [34], Multi-criteria Assessment of Usability for Virtual Environments (MAUVE) system [35] (especially statements originally by R.S. Kalawsky, J.L. Gabbard and D. Hix), and usability factors and goals [36]. The final 40 statements concerned wayfinding, navigation, object selection and manipulation, visual output, presence, immersion, comfort, aftereffects, and the operating concept in general.

Data Analysis. Basic descriptive statistics were calculated from the questionnaire data. The interview answers were grouped regarding pros, cons and improvements of the interfaces as well as any comments on the control modes and multimodal interaction. The three video views and the HMD view were replayed synchronously, and a video analysis was performed. Each test was watched 1–3 times, and the following aspects were noted during each task phase: general description of the nature of interaction, simultaneous use of the HMD and the glove, keeping gaze on target in the ROVER mode, ergonomics issues, mistakes, errors and help given. These findings were combined with the written notes.

3.3 Results

Usability, Ergonomics and Immersion. Based on the heuristic evaluation, the control system was not stable and mature enough to provide a required usability level for users, and therefore most questionnaire results are not reported in detail. In general, the gesture-based control system was natural to use but too insensitive and not always responding to gestures. Identified issues regarding the visual display were image lag and narrow field of view (FOV). Furthermore, the camera image drifted with abrupt head movements, and it had to be reset on several occasions.

Five participants successfully completed all five phases of the task. In three cases, technical problems affected the rover control and some test phases were skipped; and one participant ran out of time. A researcher helped each participant during the test, e.g., by giving verbal instructions to move the robot to a better position if the participants lost their sense of orientation. Three participants mentioned more training would have been useful, for example, to better estimate the mapping between their arm position and the robot speed. The NASA-TLX results and interviews indicated that the participants experienced the test as frustrating and mentally demanding, because the system missed their gestures. Compared with others, the three participants with prior experience of telerobotics had evaluated the task less demanding on all accounts.

The best benefits of the wearable control were mentioned to be the feeling of presence and immersion in the task, and that the wearable interface would be a natural way to operate. Most participants thought they could act naturally with the wearable devices, supported by the questionnaire data ("The HMD did not feel clumsy to wear.", mean and standard deviation 4.1 ± 1.1, scale 1–5 disagree–agree; and "The glove allowed me to move my hand naturally.", 4.3 ± 1.0) and user comments. There were, however, several comments on the hand postures, mostly about difficulties in remembering the control modes but also some on the formation of the posture. The mode changing in general seemed to work better when the IDLE mode was activated between the active modes. Table 1 lists the pros and cons of the devices that were brought up in the interviews.

Table 1. Users' evaluations of wearable devices.

Device	Pros	Cons
HMD	Comfortable, not heavy Nice fit Realistic transmission delay Adequate resolution Clear view to surroundings Camera orientation with respect to body	Neck pain due to posture Not securely attached Long delay Poor image quality Small FOV, perspective Depth vision missing Drift
Data glove	Light-weight, soft Easy to move with Operating without a medium	Sweaty Loose fit No feedback

According to SSQ, there was a minor increase in general discomfort due to the HMD, but otherwise no negative symptoms were mentioned. Regarding ergonomics measured using the bodymap, the main finding was that the participants felt more discomfort in their right shoulder after performing the test (discussed in more detail in S. Aromaa et al. (in review)). Some participants mentioned the required arm trajectory was too wide and therefore uncomfortable. Furthermore, there were comments on awkward postures when the participant's head was "in the right armpit" and the right arm was stretched to upper left. Our observations support these comments.

The participants suggested many improvements. Several comments were made on improving the perspective and FOV of the HMD to show the robot arm at all times. Stereo image, or alternately a depth indicator and the ability to zoom were also wanted. An indicator was also suggested for showing the position of the robot arm. Furthermore, the image should follow gaze more smoothly and with less delay. There were suggestions to include haptic feedback to the glove, especially for object manipulation. The sensitivity of the glove should also be improved. Suggestions were also made to make the required arm movements smaller, and provide elbow support and a physical "knob" to hold onto for position estimation. Regarding the changing of the control modes, one suggested that the left hand could be used for that purpose, or the glove be replaced by a keyboard. Another participant suggested using a joystick for driving the rover and using the glove for the robot arm. For operating in the GRIPPER mode, a pinch-like hand movement was suggested.

Multimodal Interaction. Multimodal interaction was assessed mostly based on the video material. Although individual aspects of the robot control were considered difficult due to technical issues (and thus not reported further), five of nine participants—including all participants with prior teleoperation experience—agreed the concept of operation was logical ("The system was operated in a way I would expect it to be operated.", mean and s.d. 3.2 ± 1.3).

The HMD and the hand gestures were used simultaneously by all participants in the ROVER mode. The most common working strategy was to keep the target (the rock or the box) in the visual field while driving straight forward. If the target was located slightly toward either side, however, the participant did not always realize that the robot heading was not that shown in the centre of the HMD, and the robot passed by the target. One participant was noticed to manoeuvre the rover while turning and simultaneously keeping the target in the view.

We could also observe that some participants turned their head to the direction of their extended arm; either slightly toward a side when turning, or up and down when accelerating and decelerating. When the robot was mobile, the head movements were small and slow with the exception of one participant who moved his head with bigger, jerkier movements. Bigger, searching head movements were clearly done in the IDLE mode. In the ARM and the GRIPPER modes, the HMD view was hardly altered. Typically, the HMD was moved 1–2 times to get a new viewing angle while the arm was kept still. Similar to the ROVER mode, the participant's head tended to follow the arm, but the movements were very small.

4 Discussion

The tests showed that the concept of the multimodal control system was workable and the participants could, despite short training time, teleoperate the robot, although the overall usability could not be evaluated due to low maturity level. Both the HMD and the data glove were felt comfortable for the most part, which could be expected as they are commercial products, and the participants could move naturally while wearing them. However, uncomfortable body postures (especially those related to using both devices) were observed and reported by the participants.

The participants intuitively used the HMD and the hand gestures simultaneously, even though they had not been specifically instructed to do so—which could have caused bias towards using the modalities in a certain way [37]. Regarding the simultaneous use, more training, and perhaps an instructive video, might be useful in making operators aware of typical human actions. For example, when you are learning to drive a car, you need to put a conscious effort not to turn the steering wheel when you check over your shoulder. A similar coupling was observed in the user study. Likewise, it seemed easy to forget that the view on the HMD did not necessarily show the heading direction of the robot—many times the robot or its parts were not visible in the HMD. Adding a heading indicator on the visual display could be helpful.

Originally, the research focus of the case study was on developing the technology of the robot system, and therefore the selection of gestures was done in a very late stage. Ideally, the gestures would have been iteratively designed and tested with users; our participants made valid suggestions for improvement, which can be accounted for in the future. Many of the questionnaire responses reflected the users' frustration on the technical issues, and therefore the interviews and videos proved very valuable in evaluating the user interaction. In the future, the questionnaire and interview items should probe deeper into the nature of multimodal interaction, and some of the user tests could be performed using a simulated robot to overcome the problems related to the robot technology—preferably as a part of iterative design of the user interfaces.

The benefit of doing the case study—regardless of the technical difficulties—was the realization that the multitude of questionnaires and interviews did not cover the multimodal interaction, which was observable in the videos. Furthermore, the human aspects of multimodal interaction are also neglected in the HRI literature, with the exception of multimodal dialogue research. We think multimodal interaction should be studied more rigorously because it will affect the human performance. In addition, we also feel that the wearability of different devices is essential in immersive telerobotics and suggest it should also be used as a HRI metric.

4.1 Suggested Metrics for Wearable and Multimodal Systems

Some of the existing HRI metrics [7] can be useful in evaluating the human aspects of multimodal devices, for example, "Accuracy of mental models of device operation" and "Degree of mental computation". In addition, mental and physical workload and situation awareness apply to multimodal interaction in any domain, and also to wearable interfaces. For ensuring good HRI in telerobotics with wearable and multimodal interfaces, two new metrics are suggested: Type of multimodal interaction and Wearability.

Type of Multimodal Interaction. By this metric we mean to cover the multimodal interaction that (1) the user engages in and (2) the system is capable of. This is close to the quality measure "ways of interaction 'n-way communication (several modalities possible at the same time?)'" used in PROMISE [13]. In addition, four categories (Exclusive, Alternate, Concurrent, Synergistic) have been used for describing multimodal interaction along two axes: use of modalities (sequential or parallel) and data fusion of different modalities (combined or independent) [38]. These categories can be useful in describing interaction for both the system and the user.

More importantly, user tests are needed to evaluate if the users can and will use all the multimodal capabilities the system offers, and how. In practice, we suggest using several methods to evaluate the quality of multimodal interaction. First of all, the experimental task should be designed so that there are possibilities for using the modalities individually and in parallel to facilitate evaluation.

To tackle the multimodality and parallel use, questionnaire statements such as those introduced in MMQQ [17], could be used, e.g., "The different input modalities are blocking/complementing each other." In addition, evaluating single modalities on their ease of use and learnability is important, as well as the logic on the system level, e.g., "The system was operated in a way I would expect it to be operated.", and "The way the system was operated was convincing and suits professional use." [34].

In interviews, these issues can be elaborated further: what aspects were easy or difficult; how natural did the users experience the combination of modalities; did the users have a conscious strategy to use the modalities sequentially or in parallel, and how did this strategy evolve. Furthermore, observations—preferably complemented with videos—are needed to evaluate how the users actually used the modalities, e.g., preferences, disuse or mistakes, and changes in behaviour or speed. Some information can also be deduced from performance measures and log files, if available.

Finally, when evaluating multimodal interaction involving multiple sensory modalities, the psychological effects related to multimodal processing need to be considered [11, 39]. The evaluation gets more complicated when the system output (feedback to user) is multimodal, and it cannot be directly observed which modalities affected the user's actions—one possible solution is to test the system using combinations of the available modalities.

Wearability. In the telerobotics context, we consider wearability, or "the interaction between the human body and the wearable object" [40], to be characterized by comfort, ergonomics, freedom of movement, and intuitiveness of learning and using the system. Intuitive control, especially when the designed physical representation feels natural, has been associated with improved performance [6, 28], and is closely related to immersion [29]. Intuitiveness is also indispensable if the users have very little training or when attention cannot be allocated to secondary tasks (e.g., [20]).

Regarding HMDs, wearability also involves issues related to virtual displays in general, such as simulation sickness, immersion, situation awareness, sense of direction, and quality of display (2D vs. 3D, resolution, delay; e.g., [29, 30]). In addition, when combined with other wearable devices, it is important to observe if the users adopt awkward body postures without noticing.

In practice, many of the wearability aspects can be measured using customized usability questionnaires such as those used in the case study. The guidelines [40] and methods [41] for wearable computers can be used as well. Additionally, performance measures (e.g., training time) can be useful in determining the intuitiveness of use. User comments and observations are needed to complement the quantitative data.

4.2 Conclusion

In telerobotics research, the human aspects of multimodal interaction have not attracted much attention. We studied human-robot interaction in the context of teleoperating a mobile robot using a wearable multimodal control system. In the case study, we noticed the complex nature of the multimodal interaction and realized there is a need for user evaluation metrics for immersive telerobotics. Two metrics were introduced: Type of multimodal interaction and Wearability, along with methods for measuring them. In future work, the metrics and methods should be researched further. The metrics can help in the design and evaluation of HRI in immersive telerobotics, and also in other teleoperation tasks such as in crane operation and mining.

