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A Sound Approach Toward a Mobility Aid for Blind and Low-Vision Individuals

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2023

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Isaksson-Daun, J. (2023). *A Sound Approach Toward a Mobility Aid for Blind and Low-Vision Individuals*. [Doctoral Thesis (compilation), Department of Biomedical Engineering]. Department of Biomedical Engineering, Lund university.

Total number of authors:
1

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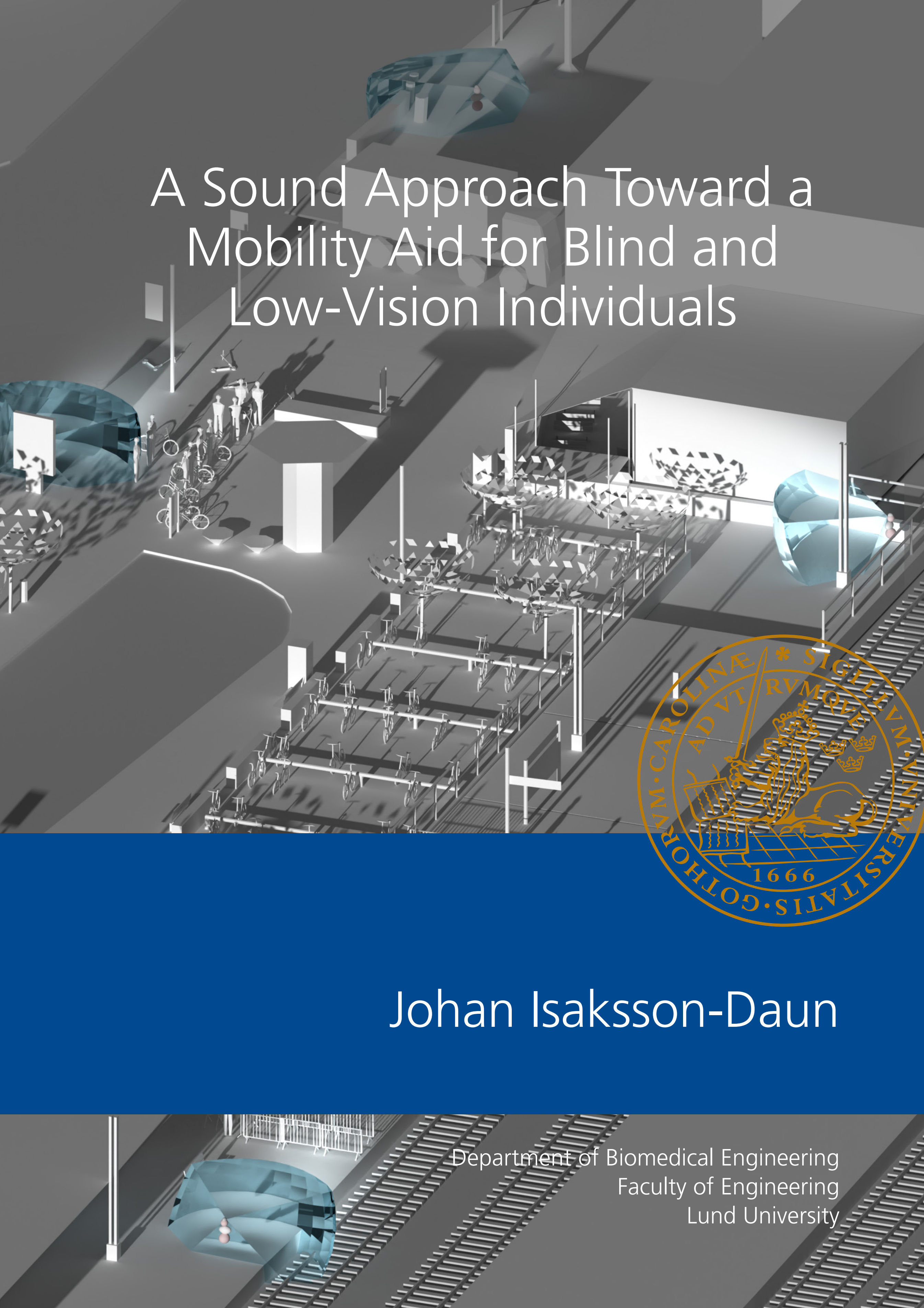
Download date: 17. May. 2023



A Sound Approach Toward a Mobility Aid for Blind and Low-Vision Individuals

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A Sound Approach Toward a Mobility Aid for Blind and Low-Vision Individuals

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LUND UNIVERSITY

DOCTORAL DISSERTATION

by due permission of the Faculty of Engineering, Lund University, Sweden.

To be defended in E:1406, Ole Römers väg 3, Lund.

June 2, 2023 at 09:00

Faculty opponent

Professor Edwige Pissaloux

Organization LUND UNIVERSITY Dept. of Biomedical Engineering P.O. Box 118 SE-221 00, Lund, Sweden	Document name DOCTORAL DISSERTATION
	Date of issue 25 April 2023
Author(s) Johan Isaksson-Daun	Sponsoring organization The Promobilia Foundation (Ref nr. F17510)

Title and subtitle
A Sound Approach Toward a Mobility Aid for Blind and Low-Vision Individuals

Abstract

Reduced independent mobility of blind and low-vision individuals (BLVIs) cause considerable societal cost, burden on relatives, and reduced quality of life for the individuals: including increased anxiety, depression symptoms, need of assistance, risk of falls, and mortality. Despite the numerous electronic travel aids proposed since at least the 1940's, along with ever-advancing technology, the mobility issues persist. A substantial reason for this is likely several and severe shortcomings of the field, both in regards to aid design and evaluation.

In this work, these shortcomings are addressed with a generic design model called Desire of Use (DoU), which describes the desire of a given user to use an aid for a given activity. It is then applied on mobility of BLVIs (DoU-MoB), to systematically illuminate and structure possibly all related aspects that such an aid needs to aptly deal with, in order for it to become an adequate aid for the objective. These aspects can then both guide user-centered design as well as choice of test methods and measures.