Acknowledgements. We thank test participants. Research funded under the European Commission's Seventh Framework Aeronautics and Air Transport (AAT) programme in the project VR-HYPERSPACE (AAT-285681) 'The innovative use of virtual and mixed reality to increase human comfort by changing the perception of self and space'. The work of I. Aaltonen was supported by Wihuri Foundation.

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Publication V

Aaltonen, Iina; Wahlström, Mikael. 2018. Envisioning robotic surgery: surgeons' needs and views on interacting with future technologies and interfaces. John Wiley & Sons, Inc. The International Journal of Medical Robotics and Computer Assisted Surgery, e1941. https://doi.org/10.1002/rcs.1941.

Received: 13 November 2017 | Revised: 30 May 2018 | Accepted: 11 June 2018
DOI: 10.1002/rcs.1941

ORIGINAL ARTICLE

WILEY The International Journal of **Medical Robotics** and **Computer Assisted Surgery**

Envisioning robotic surgery: Surgeons' needs and views on interacting with future technologies and interfaces

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Abstract

Background: The development of technology in robotic surgery is typically presented from a technical perspective. This study considers the user perspective as an input to the development of technology by exploring potential solutions within and beyond the field of robotic surgery.

Methods: Advanced technological solution concepts were selected based on a technology review and an ethnographic study. Using a future workshop method, these were rated and discussed by a group of surgeons from three perspectives: enhancing operation outcome, user experience and learning in the operating theatre.

Results: Diverse technologies were considered to offer potential for supporting the surgeons' work. User experience and learning could be improved especially via solutions novel to robotic surgery. Robotic surgery technologies currently under development were mainly considered to support a good operation outcome. Suitability for practical work was elaborated upon, and related concerns were identified.

Conclusions: The results can support development of robotic surgery to enhance surgeons' work.

KEYWORDS

future workshop, human–robot interaction, learning, robotic surgery, user experience

1 | INTRODUCTION

Robotic surgery is the most recent advance in minimally invasive surgery. Although laparoscopy too enables such surgery, robots offer better ergonomics,[1,2] visualization opportunities, more degrees of freedom and decreased tremor effect.[3] Surgical robots have been criticized for their high costs, however, and they tend to be large and cumbersome to handle in the operating theatre.

The literature reviewing the state of the art and future directions in robotic surgery focuses on solutions for surgery in general,[4-11] or for distinct domains, such as neurosurgery,[12] head and neck,[13] coronary bypass[14] and gynaecological surgery,[15] and operations on the abdomen[16] and pelvis.[3,17] In addition, there are reviews with a mechanism-specific focus, considering, for instance, autonomous robotic systems,[18] magnetic resonance-compatible systems,[19] future interfaces,[20] and training and learning tools for future surgeons.[21-23] In most of the above-mentioned reviews – especially the general ones – the focus is very technology-oriented, although user interfaces, workload, training and ergonomics are often briefly brought up.

The literature acknowledges the need for a multidisciplinary approach to developing robotic surgery.[5,24-26] Taylor[24] has reported on multidisciplinary meetings focused on future technological developments that have brought together surgeons, academic mechanical engineers, researchers and representatives of the industry. The need for sharing knowledge goes both ways: many surgeons are unaware of the possibilities and limitations of the various technologies that could solve surgical problems, and engineers must know what problems the surgeons face. Taylor's report considered primarily technologies that are already available, but clear weaknesses have been identified – many surgeons pointed out the difficulties with current minimally invasive techniques (access, dexterity and ergonomics issues) – and the need for user-friendly devices has been raised.[24]

In the same vein, Marcus *et al.*[26] emphasized the importance of close cooperation between engineers and clinicians in all phases of development, because the absence of this could result in technically impressive but clinically ineffective robots. Similarly, Marescaux and Diana[25] called for drawing together the knowledge of computer science and robotics experts with that of surgery, interventional radiology and endoscopy departments, for development of more hybrid therapies. Additionally, the need for new workflow and operating-theatre designs has been brought up.[3,27]

1.1 | Aims for the study

In the existing review literature, the surgeons' voice is absent, and their needs in the operating theatre have not been emphasized, despite the recognized need for multidisciplinarity. Our study promotes the user perspective in the development of robotic surgery. It narrows the gap between technical developers and surgeons by providing the developers with an understanding of the work context and giving the surgeons an understanding of the technological possibilities. The study combines a technology review – with a focus on novel interaction solutions – and qualitative research on the users' perspective: surgeons elaborated on the benefits of future solutions in the context of surgical work.

The aim was to explore what kinds of improvements future technologies could bring to the surgeons' work, from three angles:

1) operation outcome,
2) user experience,
3) learning and training in hands-on robotic surgery.

The focus was on the user-related aspects of the human–robot interaction (HRI) and the surgeons' needs in the operating theatre as viewed from these three perspectives. In previous work, we looked at the work of surgeons performing robotic prostatectomies – a surgical operation in which a cancerous prostate gland is removed[28] – to uncover clues about what sort of technological advancement could benefit the surgeons the most. In the case of prostatectomy, operation outcome depends principally on the removal of all cancerous tissue and secondarily on post-surgery complications and how well the nerves and other important structures that affect erectile and urinary functions are preserved.[28] In this paper, the operation outcome is considered from the potential of the technologies in the surgeons' eyes; discussion on actual patients' outcomes is excluded (see, e.g., Ahmed *et al.*[3] and Luz *et al.*[29]). In examining the second angle, user experience, we refer to good human–robot interaction with regard to usability, user feedback and interfaces, immersion, physical and cognitive ergonomics, communication in the operating theatre and comfort. Finally, teaching and learning of hands-on robotic surgery involves the mentoring, or apprenticeship-style learning, that is observable in the operating theatre. The technologies chosen are intended to support the currently available master–slave type of teleoperated surgical robots, so options such as microluminal or endoluminal mobile robots were not presented.

1.2 | Related work

1.2.1 | A review of future directions in robotic surgery

A systematic literature search was done regarding the expected future technology development in robotic surgery. Three databases were included: PubMed, Scopus and Web of Science. The search was done using words appearing in the titles of articles: robot or robotic or computer-assisted AND surgery or surgical AND one of the following words: future, tomorrow, advances, developments or evolution. The search was limited to 2002–2017 and the English language. Only review papers were included to delimit the number of articles and to cover technologies that have passed the initial screening of the robotic surgery community. Initially, 150 references were found, resulting in 82 unique references. The titles and abstracts of these articles were then screened to exclude articles focusing on cost assessments, operating techniques, clinical results, the developments of a single technology, technical limitations, and comparisons between traditional laparoscopy and robotic surgery; additionally, a future perspective needed to be implied in the abstract. The full texts of the remaining 25 articles were then read and screened based on the same criteria. Finally, 16 articles were included in the final review, and from these papers, the state-of-the-art and emerging technologies supporting the master–slave type of robotic surgery were collected (Table 1).

It seems to be generally expected that robots are going to become smaller, more flexible and accessible, and that it will be possible to reduce the number of surgical entry ports (see Table 1 for references). Imaging technologies (e.g., magnetic resonance imaging (MRI) and computed tomography (CT)) were mentioned very often. The images can be acquired pre-operatively or in real time, and they can be used

TABLE 1 A review of state-of-the-art and suggested technology developments for surgical master–slave robot systems

Development	References
Voice control	5,8,13
Audio feedback	5,10,11
Haptic feedback	3,5-13,15,17,18
Visual display	7,10,12
Drawing on the video image (telestration)	7
Wearable interfaces	4
No-go zones	5,9,11,12,18
Autonomous or semiautonomous functions	4,5,9,11,13,18
Assistive or automated tools	4,5
Computational capabilities, artificial intelligence, decision support	4,5,9,18
Operating theatre modifications,e.g., ceiling-mounting	3,4,7,13-15,18
Smaller robots, less space needed around the patient	7,10,11,13,16-18
Single-port, natural orifice	3,7,10,17
Snake arms, flexible arms	7,10,13,18
Instrument improvements	4,6,11,17
Pre-operative imaging	4,6-10,12,15,16,18
Real-time imaging	5,7,8,11,12,14,16-18
Digitized brain atlases, fused images	12
Tissue visualization,e.g., dyeing of cells, multiphoton microscopy	6,7,10,11
Pulsatile blood flow identification using Doppler	10,11
Force feedback sensor	5,8,12
Probes for real-time nerve imaging or stimulation	6,10,18

both for pre-operative planning as well as for navigation during the surgery. The images can also be augmented onto the robot video (acquired pre-operatively[6,7,9,10,18] or in real time[5,16,17]) using augmented reality (AR) technologies.[30] Tissue identification and visualization could also be aided using probes (force feedback sensors; nerve stimulation), Doppler and cell dyeing. Increased robot autonomy could be realized using autonomous functions such as suturing and autonomous assistive tools (e.g., automatic tool changer[4]). The system could also assist surgeons by warning about no-go zones or deviating behaviour (e.g., Lendvay *et al.*[11]), and by providing decision support.[4]

Regarding user interaction and feedback, the literature mainly focused on haptic feedback for the surgeon. Other sensory-related improvements included visual displays (e.g., additional displays or picture-in-picture), voice control and audio feedback (especially for alerting the surgeon). Wearable interfaces such as electronically wired gloves and head-mounted displays (HMDs) were briefly mentioned,[4] as was a more immersive operating experience for the surgeon.[5]

Additionally, the surveyed literature included several references on the use of simulations for training[3-5,7,8,11] and planning[12] purposes; dual consoles for training or collaboration[7,9-11,17]; telementoring[7,11,14,15]; telesurgery, i.e., operating from a distant site[3,7,9-11,14]; telecollaboration[7,14,15]; and also micro-robots or intra-abdominal robots.[3-5,7,9-11,16,18]

Several challenges that stand in the way of achieving these improvements must be recognized. In addition to costs and legal barriers, there are numerous engineering hurdles, related to issues such as size, mobility, haptic feedback, imaging capabilities, latency and signal security.[11]

1.2.2 | Human–robot interaction in robotic surgery

Research on robotic surgery has focused largely on operative techniques and technological development of robot instruments and interfaces, while fewer studies address HRI in the context of surgery. The HRI field is a multidisciplinary area of study that has been influenced by cognitive sciences (including psychology) and work on human factors, human–computer interaction, robotics, artificial intelligence and natural-language processing.[31] In connection with robotic surgery, we were able to identify five areas of research focusing on the user aspect of HRI: (1) ergonomics and workload, (2) visual and haptic feedback, (3) human factors in image-guided navigation, (4) learning and training issues and (5) team-level interaction.