One such measure is then demonstrated in the Desire of Use Questionnaire for Mobility of Blind and Low-Vision Individuals (DoUQ-MoB), an aid-agnostic and comprehensive patient-reported outcome measure. The question construction originates from the DoU-MoB to ensure an encompassing focus on mobility of BLVIs, something that has been missing in the field. Since it is aid-agnostic it facilitates aid comparison, which it also actively promotes. To support the reliability of the DoUQ-MoB, it utilizes the best known practices of questionnaire design and has been validated once with eight orientation and mobility professionals, and six BLVIs. Based on this, the questionnaire has also been revised once.

To allow for relevant and reproducible methodology, another tool presented herein is a portable virtual reality (VR) system called the Parrot-VR. It uses a hybrid control scheme of absolute rotation by tracking the user's head in reality, affording intuitive turning; and relative movement where simple button presses on a controller moves the virtual avatar forward and backward, allowing for large-scale traversal while not walking physically. VR provides excellent reproducibility, making various aggregate movement analysis feasible, while it is also inherently safe. Meanwhile, the portability of the system facilitates testing near the participants, substantially increasing the number of potential blind and low-vision recruits for user tests.

The thesis also gives a short account on the state of long-term testing in the field; it being short is mainly due to that there is not much to report. It then provides an initial investigation into possible outcome measures for such tests by taking instruments in use by Swedish orientation and mobility professionals as a starting point. Two of these are also piloted in an initial single-session trial with 19 BLVIs, and could plausibly be used for long-term tests after further evaluation.

Finally, a discussion is presented regarding the Audomni project — the development of a primary mobility aid for BLVIs. Audomni is a visuo-auditory sensory supplementation device, which aims to take visual information and translate it to sound. A wide field-of-view, 3D-depth camera records the environment, which is then transformed to audio through the sonification algorithms of Audomni, and finally presented in a pair of open-ear headphones that do not block out environmental sounds. The design of Audomni leverages the DoU-MoB to ensure user-centric development and evaluation, in the aim of reaching an aid with such form and function that it grants the users better mobility, while the users still want to use it.

Audomni has been evaluated with user tests twice, once in pilot tests with two BLVIs, and once in VR with a heterogenous set of 19 BLVIs, utilizing the Parrot-VR and the DoUQ-MoB. 76 % of responders (13 / 17) answered that it was very or extremely likely that they would want use Audomni along with their current aid. This might be the first result in the field demonstrating a majority of blind and low-vision participants reporting that they actually want to use a new electronic travel aid. This shows promise that eventual long-term tests will demonstrate an increased mobility of blind and low-vision users — the overarching project aim. Such results would ultimately mean that Audomni can become an aid that alleviates societal cost, reduces burden on relatives, and improves users' quality of life and independence.

Key words: Audomni, blindness, electronic travel aids, Desire of Use, DoUQ-MoB, low vision, mobility aids, Parrot-VR, patient-reported outcome measures, sonification, sensory substitution, sensory

Classification system and/or index termes (if any):

Supplementary bibliographical information:
ISRN: LUTEDX/TEEM-1133-SE, Report No. 1/23

Language
English

ISSN and key title:

ISBN
ISBN: 978-91-8039-697-4 (print)
ISBN: 978-91-8039-698-1 (electronic)

Recipient's notes

Number of pages
253

Price

Security classification

DOKUMENTDATABLAD enl SIS 61 41 21

To my family, friends, and all who
have helped along the way

I see terribly good potential, and this is missing.
– Test participant with severe vision loss

Public defence
June 2, 2023, 09:00 in E:1406, E-building, LTH, Ole Römers väg, 223 63 Lund, Sweden.

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Cover illustration
Virtual reconstruction of a busy Lund Central Station, Sweden. Four avatars fitted with a virtual versions of the Audomni electronic travel aid for blind and low-vision individuals are depicted, the field-of-views of which are illustrated in semi-transparent cones.
Illustration by: Johan Isaksson-Daun.

ISBN: 978-91-8039-697-4 (print)
ISBN: 978-91-8039-698-1 (electronic)
Report No. 1/23
ISRN: LUTEDX/TEEM-1133-SE
Printed by Tryckeriet, E-building, Faculty of Engineering, Lund University, Lund Sweden

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Populärvetenskaplig sammanfattning

Det finns runt 100 000 blinda och kraftigt synnedsatta individer (BKSI:er) i Sverige. Sådan synnedsättning leder till en kraftigt minskad förmåga för självständig förflyttning och lägre livskvalité, med ökad risk för arbetslöshet, trafikolyckor, en stillasittande livsstil och depression. Hälften av alla käpp- och hundanvändare är med om en huvudkollision årligen, och drygt var tredje för en fallolycka — vilka kan föra med sig öppna sår, brutna tänder och höftfrakturer. Det finns många som inte vågar eller kan ge sig ut på egen hand överhuvudtaget. Överlag har en blind person sju gånger högre risk att dö under ett år än vad en normalseende person har.

Denna bristande rörlighet leder också till stora samhällskostnader. I Sverige är kringkostnaderna till kraftig synnedsättning och blindhet, såsom för transport, assistans, depression, fallolyckor och minskad produktivitet, åtminstone 25 miljarder kronor om året. En betydande del av detta axlas av individerna själva, och av deras närstående. Mer individuellt kostar en enda ledarhund 100 000 kr om året för staten.

Den lägre förmågan för självständig förflyttning hos BKSI:er är trots dagens hjälpmedel, vita käppar och ledarhundar. De är alltså otillräckliga. Detta har varit känt länge, och därför har hundratals tekniska hjälpmedel föreslagits de senaste 70 åren, men dessvärre utan större framgång. Detta beror i stor del på hur utveckling i fältet sker, för det visar sig att det finns kraftiga brister i att: utnyttja tidigare forskning och designvetenskap; välja välmotiverade och lärorika metoder och mätvärden; utföra långsiktiga tester; fråga BKSI:er vad de tycker, och speciellt jämfört med deras nuvarande hjälpmedel; samt inkludera tillräckligt många BKSI:er i användartest.

I denna avhandling presenteras därför först ett allmänt designverktyg, Desire of Use (DoU). Detta används sedan för att knyta ihop designvetenskap, tidigare lärdomar och vilka behov BKSI:er har för förflyttning, för att på så sätt försöka undvika de problem som fältet i stort har, och maximera möjligheterna att nå ett lyckat hjälpmedel.

DoU används sedan för att konstruera ett nytt mätverktyg i form av ett omfattande frågeformulär som fokuserar på förflyttning hos BKSI:er, samt aktivt främjar jämförelse med dagens hjälpmedel. Dessutom används det som utgångspunkt i utvecklingen av nya testmetoder och andra mätvärden.

För att kunna utföra reproducerbara tester, men som också sker i relevanta stadsmiljöer och med ett tillräckligt antal testare från målgruppen, beskrivs också ett nytt portabelt VR-system. Det gör det möjligt att t.ex. testa hemma hos BKSI:er — vilket kraftigt ökar mängden möjliga testare.

Dessa verktyg, DoU, frågeformuläret, och VR-systemet, används till sist för att utveckla och utvärdera ett nytt slags förflyttningshjälpmedel, Audomni, på ett så effektivt, lärorikt och användarcentrerat sätt som möjligt. Audomni går ut på att, lite som ekolokalisering, omvandla en användares synfält till ljud. På så sätt blir det möjligt att förstå omgivningar på ett större avstånd, och att förflytta sig i dem på ett nytt sätt. Kortfattat omvandlas avstånd till volym, höger–vänster till stereo och uppåt–nedåt till olika toner. Allting sker samtidigt och i realtid. Olika former förmedlar därigenom olika ljud, och användaren själv lär sig att tolka sina miljöer.

Med hjälp av de utvecklade metoderna och mätvärdena, kunde Audomni under 2022 testas med 19 BKSI:er från fem olika regioner i Sverige. Det sannolikt mest intressanta resultatet var att 76 % (13 av 17) av dem svarade att det var *mycket* eller *extremt sannolikt* att de skulle vilja använda hjälpmedlet tillsammans med deras nuvarande hjälpmedel — och med kommentarer som “Jag ser fruktansvärt bra potential, och det här saknas.” Det kan vara det första arbetet som visar att en majoritet av deltagare från målgruppen faktiskt vill använda ett nytt förflyttningshjälpmedel.

Slutligen presenteras också vägen framåt för Audomni, eller andra hjälpmedel, i form av en tidig redogörelse för hur långsiktiga tester kan utformas för att visa om ett hjälpmedel faktiskt ger en ökad rörlighet hos användarna.

I stort beskriver denna avhandlingen nya verktyg som kan möjliggöra ett nytt funktionellt och vida använt förflyttningshjälpmedel för BKSI:er — exemplifierat med hjälp av den parallella utvecklingen och utvärderingen av Audomni. Målsättningen är att detta är ett steg på vägen till ett hjälpmedel som minskar stora samhällskostnader och bördan på familj och vänner, samt för användaren innebär ökad livskvalité och självständig förflyttning.

Abstract

Reduced independent mobility of blind and low-vision individuals (BLVIs) cause considerable societal cost, burden on relatives, and reduced quality of life for the individuals, including increased anxiety, depression symptoms, need of assistance, risk of falls, and mortality. Despite the numerous electronic travel aids proposed since at least the 1940's, along with ever-advancing technology, the mobility issues persist. A substantial reason for this is likely several and severe shortcomings of the field, both in regards to aid design and evaluation.

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The thesis also gives a short account on the state of long-term testing in the field; it being short is mainly due to that there is not much to report. It then provides an initial investigation into possible outcome measures for such tests by taking instruments in use by Swedish orientation and mobility professionals as a starting point. Two of these are also piloted in an initial single-session trial with 19 BLVIs, and could plausibly be used for long-term tests after further evaluation.

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List of papers

Included

I. **Desire of Use: A Hierarchical Decomposition of Activities and Its Application on Mobility of Blind and Low-Vision Individuals**

J. Isaksson, T. Jansson, J. Nilsson

Published in: IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 28, no. 5, pp. 1187–1197, 2020.

Author's contribution: The literature reviews, the research and design of the model, the research and application of the model, the graphical content, and the writing.

II. **Audomni: Super Scale Sensory Supplementation to Increase the Mobility of Blind and Low-Vision Individuals — A Pilot Study**

J. Isaksson, T. Jansson, J. Nilsson

Published in: IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 28, no. 5, pp. 1187–1197, 2020.

Author's contribution: The literature review; the research and design of the algorithms; the research and implementation of the hardware and software; the design, ethical application, recruiting, and execution of the user tests; the design of, and the data analysis; the graphical content; and the writing.

III. **Assessing Mobility of Blind and Low-Vision Individuals through a Portable Virtual Reality System and a Comprehensive Questionnaire**

J. Isaksson-Daun, T. Jansson, J. Nilsson

Manuscript, ready for submission in May 2023.

Author's contribution: The literature reviews; the research and design of the VR-system; the research and implementation of the hardware and software; the research and design of the questionnaire; the research, design, recruiting, and execution of the validation round; the design of, and the data analysis; the graphical content; and the writing.

IV. Using Portable Virtual Reality to Assess Mobility of Blind and Low-Vision Individuals with the Audomni Sensory Supplementation Feedback

J. Isaksson-Daun, T. Jansson, J. Nilsson

Manuscript, ready for submission in May 2023.

Author's contribution: The research and development of the VR-environments; the research and design of the modified algorithms; the research and implementation of the hardware and software; the design, ethical application, recruiting, and execution of the user tests; the design of, and the data analysis; the graphical content; and the writing.

Related

A. Audomni: Towards a Primary Mobility Aid for Blind and Low-Vision Individuals Using Super Scale Sensory Supplementation

J. Isaksson, T. Jansson, J. Nilsson

One-page-abstract, presented with poster at: 41st IEEE EMBC International Conference 2019.