Ergonomic comparisons between standard laparoscopy and robotic surgery have found reduced physical workload and physical discomfort with the robot-assisted systems.[1,2,32] The predominant discomfort symptoms experienced by surgeons include numbness, stiffness and pain.[32] Although Hubert *et al.*[1] found no difference in the mental stress experienced, others have reported a reduction in the cognitive workload.[2] The mental stress is affected by the surgeon's experience of the procedure and can be different in clinical and experimental conditions.[1]

In a comparison of robotic surgery using 2D and 3D vision to traditional laparoscopy (the article implied that the laparoscopy was performed in 2D; in recent years, the use of 3D laparoscopy has increased), there was a significant improvement in the time taken and the path travelled by either hand with the 3D vision.[33] The lack of haptic feedback in most surgical robots notwithstanding, surgeons currently use the 3D display for obtaining visual cues on the properties of various tissues when they grasp, poke and pull the tissues with the robot instruments.[34]

Implementing haptic feedback in surgical robots is expected to reduce surgical errors,[23] and attempts to introduce it in robots are numerous (there are various reviews[10,23,35]). However, its added value for robotic surgery has not yet been ascertained, partially because today's systems do not incorporate haptics.[23] That said, the lack of haptics represents evident drawbacks, and most reports on studies cite benefits from adding force feedback to minimally invasive surgical devices. In addition, it has been hypothesized that a hand-controller designed with a linkage structure similar to that of a human upper extremity may result in improved surgical performance.[36]

The human factors associated with image-guided navigation (chiefly, supporting the surgeon's spatial orientation and navigation within the patient) have been considered. Manzey *et al.*[37] reported improvements in performance and patient safety – at the cost of increased time pressure and mental workload for inexperienced surgeons – but there were differences between surgeons in reactions when the information from the navigation system conflicted with their own assessment of the situation.[37] In addition, interruptions in the surgeon's workflow caused by the technological implementation have been addressed.[29]

The learning curve in robotic surgery varies, depending on the complexity of the procedures and on the surgeon's experience of similar technology and familiarity with the procedure in question.[22] In recent work, it was suggested that the minimal training before patient-related console time should involve live and video observations and should confer knowledge, table assistance and basic skills.[38] The technical means available to support learning include simulators, virtual reality (VR) and a mentoring console. Finally, the robot itself can provide some input to the evaluation of surgical performance: the robot-instrument parameters recorded during the operation can be used for describing various aspects of performance.[39]

Studying human–robot team interaction, Cunningham *et al.*[40] found differences in workflow, timeline, roles and communication patterns as a function of experience and workplace culture. Nyssen and Blavier[41] identified distinct categories of verbal communication between the operating surgeon and the surgeon's assistant. Their balance differed between robotic surgery and laparoscopy: with the robot, there was more communication related to actualizing the operation, such as orders, confirmations, demands and clarification. The authors suggested that the separate robot console reduces implicit face-to-face communication (nods and gestures), hence creating a need for more talk.

2 | MATERIALS AND METHODS

2.1 | The future workshop

The format of the future workshop was inspired by Future Workshop,[42] Future Technology Workshop[43] and Anticipation Dialogue Method,[44] all of which are research methods for envisioning and co-designing the interactions between current and future technology and the activity in small groups. The methods have been successfully applied in development of scenarios for the future, to support the design of information and communications technology (ICT) tools for complex work systems, and in product design and workplace development.

The workshop had four phases (Figure 1). In the first phase, the surgeons were shown inspiring technologies aimed at encouraging their imagination. The surgeons envisioned how the technologies could be used in their work and rated each of them by selecting from among four options describing different levels of usefulness (‘Useless or disadvantages exceeding the benefits’, ‘Useful for some but not me’, ‘I could try, potential’, ‘I would instantly bring this into use’). For each technology, there was an approximately one-minute slide and video presentation, then a set amount of thinking time. The slides and the timing evened out the possibilities for considering potential across the technologies, which was advisable since some of them are not yet on the market or had not yet been suggested for the surgical context. The surgeons were encouraged to keep an open mind and to envision and evaluate the technologies without worrying about the feasibility of their technical implementation or considering costs. In the second phase, the surgeons were instructed to indicate which five technologies they considered the most important. In addition to the earlier rating of usefulness, each surgeon was given handouts of the slide material presented, to aid in recollection. After making their selection, the surgeons wrote down arguments supporting the technologies chosen. The surgeons were asked to refrain from discussion during the first two phases.

In the third phase, the technologies selected were discussed at group level. One at a time, the surgeons presented their arguments for one of the technologies selected earlier. After the surgeon had finished expressing these opinions, the others were given a chance to comment and discuss the technology. Then, it was the next surgeon's turn to choose and present one of the ‘top five’ technologies that had not been mentioned yet. With discussion continuing in this manner, the surgeons covered nine technologies in about 45 minutes. On account of time constraints, two of their selected technologies were not covered, but these and some other technologies too had been brought up in the course of the discussions. The researchers took part in the discussion by asking clarifying questions and guiding the discussion to consider the three aspects mentioned earlier in the paper: user experience, learning and teaching, and operation outcome. In the final phase, the surgeons discussed their expectations and concerns for the future of robotic surgery.

2.1.1 | The workshop participants

Five surgeons (one female and four male urologists), all from the same hospital participated in the future workshop. Their ages ranged between 35 and 52 years (mean age: 41). Two of the surgeons had 6 years of active experience of robotic surgery (da Vinci S Surgical System, Intuitive Surgical, Inc.; Sunnyvale, CA), with one of them having 3 and the other 8 years' experience of open (prostate) surgery. The other surgeons' experience ranged from 10 operations to two years of independently performed robotic surgery, although they all had assisted in operations for several years. These three surgeons had not performed any open surgery although one reported having assisted in open (prostate) surgery operations. None of the surgeons reported having any specific interests in novel technology (e.g., AR).

2.1.2 | Finding and generating alternative technological solutions

There were two sources for the technological solutions presented at the workshop. The first was a literature review focused on future directions for robotic surgery (see ‘Related work’, above). Secondly, possible technological solutions were drawn from the body of generic technical developments in human–computer interaction, VR, AR and image processing. The latter process involved considering the concrete challenges that the surgeons face in their operating-theatre work generally and in radical prostatectomy in particular. These challenges had been identified via ethnographic field studies exploring the matter (including both several interviews in different Finnish hospitals and observations of prostatectomy operations). More specifically, the core-task analysis method[45] was applied: its conceptual model offers a framework for identifying complexities and uncertainties alongside the means by which these are addressed within a work assignment.

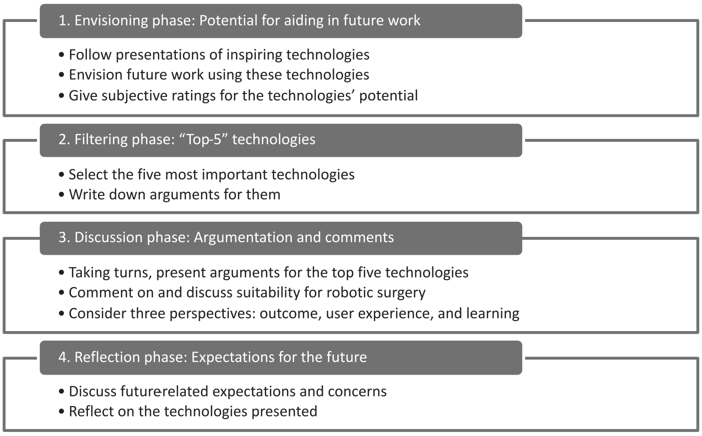


FIGURE 1 Phases of the future workshop

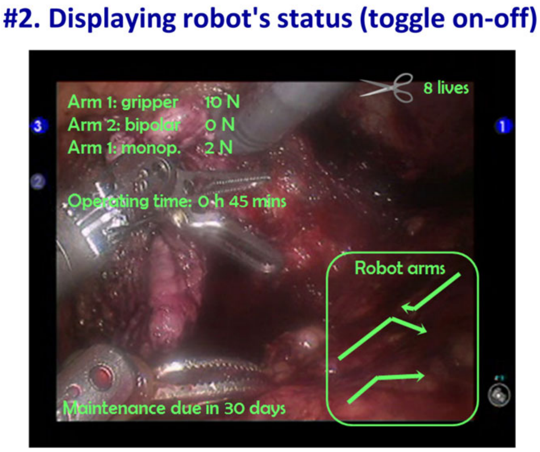
This core-task analysis and ethnography have been reported upon in full by us elsewhere.[46] In summary, the key challenges in robotic prostatectomy pertain to (1) *decision-making*: determining what is best for the patient during the operation involves uncertainty arising from the enormous complexity of the human body and the lack of full scientific consensus on certain issues (e.g., the location and importance of certain nerve bundles); (2) *navigation*: 'travelling' within the patient involves landscape-making (that is, the way in which the route within the patient is initially 'opened' influences later stages of the operation); and (3) *object recognition*: differentiating organs and tissue types from one another requires various pulling, poking and pushing techniques, coupled with consideration of various colours and forms and of the dynamic response to palpation, in the absence of haptic feedback.

In all, 45 solutions were either taken directly from the existing literature or conceptualized on the basis of our understanding of surgical work – the core-task analysis – and of recent and forthcoming developments in interaction technologies. To reduce this pool of solutions to a size more manageable in our workshop setting, categorization was performed, in which overlapping technologies were identified and grouped together as one (for example, various approaches that enable single-port surgery were lumped together as a single technology). In the end, 26 technologies (see results) were chosen to stimulate the participants' imagination during the future workshop. These technologies ranged from commercial products – which represented the minority – to technologies that could enter use within approximately 5 years. In line with the key challenges identified, the possible solutions our team generated (which, to the best of our knowledge, had not been introduced to this work domain at the time of writing) were aimed at supporting decision-making (solutions #14 and #17 introduced in results), navigation (solutions #17 and #19–#21 in results) and object recognition (solutions #2, #8, #21 and #25 in results). The multidisciplinary research team included experts in engineering and psychology. An example of the solution generation process took place during a brainstorming session, when the team was thinking about solutions for aiding surgeons in object recognition and bleeding prevention. An expert on visual signal processing suggested Eulerian video magnification,[47] which resulted in solution #25 (see results).

Each of the technologies was visualized by means of one slide (see Figure 2). A slide featured 1–7 images representing the idea; 10 slides had a clarifying text box also, such as 'Setting up virtual walls that cannot be penetrated with the robot arms' (solution #11 in results) and 8 included a brief video clip. The visualization material was extracted from surgery videos, literature and online sources, then edited.

2.2 | Collection and analysis of the data

The participants gave written consent to participation in the study represented by the future workshop, which was audio-recorded and video-recorded. The audio recording was transcribed by a subcontractor. One researcher led the discussion, with the aid of two other researchers. All three took notes. The evaluations by the surgeons and all written notes were input to a spreadsheet application for qualitative content analysis.[48] From the transcript, comments on each of the technologies were compiled, in line with the three facilitation foci studied.



#2. Displaying robot's status (toggle on-off)

FIGURE 2 Slide #2 (Table 2). Displaying the robot video augmented with the robot's status. The positions and forces applied by the arms are shown, along with some maintenance information

3 | RESULTS AND DISCUSSION

All of the surgeons participated actively in the workshop. The surgeons were unfamiliar with some of the technologies presented, which indicates the ability of the technology selection to extend beyond the robotic surgery technology typically represented in the literature they read. Although the technology ratings given in the first phase of the workshop (see Figure 1) were used mainly for later aiding in the surgeons' selection of the most important technologies for further discussion, they demonstrate the variety of opinions well so they are shown in Table 2. Of the 26 technologies included in the workshop, 19 were assessed by at least one surgeon as worth being brought into use immediately while 7 received ratings of uselessness (see Table 2). Two technologies (#2 and #12) were given ratings at both extremes of the scale. One surgeon opted for 'Don't know' for technology #15. All surgeons used the full response scale, and no difference between the answers given by surgeons with different levels of expertise was evident.