B. A VR-Approach to Assess Mobility of Blind and Low-Vision Individuals Using the Audomni Sensory Supplementation Device

J. Isaksson, T. Jansson, J. Nilsson

One-page-abstract, presented on stage and with poster at: Medicinteknikdagarna 2021.

C. Assessing the Audomni Electronic Mobility Aid for Blind and Low-Vision Individuals Using Virtual Reality and the Desire of Use-Questionnaire

J. Isaksson-Daun, T. Jansson, J. Nilsson

One-page-abstract, presented on stage at: Medicinteknikdagarna 2022.

Acknowledgments

Even though the start of my PhD studies was not the start of my work on this project, and they ending will not be the end of my work on it, this period has been an immense journey. Both for me and the project. While I started the project alone, I would not be here, putting this into writing, without the considerable, essential, and unwavering help, interest, and encouragement from a great number of great people.

I would like to extend the full capacity of my gratitude to my main supervisor Johan Nilsson and co-supervisor Tomas Jansson. For more than six years, starting even before my doctorate period, and out-of-the-blue with a project you were not familiar with, you somehow managed to perfectly balance my ambition regarding research goals and plans, project development, pursuit of knowledge, and writing, with my existing skills, accessible resources, mental health, and available time (± half a year, give or take). You also imbued the work with your knowledge and your insight, and this thesis has benefitted substantially from it. I will always appreciate all you have done for me.

Additional thanks also to Johan for your help with various applications, and all the administrative stuff you must have endured.

My other colleagues at the Department of Biomedical Engineering also have my sincerest appreciation for providing a relaxing and interesting, yet productive workspace, and for all your help. Special thanks to Ammi, Axel, Christian, Désirée, Nebojša, and Ulrika for putting up with my multitude of questions and requests. Very special thanks to my old office mates Kevin, William, and Jonathan, you were a pleasure to share rooms with; and to my ongoing office mate Mahdi — who needs shelves when we have each other?

Many thanks go out to Öivind Andersson at the Department of Energy Sciences, Mats Johansson at Medical Ethics, Marcus Nyström at Lund University Humanities Lab, the dearly missed Anders Robertsson of the Department of Automatic Control, as well as Charlotte Magnusson and Kirsten Rassmus-Gröhn at Certec - Rehabilitation Engineering and Design, who together contributed with valuable knowledge, discussions, and ideas regarding test methodology, sensor technology, ethical applications, and participant recruitment.

All orientation and mobility professionals I have interviewed have great thanks for aiding with the development of the questionnaire.

I am also massively grateful to all blind and low-vision test participants, who have given their time and best efforts in evaluating Audomni. Without your help, the project could never progress, so it is of immeasurable value. The groups that aided in recruitment also have my deep appreciation.

For almost a decade, I have enjoyed the continuous support of my friends with this project, and you should know I appreciate it exceedingly. Special thanks to Camilla, James, Joanna, Björn, Dani, and Martin who willingly subjected themselves to various prototype versions; and very special thanks to the latter three, who remained supportive even though their versions unknowingly missed critical functionality, and were hopelessly difficult to make sense of.

Åsa, Ola, and Patrick, whereas you could not from the start — if only Elin and I had met earlier — you immediately showed your support for me and the project once you had the chance, and for that I am very grateful.

Of course, I want to give my warmest thanks to you, mom and dad, for remaining supportive of the project over all these years (while giving fair criticism), and having taught me to work so that I can take pride in the result. I believe that most of my achievements rest on that foundation. Such thanks also extends to you, Tim, Josefine, and Cecilia, for unfaltering interest in the project developments, and overall support. Special thanks to Tim and Josefine, the greatest siblings one could imagine. Tim, without your brutally thorough proofreads of various texts over the years, I would be a substantially worse writer; and your overall attitude in life, and way with people, are both truly inspiring — and only rivaled by Josefine. Because Josefine, whenever I am about to meet, interview or test with someone, you are my role model in how I want to interact with them; and overall it is a privilege to be your (and your brother's) brother. Leonelle, you have my thanks in advance for likely pushing the limits of any prototype you get your hands on in the future.

Elin, you are wholly amazing and I love you with the entirety of my being. Thank you for supporting, helping, and believing in me, in work, and in life. You have made years of PhD studies flash by in an instant, while also making them wonderful and unforgettable. Indeed, Elin är bäst!

In addition, I would like to give my sincere thanks to:

- Andrew Wissler — without you this project would not exist.
- All the bright people of LU Innovation, LU Holding, and VentureLab I have had the pleasure of meeting and discussing the project with from various perspectives over the years; and for the Leapfrogs scholarships and VentureLab tenure — it all really helped both me and the project get off the ground. Special thanks to Embla Ardal, Fredrik Edman, Per Mercke, Maryam Olsson, Sven Olsson, Thomas Rundqvist, and Louise Wrange for all your help, time, and effort.
- All my fellow Leapfrogs and VentureLab alumni — you are all an inspiration, and I wish you the best in your current and future endeavors.
- Nordic Innovation, including all the hard-working people involved with the Nordic Independent Living Challenge — your remarkable competition gave me learnings and an opportunity for life.
- Vinnova, and especially Johanna Ulfvarson — the step from side project to profession was through you, and I will never forget it.
- Melexis, and especially Kristof Lieben, for all your help with the time-of-flight sensors — I really appreciate and value it.

Lastly, Vinnova — the Swedish Agency for Innovation Systems, as well as the foundations of Sten K Johnsons stiftelse, the Promobilia Foundation, and Familjen Knut och Ragnvi Jacobssons stiftelse, have my deepest gratitude and appreciation. The funding you have granted has been, and is, essential for the development of the project and for a possible future aid. Special thanks to Vinnova, the Promobilia Foundation, and Familjen Knut och Ragnvi Jacobssons stiftelse for financing my positions at Lund University; and very special thanks to the Promobilia Foundation for financing my PhD studies, and this thesis.