In total, 16 technologies were discussed at the workshop, with some of them cited as supporting more than one of the three facilitation aims studied (see the rightmost column in Table 2). To aid the reader, we have organized the results for the technologies discussed below by the aim that was given the most emphasis. The results are qualitative and reflect the surgeons' subjective opinion.

3.1 | Operation outcome

3.1.1 | Use of imaging technologies, tissue identification and nerve-sparing (#22–24 and #26 in Table 2)

The surgeons were fairly unanimous in what they deemed the best methods to improve operation outcome: technologies #22, #23, #24 and #26 (see Table 2, with references) would support improving the oncological (i.e., cancer-elimination) and functionality (i.e., preservation of urinary and erectile function) objectives, by identifying tissue types,

TABLE 2 Technologies presented at the future workshop that surgeons evaluated and elaborated upon. The number of circles denotes the number of responses in each class (●for more experienced and ◐ for less experienced surgeons). References (see also Table 1) and surgeons' opinions on aspects of work supported by each technology are indicated where applicable

		Surgeons' opinions				
Technology	References	'Useless or disadvantages exceeding the benefits'	'Useful for some but not me'	'I could try, potential'	'I would instantly bring this into use'	Supported aspect
1. Voice command	5,8,13		◐	●◐◐	●	
2. Displaying the robot's status (toggle on/off)[c]	force bars in 35	◐	◐	●◐	●	
3. Picture-in-picture	7,10		◐◐◐	●	●	User experience
4. Head-mounted display	4,20,49			●●◐◐	◐	User experience
5. Single-port operation	Table 1			●◐◐	●◐	Outcome
6. Snake arms	Table 1; 26			●◐◐	●◐	
7. Haptic feedback to motion controls	Table 1; 34,35			◐◐	●●◐	User experience, learning, outcome
8. Haptic feedback to a body part (e.g. a vest)[c]		◐◐	◐	●●		
9. Defogging of the camera lens using gas flow	50				●●●◐◐	User experience, outcome
10. Adaptive illumination				●	●◐◐◐	User experience
11. Virtual 'no-go' zones	Table 1; 34		●◐	◐◐	●	
12. Comparison data and advice during operation	11,18,34,51	◐	◐	●◐	●	Learning, outcome
13. Automated clip placement	Table 1; 52		●◐	◐◐	●	
14. Patient monitor information[a]		◐◐	●●	◐		
15. Drawing on the video image (telestration)	Table 1; 22		●◐	◐◐		Learning
16. Eye-tracking and path tracing functions	26,53	◐	●●	◐◐		
17. Rewinding[a,b]		●	◐◐	●◐		Learning
18. Ego- and exocentric views	54		◐	●●◐◐		
19. Leaving landmarks on an image[b]				●◐◐	●◐	Learning
20. Ambient sounds (stereo or point source)[b]		●●◐	◐◐			
21. General 3D model of internal organs (rotatable, overlaid on video image)[b,c]			◐	●◐◐	●	Learning
22. CT/MRI image overlay (augmented)	5-7,9,10,16-18,34,49				●●●◐◐	Outcome, learning
23. Tissue identification using photon microscopy and augmenting tissue edges	6,10			◐◐	●●◐	Outcome, learning
24. Fluorescence tagging and coloured lens	6,10,11,26,34			◐	●●◐◐	Outcome, learning
25. Amplification of imperceptible motion (computational)[c]	47, cf. 'Doppler' in 10,11		◐	●◐	●◐	
26. Location of nerves and augmented representation of nerve pathways	55, also 6,10,26,30,49			◐	●●◐◐	Outcome

[a] Solution generated to support decision-making.

[b] Solution generated to support navigation.

[c] Solution generated to support object recognition.

making operations faster and reducing complications. The main finding was that, in an idealistic case, if surgeons were able to see for certain where the cancerous tissue is (via the dyeing of cancer cells, #24 in Table 2), improvements in other technologies would be unnecessary, since the main aim is to remove the cancer and all affected tissue. Also, one of the most difficult things to learn in robotic surgery, identification and separation of tissues in the right place, would be supported by all of the imaging-related technologies (especially #22 and #23 in Table 2), with which the robot's video image could be given a real-time overlay of the patient's anatomy as revealed by earlier imaging.

In prostatectomy, preservation of the nerves is very important for the patient's quality of life. If the nerves (more specifically, nerve bundles) were shown augmented on the video image (#26 in Table 2), the surgeons felt they could operate optimally in these areas. The surgeons stated that if it were feasible (and, preferably, implemented in a user-friendly manner), they would go to the effort of identifying the nerves even if it added approximately 10 minutes to the total operating time. In addition to identifying the areas on which to operate, the aforementioned technologies could aid in coping with differences between individuals in the anatomy of the prostate gland, which reportedly are greater than textbooks imply. The surgeons also listed several other areas of surgical application (neurology, lymph-node work, liver surgery and gynaecology) in which these technologies could be useful.

3.1.2 | Single-port operation (#5 in Table 2)

Single-port surgery (#5 in Table 2) decreases the invasiveness of an operation and the number of wounds. It could also improve patients' safety. Using a smaller number of ports reduces the possibility of damaging blood vessels. The surgeons felt that, on the assumption that instrumentation reaches a suitable level, operating through a single port would be as easy, or nearly as easy, as it is with six ports, and that it would require only a small amount of training. The question of the total number of ports needed was not settled, because it was assumed that the assistant surgeon would still require a certain number of ports for suction and clip placement.

3.2 | User experience and ergonomics

3.2.1 | Visibility and landscape (#9 and #10 in Table 2)

Because robotic surgery currently relies on visual feedback, maintaining a clear landscape within the patient is crucial. The surgeons opted for two supportive technologies: defogging of the lens (#9) and adaptive illumination (#10 in Table 2). Typically, the lens of the robot's camera is manually wiped clean several times during an operation; for this, the camera must be pulled out of the patient. Therefore, in addition to saving time, the surgeons felt that cleaning the lens automatically would increase comfort levels and possibly accuracy in the operation.

Furthermore, the surgeons mentioned that, while adaptive illumination should be an obvious aid, they often encounter situations in which the landscape is very dark (with dark blood absorbing the light) and there is difficulty in identifying various tissues. They explained that they try to overcome this hindrance by zooming in with the camera, which results in more intense lighting of a small area, but this comes at the expense of situational awareness. Automated adaptive illumination and/or colour correction received an enthusiastic reception from the surgeons, and some recalled that this has already been implemented in some laparoscopic towers. Although the surgeons were convinced that automated illumination and colour enhancement would function correctly in most situations, they also wished to retain the option of switching to manual control.

3.2.2 | Haptic feedback (#7 and #8) and head-mounted displays (#4 in Table 2)

Haptic feedback, or the lack of it, was discussed in detail. Currently, the acts of pushing, poking and pulling tissue play a significant role in tissue identification with the visual sense. In the participants' opinion, haptic feedback would improve tissue identification and thereby improve patient safety. It could also aid in learning about the qualities of individual types of tissue and in learning how to operate the robot.

The surgeons were slightly cautious in their evaluations related to haptic feedback, although they did see potential in it. One surgeon elucidated that he did not believe that haptic feedback could be implemented on an appropriate level of realism in the near future, so he found the idea too far-fetched (see also the attainable degree of realism mentioned by Van Der Meijden and Schijven[23]). In addition, sensory substitution using the visual and auditory senses has been suggested as an attractive alternative for force feedback[35]; however, displaying the pushing or pulling force applied in newtons (cf Slide 2, in Figure 2) would not qualify, because the differences between tissue types in their response to a given force are so great. As exemplified by the surgeons, it takes almost no force at all to puncture the small intestine.

The surgeons assumed that haptic feedback could be applied either by pressure or via vibration (see,e.g., Wedmid *et al.*,[10] Van Der Meijden and Schijven[23] and Okamura[35]). Additionally, if the robot has to pull hard, the surgeon would feel this as increased resistance. A data glove was mentioned as offering potential for mediating the feedback. Furthermore, the surgeons brought up the idea of haptic feedback amplification. While they remained unsure whether the amplification should remain constant or instead be adaptive, they were interested in trying it out.

We prompted the surgeons to discuss a situation in which the visual image and haptic feedback provide conflicting information or in which the haptic feedback ceases to function during surgery. The surgeons postulated that they would eventually develop a joint sense – visual+haptic, instead of ‘visual haptics’[34] – for operating the robot, which renders it difficult to contemplate losing part of this sense. Their only point of comparison offered by the current situation is the reduction of 3D to 2D vision (e.g., due to a disconnected cable, which results in the same image being shown to both eyes), which is almost unmanageable if it occurs during an operation.

If robotic surgery evolves towards a more immersive experience, as has been suggested,[5,20] there may be potential in the use of many wearable devices for both control (e.g., capturing arm motions[56]) and feedback (e.g., HMDs[20]). Wearable devices for tactile feedback have been used in wayfinding outdoors (e.g., a vibrotactile vest[57]), and the concept could be expanded to robotic surgery (see #8 in Table 2). In the operating theatre, however, having only one member of the surgical team immersed within the patient while blocked from any external stimuli, would likely affect the interaction between staff members (especially with the assistant surgeon and nurse), and the communication and workflow would need to be rethought (cf Cunningham *et al.*[40]).

At the time our study was done, the robot's camera was moved with the same hand controls as the robot's arms. The HMD was seen by the participants as taking the robot control to a new level; the movement of the camera would follow natural movements of the human head. The surgeons were inspired by this line of thought and began developing ideas for full-body control systems, including data gloves and a vibrating vest (#8 in Table 2), with which the movements of the surgeon's hands would directly map onto the movements of the robot instruments, and the surgeon would receive small electrical discharges when encountering a nerve. Two surgeons, however, found the current console very comfortable in the sense that it provides support for the arms and neck (see also Hubert *et al*.,[1] van der Schatte Olivier[2] and Lundon *et al*.[32]). Although the HMD could compromise these ergonomics, the surgeons believed that they could get used to operating without a stationary support.

3.3 | Learning and teaching of robotic surgery

3.3.1 | Rewinding (#17) and picture-in-picture (#3 in Table 2)

In addition, rewinding (#17 in Table 2; Figure 3) and replaying of the robot's video during the operation was discussed at length. The surgeons noted that rewinding, while not feasible when haste is required, is relevant for teaching or demonstration. An experienced surgeon operates quickly, and it was suggested that the assistant surgeon could ask for a replay and for comments on a difficult part of the operation. In addition to teaching, one surgeon thought that he would use rewinding if he suspected he had penetrated and entered the prostate tissue (an undesirable act): he could rewind to see when and where the entry took place. Two surgeons were sceptical about rewinding, but one of them still considered it possibly useful to save, for instance, the minute of footage prior to pressing a Save button, for later viewing and analysis. The robot video is recorded in any case, so this effect could be achieved by adding a tagging feature.

The safety of using rewinding during surgery was discussed too. The surgeons concluded that the instruments need to remain disabled during replay and that it would be important to see the ongoing real-time situation in a small picture-in-picture display (#3 in Table 2; Figure 4). In addition, one surgeon listed picture-in-picture among his top five technologies, with the comment ‘This could help in operating’.

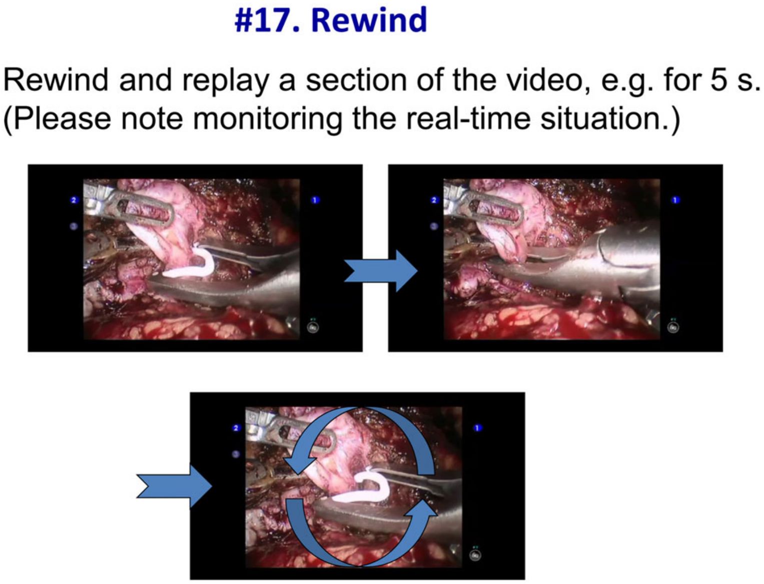
3.3.2 | Telestration (#15), virtual landmarks (#11 and #19) and a general model of organs (#21 in Table 2)

The use of telestration (i.e., drawing over the video image, #15 in Table 2) to support teaching was considered. Two of the surgeons were unaware that this function was already available in their current system. This was because the more experienced surgeons had not considered it beneficial, for two reasons: that the lines drawn should be fixed to the site and the impracticality related to the sterile vs. nonsterile surfaces involved.

Leaving virtual landmarks on the image (#19 in Table 2) could serve several functions. In addition to helping surgeons orient and navigate (cf image-guided navigation[29,37]), the surgeons saw potential in marking areas where extra caution is needed (cf ‘no-go’ zones[5,9,11,12,18,34]; #11 in Table 2). The use of markers in a 3D environment for realigning the robotic instruments has already been suggested.[58] The landmarks could be displayed in both ego- and exocentric views (#18 in Table 2) – the surgeons judged both to have potential. In addition, showing a general 3D model of internal organs could be useful, but only if the patient does not have significantly atypical anatomy.

3.3.3 | Comparison data (#12) and computation-based methods (#25 in Table 2)

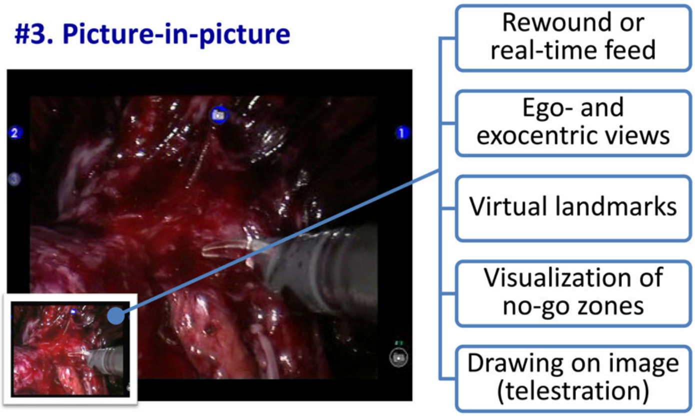
So far, the robot data have been used at least for evaluating surgeons' skills and documenting performance.[34,51] Additionally, with online data analysis, the surgeon could be given context-specific information or motion enhancement.[51] Following this line of thought, the surgeons concluded that, instead of calculating the best trajectory for a task, providing comparison data from earlier performance (one's own or colleagues') and offering advice on further actions (#12 in Table 2) would be a motivating factor for improving their performance and also



#17. Rewind

Rewind and replay a section of the video, e.g. for 5 s.
(Please note monitoring the real-time situation.)

FIGURE 3 The slide presenting technology #17 (Table 2), rewinding



#3. Picture-in-picture

Rewound or real-time feed

Ego- and exocentric views

Virtual landmarks

Visualization of no-go zones

Drawing on image (telestration)

FIGURE 4 Potential solutions for using the visual display more extensively, exemplified by an inset picture in the corner of the display (picture-in-picture, #3 in Table 2) that could display various video feeds: rewound (#17) or real-time feed, ego- and exocentric views (#18), virtual landmarks (#19), visualization of no-go zones (#11) or drawing on image (telestration, #15 in Table 2)

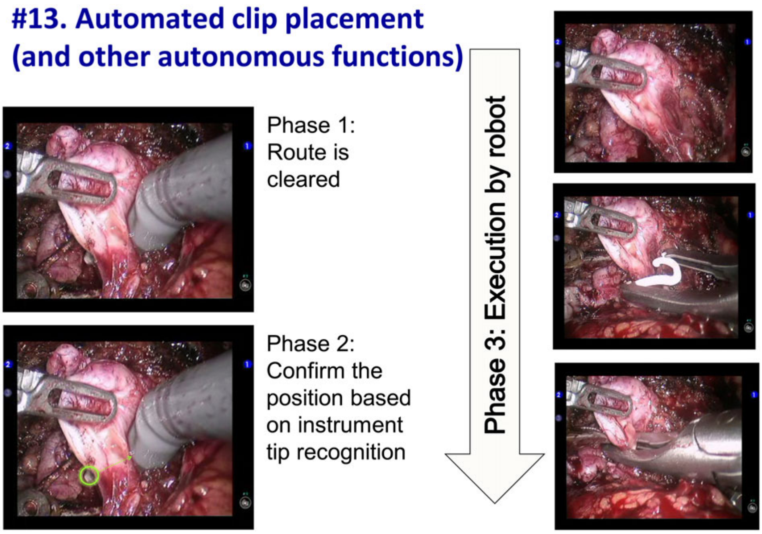
would support both learning and a positive surgical outcome. In the participants' opinion, the data could support two functions especially: learning to suture or perform other procedures with minimal movements (cf a sports tracker application) and, simultaneously, supporting interaction within the surgical community. Also, one participant brought up the idea that the robot could alert the surgeon if the operation in progress is proceeding in a radically different manner than a computationally average operation (see also Lendvay *et al.*[11]). Furthermore, computation-based methods could enable surgeons to detect minuscule motions imperceptible to the human eye, and therefore make it possible to show pulsatile motions behind a cell wall (#25 in Table 2) and hence prevent blood loss.

3.4 | Surgeons' expectations and concerns for the future

The surgeons' future-related expectations were in line with the literature (see Table 1). The surgeons predicted that the robots will decrease in size. With a smaller, and at least partially mobile, robot, larger areas could be operated on without anyone having to turn the robot manually. This would also leave more room for the assistive staff beside the patient cart, and single-port technology too would support this aim. As for user interaction, haptic feedback was expected to become reality in the future, and the potential for a more immersive experience seemed inspiring.

Autonomous functions were discussed briefly. Automated clip placement (#13 in Table 2, with the corresponding slide shown in Figure 5), at a level of automation comparable to that of an automated parking system, was seen as possessing potential but also being frightening. Concerns about trust, safety and acceptance have been brought up by others also.[18,37] In addition to possibly saving on operating time, autonomous functions would affect team dynamics, because they could take over some of the actions currently done by the assistant surgeon.

An unfavourable line of development might involve a robot using artificial intelligence to control or restrict surgeons' actions. Moreover, data security and hacking were among the concerns expressed for the



#13. Automated clip placement (and other autonomous functions)

Phase 1: Route is cleared

Phase 2: Confirm the position based on instrument tip recognition

Phase 3: Execution by robot

FIGURE 5 The slide for technology #13 (Table 2), automated clip placement and autonomous functions future. In contrast, one positive element highlighted was that, as far as the surgeons' know, the robotic systems are being developed in close cooperation between engineers and medical professionals, such that, for example, usability factors will be addressed – if not for surgeons' enhanced user experience, at least to reduce operating time and save money.

3.5 | Methodology-related considerations

In a counterbalance to the dominant trend in the literature –i.e., discussing the future of robotic surgery from the perspective of technological developments – the rationale for the study reported upon here was to gain understanding of how a wide range of technologies could support the surgeons' work in the future. A qualitative approach, in the form of the future workshop, was chosen because it provided a level playing field on which the surgeons could envision, evaluate and elaborate on multiple technologies that they were initially unfamiliar with. This would not have been possible with a survey or a typical case-by-case technology-validation process. The number of surgeons was chosen to afford active participation in the future workshop.[42-44] This points to another of the method's benefits: disengaging a larger group of specialized surgeons at a given hospital can be difficult if not impossible. It should be noted that this study does not provide a complete list of user requirements or issues regarding human factors related to the technologies, but it gives a starting point for iterative, human-centred design (ISO 9241–210:2010) aiming to make systems easy to use, usable and useful for the users.

The list of technologies presented at the workshop was not exhaustive (cf Tables 1 and 2), nor was it meant to be. This choice served the purpose of future workshops, where the solutions presented are used for stimulating the participants' visions for the future.[42-44] The number of technologies introduced at such a workshop thus has to be limited in order for meaningful discussion to emerge within the time available. The solutions were new to many of the participants, so use of the rating scales and silent musing supported the surgeons in selecting the most important technologies for the discussion part of the workshop. Because the nature of this study was qualitative and there was a small number of participants, the ratings of the technologies should not be used as a guide *per se*.

4 | CONCLUSIONS

Taking part in a future workshop, the surgeons envisioned and elaborated on the potential of a wide range of future technologies for their work. In the surgeons' opinion, the technologies currently being developed for robotic surgery would primarily support operation outcome, although effects on learning were brought up as well. It seems, however, that there is still untapped potential with regard to improving the learning aspect of the surgery, along with the user experience. Promising, novel solutions could be found especially in utilizing the robot's display and video more extensively –e.g., in leaving landmarks for navigation or rewinding the robot video (see Figures 3 and 4). Concerns related to trust, safety, security, situational awareness, acceptance, ergonomics, the quality of the implementation and team-level interaction were raised. It is important to address these aspects in the development of robotic surgery. In the future, engaging surgeons from different surgical domains and various countries will help to get a deeper understanding of these issues.

This paper was aimed at benefiting professionals in diverse fields, among them surgeons, engineers and industry representatives. For operating surgeons, our study offers insights into what kinds of technologies might be expected to arrive soon and how these could affect the work. For technology developers, we hope to provide work-context understanding in view of technological solutions: understanding of why certain solutions could be beneficial for surgeons. For surgeons who are engaged in technology development, utility can be found in our review and the overview of technological solutions alongside the corresponding potential benefits for surgical work. Finally, we hope that the approach we have taken provides inspiration for multidisciplinary research aimed at exploring and improving the future for surgical practice.