Contents

Chapter 1

Introduction

The ability to travel is vital to our sense of freedom and independence. Be it to a park, a grocery store, or a dear friend, being able to take yourself there — on your own terms and volition — has immense positive impact on our well-being, even if we mostly take it for granted. For most of us, regardless of how we travel to a destination, vision is critical. Crowds of travelers go without hearing by choice everyday, listening to podcasts or music through isolating headphones. They might have a somewhat higher risk of traffic collisions, but so be it. Some leave home without a sense of smell (though likely not by choice), and while it would certainly be a great loss not getting to scent freshly-made bread from a passed-by bakery, their chances in reaching their destinations safely are unaffected. If you were to lose your vision, however, the story would be different.

Worldwide, an estimated 34.8 million people have a severe vision impairment, and 43.3 million are blind [1].[1] In the UK 2013, there were an estimated 255 000 people, or 0.40 % of the UK population, with blindness or severe vision impairment [3]. This prevalence is expected to rise due to an aging population [1, 3].

Severe vision loss has profound impact on blind or low-vision individuals (BLVIs), which in turn has vast consequences for society, as well as for their family and friends. In a US study from 2016, Brown *et al.* found that patients with severe visual impairment had a yearly mean transportation

[1] ICD-11 (International Classification of Diseases 11th Revision) defines severe vision impairment as best corrected visual acuity < 6/60 and > 3/60, and various degrees of blindness as ranging from < 3/60 to no light perception [2].

cost of $10 000 and those with blindness $12 000 [4],[2] as well as a mean caregiver cost of $28 000 and $55 000, respectively. Caregiver activities included household chores, e.g. meal preparation, cleaning, and shopping for food. Another study from the US, by Schmier *et al.* in 2006, estimated caregiver costs to $62 000 per year for patients with severe visual impairment or blindness [7].

In both studies, the costs were computed regardless if it was paid or unpaid caregivers that performed it, alluding to the substantial burden on many relatives of BLVIs. Indeed, the study of Brown *et al.* further reported that for patients with severe vision loss or blindness, 79 % and 61 % respectively of the caregiving activities were performed by unpaid family and friends (for a value of $22 000 and $33 000 per year) [4]; and Schmier *et al.* had 62 % of blind or low-vision respondents reporting that they used caregiving services at an average of 94.1 hours a week, and of those, a third used no paid assistance at all [7].

Other interventions cause additional costs. For instance, the annual state grant for the Swedish guide dog operation, including procurement and placement, was $2 763 000 for 2023 [8]. With 260 guide dogs in Sweden currently [9], the mean annual cost of a single guide dog is $11 000.

Vision impairment also inflicts non-vision-related costs. In Canada 2007, the mean direct non-vision-related medical cost, i.e. related to for example falls, other accidents, or depression, for study participants with severe vision impairment or blindness, was on average $1600 more than for to those with better vision [10]. Other results from the mentioned work of Brown *et al.* was that blind patients had a mean 12-month direct medical cost of $3700 [4] due to ophthalmic-related depression and trauma.

Crucially, this segues into the serious comorbidities and sequelae of severe vision impairment and blindness. Study subjects from Canada, France, Germany, Spain, and the UK with neovascular AMD[3] — regardless of degree of vision-loss — on average reported 13 % worse overall well-being, 30 % more anxiety, and 42 % more depression symptoms than the control group. Further, they had twice the fall rate and a four times higher need of

[2]All monetary values are converted to 2021 USD purchasing power parities, rounded to the nearest thousand if > 10 000, and otherwise to the nearest hundred, using [5, 6]. For values from 2021–2023 with no conversion data available, the most recent data is used.

[3]Age-related Macular Degeneration: a medical condition resulting in vision loss. It is the predominant cause of irreversible blindness in high-income Asia Pacific, Europe, high-income North America, and Australasia [11, 12].

assistance with daily activities [13]. Overall, increased rates of depression and anxiety is well-established [10, 13–20][4], as is increased frequency of falls [10, 13, 17, 21–23]. In a larger scope, severe vision impairment and blindness has a pronounced negative impact on quality of life [13–17], and mortality [24–27], with a 2013 study finding that blind people aged 18–65 in Australia had an age-standardized mortality seven times higher than that of the control group [26].

The personal economic impact should not be overlooked either. BLVIs tend to have substantially less financial means than normally sighted individuals [20, 28], and another finding of the Brown *et al.* study was that the mean annual wage loss was $73 000 for patients reporting that they would be working without their vision loss [4].

That decreased mobility plays a major part on the reduced independence and quality of life of BLVIs is beyond doubt [14–16, 20, 21, 29–32], as is that the primary mobility aids of today,[5] white canes and guide dogs, are lacking [31,33–36]. Yet, this is not due to that the problem has gone ignored. Already 70 years ago, a review of proposed electronic travel aids (ETAs) for BLVI mobility was published [37], and countless other suggestions have emerged since, see e.g. [38–43] for recent systematic reviews.

The abundance of design proposals with their corresponding lessons learned, along with the ceaseless leaps in technology and in the design sciences, surely should result in an ETA which surpasses or complements the capabilities of the cane or dog meaningfully. However, whereas a select few proposals can boost actually reaching a purchasable end-product (see for instance [44, 45]), as yet none can claim widespread adoption, nor a significant increase in user mobility. The reasons for this are several, and predominantly stem from prevalent inadequate research practices in field of ETA development.

1.1 Aim and scope

As an increased mobility of BLVIs should alleviate the substantial issues outlined above, the aim of this thesis is threefold:

[4] [14–16] use the same dataset. [10] use a subset of the dataset used in [13].

[5] A primary mobility aid is by itself sufficient for independent mobility of BLVIs, whereas a secondary mobility aid is not. The latter are commonly GPS solutions, smartphone applications, or devices meant to provide additional information alongside the cane.

Thesis aims

1) Identify the reasons why a widely adopted ETA that allows for a significantly increased mobility has remained illusory.
2) Design and evaluate methods to mitigate those reasons.
3) Design and evaluate a proposed ETA using those methods.

Thus, this thesis should help maximize the chances that such an illusory ETA can come into fruition, whether it is the one herein, or any other leveraging the proposed methods.