ACKNOWLEDGEMENTS

The authors wish to thank the surgeons who participated in the interviews and especially in the future workshop. In addition, discussions about robotic surgery with our project group members have been highly valuable. Special thanks to Jarno Riikonen, MD, PhD, for helping with the medical aspects of robotic surgery. We also appreciate the expertise of our colleague Jari Laarni, PhD, in designing future workshops and the advice of Ali Muhammad, PhD, on development in robotics. This work was supported by WOBLE, a project that is funded by the Finnish Work Environment Fund and that operates in conjunction with the Academy of Finland's The Future of Learning, Knowledge and Skills (TULOS) research program. Additionally, I. Aaltonen received support from the Jenny and Antti Wihuri Foundation.

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How to cite this article: Aaltonen IE, Wahlström M. Envisioning robotic surgery: Surgeons' needs and views on interacting with future technologies and interfaces. *Int J Med Robotics Comput Assist Surg*. 2018;e1941. https://doi.org/10.1002/rcs.1941

Publication VI

Aaltonen, Iina; Laarni, Jari; Tammela, Karo. Envisioning e-Justice for Criminal Justice Chain in Finland. The Electronic Journal of e-Government, volume 13, issue 1, pages 55–66, available online at www.ejeg.com. 2015.

Envisioning e-Justice for Criminal Justice Chain in Finland

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Abstract. The purpose of this paper is to envision new ways of working in the justice sector and to present the best practices and lessons learned in current e-justice in Finland. In 2011, Finnish prosecutors, district and appellate court judges and other court staff were interviewed and engaged in a workshop to envision ICT-supported workflow for resolving criminal cases. The three-stage anticipation dialogue workshop envisioned new ways of working in 2015, the challenges in the 4-year time span preceding it, and finally the possibilities of advanced technology. Workshop participants were relatively cautious with their visions, which clearly indicated that advanced technology as such is no solution. They considered interlinked and well-structured electronic documents with online access for all parties as enablers for working e-justice. Working with electronic documents requires accessory displays, cabling and power outlets for laptops as well as wireless networks. Scheduling – a time-consuming secondary task – could be facilitated by shared electronic calendars with court room booking capabilities. Remote hearing and videoconferencing were anticipated to play a larger role in the future. Throughout the workshop, the importance of user-friendly information systems was emphasized. Even though the core task of practicing law was expected to remain the same, new technology requires a change in work practices. Adopting new ways of working can be challenging, and in addition to correctly-timed and well-targeted training, employees will also need support from their superiors.

Keywords: e-justice, criminal justice chain, case management systems, court room, work practice

1. Introduction

Implementing an information and communications technology (ICT) system for the public sector is a challenging task. Gole and Shinsky (2013) recently listed factors leading to failure for 17 public sector ICT projects in Australia, the UK and the US; projects that have been suspended or that have exceeded the planned timetables by years and expenses by millions of dollars. Several of the projects concerned the judicial administration. While many of the common factors leading to failure include problems in administration, project management and selecting vendors, the failures are often due to not fully considering the needs of the end users. The complexity of the project may have been underestimated and the working environment or work context not thoroughly understood. Moreover, the end users have not been engaged in designing the required solution.

Failures in public sector ICT projects are not unknown to other countries in Europe either, and attempts have been made in trying to renew the ICT in the judicial sector. Although the overall amount of adoption of information technologies seems relatively high (European Commission for the Efficiency of Justice (CEPEJ), 2012), there is still a long way to full-scale e-justice (see e.g. Fabri and Contini, 2001; Velicogna, 2007).

The concept of e-justice can be interpreted in multiple ways. A broad definition of e-justice can cover ICT usage in the areas of crime prevention, administration of justice and law enforcement (Xanthoulis, 2010). Furthermore, e-justice for the administration of justice contains multiple sub-areas. These include usage of IT in general, electronic methods for communication (e.g., e-mail, videoconferencing), electronic case management systems, court room technology, and even offering citizens electronic services such as online access to case files. This paper focusses on e-justice in judicial administration to the extent it concerns prosecutors, judges and other court staff.

The difficulty of adopting e-justice has been encountered and reported in Italy (Contini and Cordella, 2007), the Netherlands (Henning and Ng, 2009; Langbroek and Tjaden, 2009) and France (Velicogna et al., 2011). These studies showed that the true difficulty does not arise from technical issues nor even legislation, but from the socio-technical and organizational aspects. Courts protect judicial independence rigorously, and this is reflected in the organizational culture of judges. Courts prefer to choose ICT systems themselves instead of

Reference this paper as Aaltonen I, Laarni J and Tammela K “Envisioning e-Justice for Criminal Justice Chain in Finland” *The Electronic Journal of e-Government* Volume 13 Issue 1 2015 (pp 56-66), available online at www.ejeg.com

considering adopting a government-provided generic system. The old work practices, which have been established during the pre-ICT era, are hard to change, while adopting new work practices could be the key to collecting maximum benefits from ICT, or taking the provided ICT into use at all.

Public administration can be considered as a complex socio-technical system comprising human, social, organizational and technical factors. This kind of system is characterized, for example, by a multiplicity of elements and actors, heterogeneous perspectives, dynamic interactions between system elements and tight couplings between elements (see e.g. Carayon, 2006). The work context needs to be understood when designing a new system, and even if functional issues are resolved, the user interface will be the final link in determining whether users will accept and use the system. Organizational barriers come into play if a new system is to be used in several judicial agencies. All parties need to be motivated and equally involved in the planning – and in sharing the expenses – even if one party might be collecting most of the benefits.

Another line of e-justice development has emerged in the past few years in the form of courtroom technology, which is being tested and implemented in court rooms (Lederer, 2004; Wiggins, 2006). More specifically, there is research on evidence presentation techniques (Farrell et al., 2011; tablets: Tipping et al., 2012) and virtual environments (Bailenson et al., 2006), and also on considering the architectural and acoustic requirements in modern court rooms (Hryncewicz-Lamber, 2013).

This research paper aims to envision e-justice at its best. As Velicogna et al. (2011) put it, '…the main problem has not been finding a technically possible solution, but "creating" a solution that was in line with the needs, the expectations and the requirements of the various parties. And that some of these expectations and the requirements were not even known to the actors themselves before the first attempts were made.'

1.1 Justice system in Finland

The Finnish legal system is based on Scandinavian and European tradition. The judicial system is quite compactly described by Kujanen and Sarvilinna (2001) and the Finnish justice website oikeus.fi (Finnish courts, 2014; Prosecutors, 2014). To summarize, the district courts handle both civil and criminal cases, whose decisions can be appealed in a court of appeal, and if permission is granted, the decisions of the court of appeal can be appealed in the Supreme Court. There are also administrative courts and special courts. There are 27 district courts, 5 courts of appeal and the Supreme Court. The prosecutor's office is an independent part of the judicial administration. There are 11 local prosecution offices and a separate Office of the Prosecutor General.

Cases can be handled in two ways: in a court session where all parties are summoned or in chambers solely based on documents. The latter way also covers summary cases, such as simple undisputed debt-recovery cases, which form a large majority of the civil cases and can also be resolved by trained office clerks completely electronically.

Criminal justice chain. Criminal cases are processed in court sessions. Figure 1 shows the workflow in the criminal justice chain.

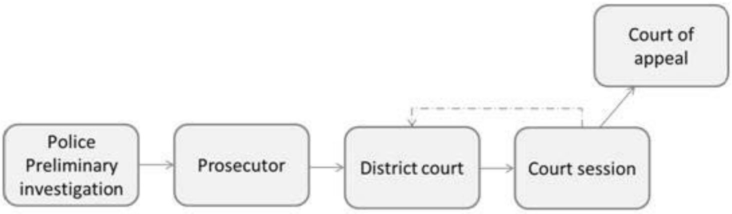

Figure 1: Criminal justice chain in Finland (unbroken arrows). The decision is made by the district court judge (dashed arrow).

Pre-trial investigation is done by the police. Prosecutors may communicate with the police already during the investigation, especially on demanding cases. After the preliminary investigation is complete, the case moves to the prosecutor's office. The prosecutor considers whether to press charges, and if so, the case moves to the district court, where it is processed further by the court staff. The case is processed in a court session, the main hearing. The court decision is pronounced orally immediately in the hearing, or pronounced later in writing. In district courts the decision can be made by one judge, with or without a composition of lay judges, or by three judges. After the judgment, the case can be appealed in a court of appeal. In courts of appeal, decisions are normally made by three members of the court (called Senior Justices or Justices). In important issues, seven or all members of the court of appeal may participate. Decisions in simple cases can be pronounced immediately at the end of the main hearing or else they are delivered in writing via the registry. (Finnish criminal procedure, 2014).

1.2 Information systems and electronic literature

There are a number of information systems in use in Finnish courts and prosecutor's offices. For case management, the courts use two systems, Tuomas for civil cases and Sakari for criminal cases. The Sakari system is also used by prosecutors and it includes links to the systems the police use. Both systems have been in active use since the 1990s and were considered state-of-the-art in Europe (Kujanen and Sarvilinna, 2001; Fabri and Contini, 2001). Although the Tuomas system was originally designed for summary cases, it was incrementally updated to cover all types of civil cases. The Sakari system was developed in the latter part of the decade and was built to include more capabilities for handling case information instead of focusing on managing the cases. The Sakari system uses different diary numbers for prosecutors and courts. Both the Tuomas and Sakari systems are based on Lotus Notes, text processing is available, and OpenOffice Writer text documents and scanned PDF files can be attached.

Other information systems in use are different registries and personnel management systems. There is also a free online database Finlex for legislative and other judicial information (Finlex Data Bank, 2014). Finlex also covers case law databases with precedents from the Supreme Court.

AIPA project. There is a large-scale on-going project called AIPA (Aineistopankki, databank in English), which aims to produce an advanced information system for prosecutors and courts of all levels. The new system is intended to be a uniform, integrated system that enables electronic data exchange and cooperation with other authorities. It is to be built with strong links to Vitja, an information system project for the police. In addition to being an electronic databank that enables electronic data archiving, the AIPA system includes advanced functionalities for case management, thus replacing both the Tuomas and Sakari systems.

The AIPA project was initiated in 2010. The planning phase was aimed to be completed by the end of 2013, with the intention of being implemented within the following few years. The AIPA project is coordinated by representatives from both the prosecutor's office and district courts. It includes several subprojects focusing on, for example, user interfaces and change management. One of the project's main goals is to develop new ways of working for prosecutor's offices and courts.

1.3 Context and scope of the study

The Finnish government has recently published a renewal program for the administration of justice (Advisory board for judicial relief, 2013). The program aims to shorten the duration of judicial proceedings – and therefore cut costs – and to improve the quality of judicial relief. Several of the measures listed in the program concern increasing the use of ICT and electronic transactions.

This research was done in collaboration with the nationwide workplace concepts by Senate Properties, a government-owned enterprise that leases premises to state agencies, and the government. The AIPA project partially overlaps with this research because it considers developing the work practices of prosecutor's offices and courts in addition to creating a new case management information system.