1.2 Thesis outline

This thesis is structured as follows. In Chapter 2, the current shortcomings of the ETA field is explored, both when it comes to ETA design, as well as evaluation. An initial response to these is given in Chapter 3, with the design model Desire of Use, and its application to BLVI mobility. Further responses are provided in Chapters 4 and 5, where this model is applied to produce both a questionnaire and a portable virtual reality system to facilitate adequate ETA evaluation. Then, an initial probe into the design of future long-term studies is carried out in Chapter 6. After this, the proposed ETA, Audomni, and the development of it, is described in Chapter 7. Following this, a summary of all included papers is given in Chapter 8, whereafter final statements of the thesis are given in Chapter 9. Finally, the papers themselves are appended at the end of this thesis, as is the questionnaire of Chapter 4.

1.3 Ethical considerations

Because movement through urban environments is inherently dangerous — and as discussed earlier, especially so for BLVIs — the ethical quandaries regarding ETA evaluation are critical. As yet, all ETA evaluation in the current project has taken place either in controlled environments indoors with no ground-level changes or solid head-height obstacles, see Chapter 7; or in virtual reality, taking place indoors with participants only turning in place, see Chapters 5 and 7; much due to the involved risks with mobility in real urban environments. In future work, the aim is naturally to evaluate in real-life settings, but before such studies, the safety of the proposed ETA must be adequately evaluated beforehand, and any possible precautions should be examined and taken.

External review boards approved the studies of Paper II,[6] as well as of Paper IV and Chapter 6,[7] including user recruitment and consent procedure. All participants in the studies gave their informed consent. Papers I and III do not include studies with participants and so are not ethically reviewed.

[6] Regionala etikprövningsnämnden i Lund, case number 2017/7

[7] The studies of Paper IV and Chapter 6 were included in the same review by Etikprövningsmyndigheten, case number 2021-04835.

Chapter 2
Current shortcomings of the field

With the massive improvements and changes in the technological landscape over the last century, one would be excused for imagining that a new aid replacing, or at least complementing, the role of canes and dogs is long overdue. It could be argued that the present lack of such, is due to scarcity in societal pushes and resources; and frequently suggested other causes are poorly developed training schemes, device costs, and that aids seldom leave the prototype stage [46–48]. While all this certainly does not help, a decisive role is undeniably played by the substandard practices in the field of ETA development itself.

2.1 Design grounds of electronic travel aids

There are hundreds of proposed ETAs readily available in the corpus, see e.g. the reviews of [35, 38–43, 47, 49–65]. Further, there is an ever-expanding body of work outlining e.g. various design learnings based on these, needs of BLVIs, mobility theories, cognitive considerations, and best practices, see e.g. [31, 35, 36, 38, 46–49, 64–79]. However, the number of works seemingly leveraging this, is lagging behind considerably. There are a few rare examples, such as the TactiBelt ETA of Riviere *et al.*, which was designed with mobility and cognition frameworks in consideration [80]; and the ETA of Di Mattia *et al.*, which utilized established informational needs of ambulatory BLVIs [81]. Besides such instances, most ETA proposals gives little or no basis for their design and evaluation choices.

In order to efficiently and effectively reach an adequate aid, it is vital to — at all times — be sure of what the most apt design issues are to prioritize, aspects are to evaluate, and features are to add, modify, or discard. For this, proper design grounds, which stem from BLVI needs and take advantage of previous learnings, are all but necessary.

Thus, for an ETA developer, an immediate approach to gain a substantial step-up on most other proposals, is to establish such grounds, and persist in letting them guide the ongoing design process.

2.2 Evaluation of electronic travel aids

As stated, regular evaluation is important to ascertain that the current design work is progressing as expected. Yet, despite the sizable corpus, how to do this is in a useful, comparable, and reproducible manner is far from settled.

To start with, there are no established test methods and outcome measures in the field [40–42, 46, 82–84], and in addition, those that do enjoy some use have serious drawbacks. Regarding methods, the indisputably most common is indoor obstacle courses. The first issue with those, is that seemingly in the vast majority of works using them, a unique course has been produced [46, 82, 84], see for instance [29, 59, 85–97]. Thus, the arguably most beneficial aspects of obstacle courses, reproducibility and comparison between aids, goes unutilized. There have been at least two attempts to produce standardized courses [98, 99]; however, they have not seen adoption, and also suffer from either being overly specific or inadequately documented, both to the effect that they become difficult to reproduce.

Further, while obstacle courses benefit from that they provide excellent control of external conditions, they surely struggle in representing large-scale, outdoor, urban environments, in which most of the BLVI mobility issues are experienced. Indeed, that more tests should employ such settings are argued from a variety of perspectives in [46, 82, 100–102]. If well-specified and quantitatively measurable aspects of an ETA are to be assessed, unnatural test settings could potentially be used if they afford such measures; however, if BLVIs' experiences of an ETA, or too general or context-specific aspects are to be collected, an indoor maze is likely inadequate.

Regrettably, while it is essential to gauge user acceptance of an aid by actually inquiring BLVIs, not only will such views be ill-informed if tested in poorly relevant settings — it is done much too seldom overall. Regarding the perspective of BLVIs, recent reviews in the field have: noted infrequency of assessing it, and limited scope of such assessment [38, 83]; argued for more qualitative safety evaluations [41]; apparently failed to find studies of

ETA user acceptance [40]; or seemingly been unsuccessful at finding any established measures of usability and functionality [42].

Concerning quantitative outcome measures, the most popular are likely time taken to complete a course, walking speed, percentage of preferred walking speed, and counting unintentional contacts or collisions [82]. There has also been quite some work in assessing cognitive map formation of BLVIs in real-life, obstacle courses, mazes, and in virtual environments (though not necessarily as an outcome measure), see e.g. [103, 104], however a detailed discussion regarding cognitive maps in particular is out of scope of this work. Regardless, these are all arguably measures of highly abstract aspects, i.e. aspects dependent on many of the lower-level aspects which mobility of BLVIs comprises of (discussed further in Chapter 3). Whereas these might be fair measures, it should be advisable to complement them with corresponding lower-level measures. This since good results of these used measures require that a tested aid is good at a variety of aspects, meaning that such measures will give a prohibitively coarse idea of what aspects of an aid are working well, and which might need improvement. In addition, all these measures are quite context dependent, diminishing reproducibility and comparison affordance. The possible exception is percentage of preferred walking speed; though a consistent method of establishing it is missing, and especially one taking varying complexity of different courses into account.

As hinted above, the various reproducibility issues outlined also effectively prevents inter-study comparison of aids, as corroborated by [82]. This issue is exacerbated by the infrequency of intra-study comparison of aids, especially between a proposed aid and the current aid(s) of participants. Such evaluation is critical to inform of the chances of any proposal being adopted by users as an available aid.

The aforementioned lack of qualitative assessment by BLVIs, is partly due to likely the most considerable issue in the field, the lack of blind and low-vision participants [38, 39, 41, 58, 60, 83, 84]. In perhaps most works, BLVIs are completely absent among participants, and when included, it is predominantly in inadequate numbers. One reason for this is the relative difficulty in recruiting blind and low-vision participants, as if tests are localized to a specific place, there is only a limited number of potential candidates able and willing to travel there, as also argued by [58].

One last point regarding evaluation is that the most motivated and reliable methodology for mobility outcomes of an aid should be long-term

TABLE 2.1
Field shortcomings

1) Widespread disregard of known user needs, previous learnings and the design sciences.
2) No agreed-upon methods and measures.
3) Methods tend to have low real-world relevancy.
4) The opinions of BLVI's themselves are too seldom heard.
5) Popular measures yield little insight.
6) Proposals are too infrequently compared with, or assessed in regards to, current aids.
7) Studies predominantly recruit too few blind and low-vision participants.
8) Proposals being tested over long time periods are much too rare.

tests, and these are close to non-existent in the field. Such tests are discussed specifically in Chapter 6.

2.3 Summary

The eight shortcomings of the field which have been discussed in this chapter are summarized in Table 2.1. All of these markedly reduce the chances of a successful ETA, and thus should be strived for to be mitigated. This is attempted in the remainder of this thesis.

Chapter 3

The Desire of Use design model, and applying it for mobility of blind and low-vision individuals

To maximize the prospect of a viable new mobility aid, the prevalent issues of the field outlined in Chapter 2 must be alleviated, and a need-focused and user-centric design ensured. Therefore, it should prove beneficial to adopt a design strategy that enables this. At this time, however, there seems to be no other design model that has been developed specifically for mobility of BLVIs. Therefore, this chapter will present the generalizable Desire of Use (DoU) design model, and its application on the present objective. This chapter is based on work originally and more thoroughly presented in Paper I [105].

3.1 Previous models and frameworks

Many design models and frameworks have been put forward from different fields, e.g. a model regarding system acceptability by Nielsen [106], later expanded by Eftring [107]; the work on user experience frameworks of Hassenzahl, Law, van Schaik *et al.* [108–113]; or the technology acceptance model UTAUT [114–116]. The two latter can readily facilitate some device assessment through corresponding questionnaires, see e.g. [117–120], though as they are generic, such evaluation will only produce results regarding high-level aspects such as *attractiveness* and *efficiency* — and little knowledge of low-level issues and features. In other words, if an aid is deemed inefficient, these tools will not provide detailed answers as to why. Further, this also means that a design strategy built upon them, while likely becoming user-centric, would gain little explicit understanding about the specific activity and user group at hand. Thus, a design model that could accommodate such understanding, and offer evaluation of both high- and low-level aspects, should prove quite advantageous.

3.2 Desire of Use

3.2.1 Definition

The DoU model can be considered a top-down approach to understand: 1) how a given entity facilitates a given activity as performed by a given individual; and 2) the individual's capabilities of, and attitudes about, making use of the entity. The first point is denoted *functionality*, and the second *ergonomical complexity*. To reach fine-grained understanding, the model uses these quite high-level terms as a starting point to branch out from, aims to eventually encompass all important functionality and ergonomic aspects of the activity as well as the entity, and ends with the lowest-level details which comprise of the entity-specific attributes that can affect those aspects.

DoU itself represents the individual's desire to use the entity for the activity, and of available entities, the one with the highest DoU will be chosen for use. Note here that an "entity" can be e.g. a device, a dog, or a person, as well as a complex of entities; that "available" is a key point, as DoU is non-existent if the individual cannot use an entity; and that DoU can change over time, e.g. with changing capabilities of the individual, familiarity, or with external conditions.

In mathematical terms, DoU (δ) is a bivariate function of functionality (ϕ) and ergonomical complexity (ϵ) as such

$$\delta = F(\phi, \epsilon). \tag{3.1}$$

To integrate low-level and activity-dependent aspects, these are structured in two sets of (not mutually exclusive) parameters, one for parameters of functionality ($\mathbf{\Phi} = \{\phi_1, \phi_2, ...\}$), and one for ergonomical complexity ($\mathbf{E} = \{\epsilon_1, \epsilon_2, ...\}$); Thus, ϕ and ϵ are themselves multivariate functions according to

$$\phi = G(\mathbf{\Phi}), \qquad \text{and} \qquad \epsilon = H(\mathbf{E}). \tag{3.2}$$

If adequately comprehensive, together $\mathbf{\Phi}$ and $\mathbf{E}$ should compose the entire relevant design space for an entity; and whereas how any given parameter of $\mathbf{\Phi}$ or $\mathbf{E}$ affects δ might vary between individuals, conditions, and experience, i.e. G and H are variable, the parameters themselves should have constant value.

Further, δ is defined to always increase with ϕ, and decrease with ϵ:

$$\frac{\partial \delta}{\partial \phi} > 0, \qquad \text{and} \qquad \frac{\partial \delta}{\partial \epsilon} < 0. \tag{3.3}$$

The same notion is also applied for ϕ and ϵ:

$$\frac{\partial \phi}{\partial \phi_p} > 0, \qquad \text{and} \qquad \frac{\partial \epsilon}{\partial \epsilon_p} > 0, \tag{3.4}$$

where ϕ_p and ϵ_p is any functionality or ergonomical complexity parameter.