The scope of this paper is limited to the use of computers and other ICT tools among prosecutors, judges and their assistants, and members of the court of appeal. The fact that criminal cases also involve other parties (the police and pre-trial investigators, prison administration, writ servers, defendants and their counsel, witnesses, experts, etc.), who use ICT in their work, should, however, not be neglected. Furthermore, technologies that are used in customer service were not treated in the paper.

2. Methods

Several qualitative methods were used to collect data: interviews, visits to the Helsinki district court and court of appeal, and a workshop employing the Anticipation Dialogue Method. The interviews aimed to acquaint the researchers with the Finnish judicial administration agencies. More specifically, the interviews and visits helped to understand the Finnish court process, including the task descriptions of the personnel and the technology used within and outside court rooms. The workshop had a narrower scope, and was targeted at the work practices and technologies of the near future.

2.1 Data collection

Two researchers interviewed 12 people from judicial administration agencies. Both end users (prosecution, judges, and office staff) and administrative persons were included. The interviews were semi-structured. The topics covered interviewees' work practices, ICT solutions currently in use, and users' satisfaction with them. Two of the interview sessions (two and five interviewees) were held at the Helsinki courts, and were more informal in nature and held while visiting the court rooms. One interviewee was from the ICT administration and was also asked about prior, current, and planned ICT projects and about purchasing new devices and applications. One interview with a judge was targeted at understanding the criminal case workflow for the purpose of planning the workshop. The interviews were audio-recorded and later transcribed for the most part.

The workshop was titled 'ICT usage in the criminal justice chain'. Nine participants came from three different counties and represented different posts: prosecutors, district and appellate court judges, and assistive staff. None of the participants had any specific ICT experience besides their everyday work, but approximately half of them had taken part or were familiar with a prior ICT project or the on-going AIPA project. Five of them participated via videoconferencing system and the other four sat in the same room with two researchers and a passive observer.

The workshop employed the Anticipation Design Dialogue method (Laarni and Aaltonen, 2013) which derives, for example, from anticipation dialog (Arnkil, 2004) and future workshop (Jungk and Müllert, 1987) methods. The workshop consisted of three stages (see Table 1).

Table 1: The three phases of the workshop employing the Anticipation Design Dialogue method on the criminal case workflow.

Workshop stage	Topic	Issues discussed
Stage 1	It's the year 2015.	Processing criminal cases is smooth. What does it mean for your own work?
Stage 2	Recall from the year 2015, …	What were the main challenges in 2011? What has changed during the past four years?
Stage 3	New ways of working, new equipment	Envisioning uses for new technology: state-of-the-art court room technology, electronic literature, IT-supported decision-making etc.

In Stage 1, the participants were urged to project into the year 2015, when new case managements systems (i.e. AIPA) were assumed to be in use. The task was to envision work practices, court sessions and related practical arrangements that would enable smooth processes. The second stage mapped the steps that need to be taken in order to achieve the vision. In Stage 3, the participants were shown an inspiring and fast-paced slide show with images and videos of today's and tomorrow's technology, including material from actual court rooms around the world. The final task was to ponder the benefits and probability of using such technology in the future.

At each stage, the participants took turns in explaining their views, while the researchers controlled the time. Everyone was given a chance to add a brief remark before the following stage.

3. Results

This section describes how the criminal justice chain works currently, what kinds of tools and work practices are used in judicial administration, and how the workshop participants envisioned processing criminal cases in the future.

3.1 Current criminal case workflow

Prosecutor. The prosecutor works mainly independently. During the pre-trial investigation prosecutors can cooperate with the investigators (i.e. the police). They can attend meetings or communicate over the phone or by e-mail. The office staff helps with preparing and finalizing the plaint. They also assist the prosecutor in keeping up with deadlines and do plenty of preparatory work related to correcting erroneous information such as checking addresses.

The pre-trial investigation material is delivered to the prosecutor's office where the cases are manually distributed to selected prosecutors. Most material is in paper format and the prosecutors find it time-consuming to search for main issues. Data in larger financial crime cases can be partially processed electronically, for example, some data can be supplied on CDs, or prosecutors can use PDF Pro to link electronic cases.

All criminal cases are handled in the Sakari system. The prosecutors' Sakari system is used for all prosecution documents, such as plaints, decisions not to prosecute, and limitations on pre-trial investigation. The documents have a structured format. The documents are written in the Sakari system or are created on Lotus Notes (typing program) document bases, which then relay information to the Sakari system. OpenOffice documents or other document formats are not compatible with the Sakari system.

Courts. The district court judges work in pairs with their assistants. The assistants (käräjäsihteeri, literally translated as district court secretary) work on routine errands but in fact their role is closer to that of a paralegal. The assistants have varying educational backgrounds; many of them are secretaries by education, but the assistants do not have and are not required to have any prior legal education. The paralegal role of the assistants is evident when resolving summary cases, which they can process independently and completely in electronic format.

All other cases besides the electronic summary cases are distributed to the judges – in fact to the assistants' desks – by the court bureau; the judges cannot choose cases themselves. The pre-trial investigation records arrive at the court bureau, where a diary number is set (written in ink on the case) to be used in the court Sakari system. The bureau also checks the system for other cases concerning the same defendant. The case is literally a paper or cardboard case, or a folder, depending on the amount of material. The judge's assistant prints the plaint and the plaint information document from the Sakari system. Electronic law literature is available, but due to archiving requirements, paper copies are made of all documents.

While the case is being processed within the district court, the case (paper file) moves back and forth between the judges' and assistants' desks. Each judge-assistant pair forms their own work practices. A common practice is that while the case is on the judge's desk, the judge processes the contents of the case, and when they need assistance (e.g. in settling dates for court sessions with parties), they pass it back to their assistant. When the assistants have the case, they handle post traffic related to the case and communicate with parties over the phone or by e-mail. E-mail is an official contact channel comparable with fax-mediated documents. Some e-mails are printed because printed documents facilitate task management.

In courts of appeal, the members' main tasks are not essentially different from those of district courts, with the exception that their clerical staff lack the paralegal role the assistants have in district courts. There are, however, legally trained referendaries, who present cases to the members for the preparation and main hearing of the case.

Court session. District court main hearings have a minimum of three parties: the judge and judge's assistant, the prosecutor, and the defendant with counsel. In district courts, the judge's assistant uses a computer for typing court records. Other parties use mainly paper and pen for taking notes, although personal laptops can be used. Some court rooms have a wireless network, but this is rarely used for accessing databases.

All court rooms have statutory audio-recording equipment for recording testimonies. Telephone hearing, such as of experts or witnesses, is possible via a speaker phone or a landline telephone with external speakers. Legislation allows video hearing in many cases, with the exception of hearing defendants in criminal cases (Mannerhovi, 2007).

In courts of appeal, main hearings are similar to those in district courts. Depending on the geographical area and especially outside the Helsinki metropolitan area, the members may be required to travel to other towns for the main hearings. Travel is also required of prosecutors.

Court sessions are typically booked by court assistants. Settling a suitable time for all parties is very time-consuming and can take many weeks. It also involves booking a court room for an estimated duration, and possibly booking separate equipment for audio-visual (AV) presentation of case material. Rebooking might be needed if there are changes to parties' schedules or if the defendant does not appear in the court session. Electronic calendars are available but not very widely used, and therefore communication is mainly over the phone or by e-mail.

Court rooms can be booked in various ways. Smaller districts use paper calendars but more sophisticated booking systems exist. For example, the Helsinki district court uses a browser-based information system for booking court rooms. The system is accessible through the court intranet, but is separate from personal electronic calendars. The booking system lists the dates and court rooms that are already booked. Items such as an AV cart (a mobile cart with equipment for presenting audio-visual material, e.g. images, video) or the need for guards can be also booked.

Typical court session preparations proceed as follows (case example from Helsinki district court). The judge's assistant arrives in the court room about quarter of an hour before the session is scheduled to start. The audio recording devices are turned on. The desktop computer is started and the Sakari (or Tuomas in civil cases) system is turned on. The audio-recording devices are also controlled by a computer program. The assistant also needs to open OpenOffice Writer or Sakari-Notes (a typing program based on Lotus Notes), depending on the location of the court records. The assistant handles the above-mentioned systems during the court session and types court records. Computer helpdesk service is available if there is a problem with the AV cart.

There are no other desktop computers in the court rooms besides the one the judge's assistant uses for the court records. Most often, the judges take notes using paper and pen – as part of the preparations, the judge can have prepared and printed a partially prefilled document ('manuscript') for the main hearing – and type them later in their offices. There are judges who use their own personal laptop computers for taking notes, but they represent a minority, and are mostly among the younger judges.

The prosecutors and defendant's counsel can use laptops. Power outlets are available, although extension cables may be needed. For presenting evidence, the laptops can be connected to the AV cart, or parties can use an evidence camera with a projector. However, the case material is mostly on paper, and in larger cases it is necessary to shuffle through several paper folders to view the necessary documents. Internet access is not available by default although individuals (mainly the defendant's counsel or audience) may use 3G or GPRS connections.

It is mandatory to use the Sakari (or Tuomas) system for court diaries, including case management records such as information on parties, dates, and status of the case including a code for the judgment. Judges can use Sakari-Notes themselves, although there are judges who have refused to use it due to usability issues, and have delegated the task to their assistants. The actual judgment is typed using OpenOffice Writer.

3.2 Paper and secondary tasks dominate current work practices

Case material provided in electronic format is currently printed. Part of the reason for printing is based on legislation, which requires one archived paper copy of each document. Printed documents also have other benefits. Paper is a familiar medium to everyone, it feels concrete, and the matt finish and good contrast are comfortable for reading. Writing or erasing notes and resuming work after interruptions is easy. In some district courts, paper is also used for organizing tasks. The case file has a physical role in determining the status of the case between judges and assistants. In addition, assistants may use printed copies for sorting e-mails that require attention later. Paper is used as a medium to avoid the chaos of electronic documents, which tend to get forgotten or lost, or buried under excess electronic information flow and long file paths; this is an important point that should be considered carefully when designing information systems for electronic documents. In addition, paper documents do not need secure – and possibly lagging – online access to information databases.

The disadvantages of paper documents are evident when the case file size increases. On the whole, it is time-consuming to search for a certain item in a large case file, such as a witness statement, and even more time is wasted when this process is repeated by all parties in all stages during the criminal case workflow. Moreover, travelling parties, such as the prosecutors and members of court of appeal, need to carry the case material to the court house, which is often located in another town and may require long-distance travel.

Another time-consuming task is related to scheduling. The judge's assistant schedules and re-schedules parties and court rooms. Re-scheduling a court session by phone or e-mail causes delays of days, or even weeks. Electronic calendars are available, but their use is not very popular, due to usability and organizational factors. Besides the parties involved in the case, witnesses, experts, and interpreters may be needed during the session, and their availability and travel time and expenses must be considered. Prosecutors also face uncertainty in whether the scheduled (or re-scheduled) court room includes a certain evidence presentation device, and may have to prepare alternative means to present data beforehand.

Although the interviewees and workshop participants considered the available desktop computers adequate for their core tasks, nearly everyone had usability issues with the word processing and case management systems. OpenOffice Writer, which was the officially supported word processing software in most judicial agencies, was found difficult to use when it came to adjusting page margins and other page layout settings. The need to adjust the settings was a typical task especially when a file created in Microsoft Office Word was imported into Writer. In district courts, the judges and their assistants might even be struggling together with the settings for a considerable amount of time.

The case management systems Sakari and Tuomas were also found to be rigid. The text processing capabilities of the systems were considered unsatisfactory, and the information systems were slow to respond. The assistants reported that saving a court records document in the Sakari system during a court session might cause a long delay. While waiting for the system to become responsive again, the session could have already proceeded. Furthermore, the few employees using portable computers had had problems accessing the information systems remotely. Working time was thus allocated to secondary computer management tasks instead of the case itself.

3.3 Vision of processing a criminal case in 2015

It was envisioned that in 2015, criminal cases would be processed smoothly and swiftly from pre-trial investigation to verdict.

Prosecutor. Pre-trial investigation material is electronically transmitted from the police information system to the prosecutor's office; the data format is structured and concise. Contact information of persons involved is up-to-date both in population registers and in the police system. The prosecutors' task load is considered when cases are distributed to individual prosecutors using automated lists.

Clear cases can be forwarded with a mouse click and an accelerated process enables resolving cases in 1-3 days. In demanding cases, the police and the prosecution co-operate in preparing the pre-trial investigation material into a plaint. All material is in an electronic databank allowing swift browsing and easy access between linked documents.

Courts. All case material arrives at the district court in electronic format, with the plaintiff's prayers and scanned or photographed evidence enclosed. The material is automatically forwarded to a selected paralegal assistant's computer. If a prosecutor sends multiple plaints concerning one defendant, assistants can transfer them to document templates with ease and without manual intervention. The assistant sends summons, writs, and notices electronically via e-mail, electronic letters (the Netposti service available in Finland) or other equivalent secure media, for example using an electronic client identifier for citizens.

The electronic documents have a clear structure and interactive links. The judges have a sufficient number of displays, which enables work on several e-documents and the examination of electronic law simultaneously. Instead of summoning parties to a court room, preparation for trial can be done orally in an office room using videoconference systems. In demanding cases, preparation for trial is done in writing. Work is mostly done within offices and court rooms.

Court session. All parties use electronic calendars. The assistants' scheduling task is facilitated by offering an overlapping view of suitable time-slots. Booking and rebooking court rooms and mobile evidence presentation equipment are integrated in the calendars.

Court room technology supports working with electronic material. A wireless network is available to all parties. An electronic databank is accessible in the court room, thus making paper files obsolete. Personal working copies of the electronic documents can be supplemented with notes.

Desks are equipped with accessory displays, necessary cabling, and power outlets for laptops. Displays have an important role in examining evidence and plaints. Remote hearing is done via video (instead of telephone), which also enables mediation of body language. In addition, the videoconferencing system can be used for remote interpreting, mediating experts' reports or even prosecutors' addresses.

3.4 Interlinked and well-structured electronic documents with online access, to enable smooth workflow

The envisioning process relied largely on the fact that the AIPA system was estimated to be implemented in 2015, which was the target year in the first stage of the workshop. Even though the renewal of the justice chain information system is considered important, the expectations for the AIPA system were cautious, since information system reforms, especially those that cross agencies' boundaries have rarely succeeded as planned.

The AIPA system (or other equivalent information or case management system) was seen as the most important enabler for new work practices. It would combine information from population registers and systems the police use, and the same system would cover the whole criminal justice chain within the judicial agencies. The amount of manual work – especially when a case crosses the boundary between two agencies – would be greatly reduced. Prosecutors emphasized the importance of well-structured documents, which could even have 'smart' attributes.

Using the AIPA system efficiently requires working online and remote access to databases. The tools mentioned in the workshop were portable computers, meaning laptops for prosecutors and judges, and wireless networks. The assistants of district and appellate courts did not see any added value in laptops, but thought they could benefit from tablet computers, which would be easy to carry around and to use side by side with desktop computers.

Smoother workflow in the criminal justice chain could also be facilitated by more extensive use of electronic calendars and videoconferencing systems in the court rooms. The existing e-calendars are not used by all agencies' employees and therefore they cannot be solely used for booking court sessions among parties. The defendant's counsel is obviously outside the agencies' network and appointments have to be scheduled manually. Because court room booking systems are currently separate from personal e-calendars, the judges' assistants saw it as extra work to use dual calendars. Moreover, the personal e-calendars could only be used from the assistants' personal desktop computers, and therefore their use was often skipped.

The use of videoconferencing systems in court sessions aroused debate. There was consensus that experts could be heard by phone or video, and that preparations for trial could be done using shared electronic documents and video-mediated meetings of the parties. District court judges felt strongly that evaluation of defendants' statements or interaction is impossible via video without impacting the main hearing. Moreover, current legislation guarantees the defendant the right to be heard in person. Prosecutors and members of court of appeal, however, saw it possible for themselves to be virtually present in the court room via video, lessening the need for travel. Videoconferencing technology has already evolved considerably over the past few years, and if or when the legislation is changed to allow for more freedom, the technology will have had time to overcome issues related to video quality and transmission delays.

4. Discussion

Although participants in the workshop were urged to project into the future, their visions on new work practices and ICT tools were quite modest. The purpose of the first and second stages of the workshop, which concentrated on the 4-year time span from 2011 to 2015, was to get a realistic view of a smooth workflow in the criminal justice chain. What was less expected was that even the third phase, with an unlimited time span, elicited realistic and quite cautious visions on uses for new technology. For example, the introduced possibilities for IT-supported decision-making or high-tech court room technology were not rejected outright, but neither were they discussed further by the participants. The participants were all conscious of both the costs of new equipment and the tight public-sector economic situation. It is a common notion that the public sector is quite conservative in adopting new technology, and employees are to manage with systems that are slightly outdated. Moreover, the current legislation seemed to constrain the participants' notions and limit the flight of their imagination.

The results may show some bias towards the work practices in southern Finland, where travel distances are considerably shorter than in sparsely populated areas. Considering the independence of the judiciary and the high level of autonomy each court and prosecutor's office exhibits, however, the work practices of the participants in the workshop were not significantly different on the level at which this research project examined them.

4.1 Towards new ways of working with advanced information systems

In a few years' time, the core of practicing law is unlikely to change. Pre-trial investigations will still be performed, prosecutors will prepare plaints, and judges will make decisions. As information systems become more automated, the systems will eventually replace some of the work the assistants and other administrative staff currently do. The assistants, who participated in the workshop, believed their professional role was about to shift toward assisting with and operating the ICT, such as new court room technology. It is a probable scenario, especially in the near future, because prosecutors and judges of older generations have only moderate computer skills and finding the time for ICT training is challenging.

Despite the unaltered core of judicial work, the ways of working can, however, go through massive changes with the introduction of the AIPA information system, which is, at the time of writing in the planning phase and expected to be incrementally implemented starting in 2018. The magnitude of change depends largely on how well the AIPA system can enable working with electronic documents.

AIPA is very ambitious, as it attempts to cover several parts of the criminal justice chain. In the Netherlands, similar large-scale approaches failed, but incremental ICT developments, which did not require radical reorganization of work practices, have been more successful (Langbroek and Tjaden, 2009). In Finland, the police will not be a part of the AIPA system – although documents are to be electronically transferred between AIPA and Vitja – and the chances of succeeding are greater, considering the fact that the Sakari system is already partially shared between the prosecution and the courts.

There are multiple obstacles in the way of new work practices, even if the information system is evaluated to be good as such. In addition to successful implementation, a system needs acceptance on both the individual and the organizational level.

Individuals see a new system through the user interface, which is naturally expected to be user-friendly. Any user interface can, however, be learnt and tolerated if the contents of the system compensate for a lack of usability. Currently, each court or office has evolved its own preferences on how cases are processed – partially due to the independence of the judiciary – and therefore, their ways of constructing documents differ. Thus, individual users are likely to experience discomfort in adapting to new electronic documents whose structure is unfamiliar, or, considering deeply rooted individual work practices, even 'wrong'.

The role of the organization in achieving user acceptance is important and manifold. Firstly, the organization needs to provide the users with adequate tools. To obviate the need to print documents and to utilize electronic documents effectively, anywhere and anytime, the users need portable computers, a sufficient number of displays to work on several documents simultaneously, and uninterrupted access to information systems online. Secondly, considerable training is needed before the new system can be used efficiently. The threshold for contacting user support should be especially low in the transition phase. In addition, user acceptance is likely to be better if users, or at least some of them, have been given a chance to participate in the design of the system, and the system has been piloted and iteratively improved to suit the target agencies. Thirdly, all actors in the criminal justice chain should have corresponding means to employ the information systems. And fourthly, the chiefs of courts and prosecutor's offices need to encourage their staff to tap the possibilities of the new systems and to prevent them from reverting to their old routines. To give an example of the last two points, the court sessions will last for as long as it takes for the slowest party to find a certain document in the case file.

Many of the above-mentioned issues have already been addressed by others, and we should learn from them. Legal matters matter (Henning and Ng, 2009), but merely removing legal obstacles from switching to electronic systems and paperless offices is not enough (Velicogna, 2007). The users are not motivated by off-the-shelf, uncustomizable applications (Velicogna, 2007), or applications that only replicate old documents in electronic format (Velicogna et al., 2011). Motivation could be spurred on by active discussion and agreements on new ways of working among users (Velicogna et al., 2011). In addition, standardization of information between judicial agencies seems to be possible although negotiation is needed (Langbroek and Tjaden, 2009). Therefore, communication with representatives from all agencies as well as the end users should go on before and after an ICT system is implemented, to ensure that problems and system updates are properly handled. This can maintain public support and keep users committed (Langbroek and Tjaden, 2009).

New work practices entail other organizational aspects, as well. New ways of managing the working time and working place should be considered, in conjunction with the introduction of flexible information systems, which no longer require the employees to sit in stationary physical offices. There is a changeover in the Finnish judicial agencies from traditional offices to more flexible multifunctional work places, and new ICT and information systems are the means to enable the change.

4.2 Conclusion

The interviewees and workshop participants in this study had a common goal: to be able to concentrate on the core work. The era of digital systems seems to add to the workload instead of alleviating it. The current information systems serve their original purpose of storing court records, but are not compatible with efficient word processing software. At the same time, information flow has increased, but a lack of powerful search engines in the systems produces extra work. Travel, whether it is a prosecutor travelling to a court house located in a distant town or an interpreter being flown across the world, is time-consuming. Added to that, the parties' schedules are tight, and manually finding suitable times for all parties is slow. These tasks are not relevant to practicing the law and processing crime cases. New ways of working and user-friendly information systems enable a positive change, allowing the parties to better focus on their core task.

Acknowledgments. We thank the Ministry of Justice and all the participants from judicial agencies, Senate Properties, consultants at Workspace, and RYM Ltd 'Built Environment Process Re-engineering' program for this most interesting research topic.

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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.

9 789526 081021

ISBN 978-952-60-8102-1 (printed)
ISBN 978-952-60-8103-8 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

978-951-38-8658-5 (printed)
978-951-38-8657-8 (pdf)
2242-119X (printed)
2242-1203 (pdf)

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