Thresholds of DoU (δ_t), and ergonomical complexity (ϵ_t) can be introduced in the DoU model. δ_t is the δ an entity would have to surpass for the individual to want to use it. ϵ_t is the highest ϵ where an entity physically and mentally can still be used by the individual.

In order to produce an example DoU function, as illustrated in Fig. 3.1, the assumption is made that if an entity provides zero functionality for the individual, or if the entity has an ergonomic complexity preventing the individual from using it, it will result in a DoU of zero regardless of the other respective variable, i.e.

$$F(0, \epsilon) = 0, \qquad \text{and} \qquad F(\phi, \epsilon)\big|_{\epsilon > \epsilon_t} = 0. \tag{3.5}$$

As an entity with a higher DoU would rather be used, a designer's job is to devise a proposal that has higher functionality, lower ergonomical complexity, or both. An important point, apparent from Fig. 3.1, is that if a higher functionality is achieved, a higher ergonomical complexity might be tolerable, and vice versa — though the former is likely of more interest if the desired outcome is an increased capability of the individual to perform the given activity.

Entity classes can be introduced in the DoU framework, where entities with similar parameter values in both $\mathbf{\Phi}$ and $\mathbf{E}$ would belong to the same class. Intra-class design iterations would result in relatively small changes in either $\mathbf{\Phi}$ or $\mathbf{E}$, and eventually none could be improved without worsening the other; the class would have reached stagnation, and the introduction of a new class might be all but necessary to yield a substantially higher DoU for the individual.

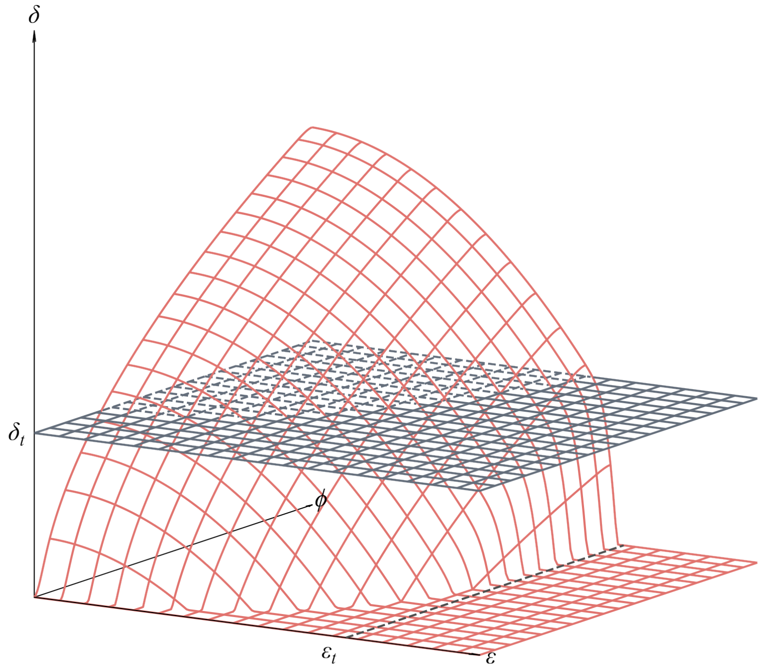

Fig. 3.1: Example of a Desire of Use (DoU) function, $\delta = F(\phi, \epsilon)$, with a threshold value δ_t. δ denotes the DoU, ϕ the functionality and ϵ the ergonomic complexity. ϵ_t denotes the ergonomic complexity threshold, above which a device is unusable for a given user for the given activity. Any device that is used will hold a $\delta > \delta_t$. Note that in many cases a point below δ_t can either be increased in functionality, or decreased in ergonomic complexity, in order to surpass the threshold. Figure and caption reprinted, with permission and slight modification, from [105], © 2020 IEEE.

To exemplify this, for mobility aids of BLVIs, long canes could be regarded as a class. Different lengths, materials, handles, and tips, if it is collapsible or not, all affect functionality and ergonomic complexity of a given cane to various degrees. However, any new long cane aiming to provide more functionality than existing long cane, will likely not be able to without also increasing the ergonomic complexity. Thus long canes are arguably a stagnated class. (Long canes with additional sensors, aka smart canes, might not be in the same class as long canes, or other smart canes, as the sensor capabilities and feedback method of different smart canes could easily have quite divergent $\mathbf{\Phi}$ and $\mathbf{E}$ parameter values).

TABLE 3.1
General Desire of Use proceeding

1) Identify the common design and technical considerations related to the given activity and user (group).
2) Adapt terminology and remove overlaps.
3) Determine item interrelatedness and investigate item hierarchy and connectivity.
4) Group items and remove redundancies.

Table reprinted, with permission, from [105], © 2020 IEEE.

3.2.2 Application

DoU can be applied to an activity for a user by following the steps in Table 3.1. Doing such should yield a wide range of aspects of functionality and ergonomics at various abstraction levels, from functionality and ergonomic complexity themselves, down to task-specific items. These aspects can then form the basis of tests, measures, and future design queries, as well as motivate which ones should be prioritized.

3.2.3 Summary

DoU is a function of the functionality and ergonomics of an entity to aid an individual with an activity. It allows for a systematic structuring of the various activity- and aid-related aspects of functionality and ergonomics, and promotes consideration of the interrelations between them. How it can be applied in practice is exemplified below. The result is then used throughout the remainder of this thesis to design and develop test measures, methods, and an ETA.

3.3 Desire of Use on mobility of blind and low-vision individuals

To make it useful in the current context, in this section DoU is applied on mobility of BLVIs (DoU-MoB) through the outlined procedure in Table 3.1:

1) In aim of a comprehensive picture of the common design and technical considerations of mobility of BLVIs, first suggestions of aspects are identified through various perspectives from relatively well-known sources and authors of the field, as shown in Table 3.2.
2) Due to different terminology of different fields, various intentions, and verbosity, the gathered aspects are adapted and merged for con-

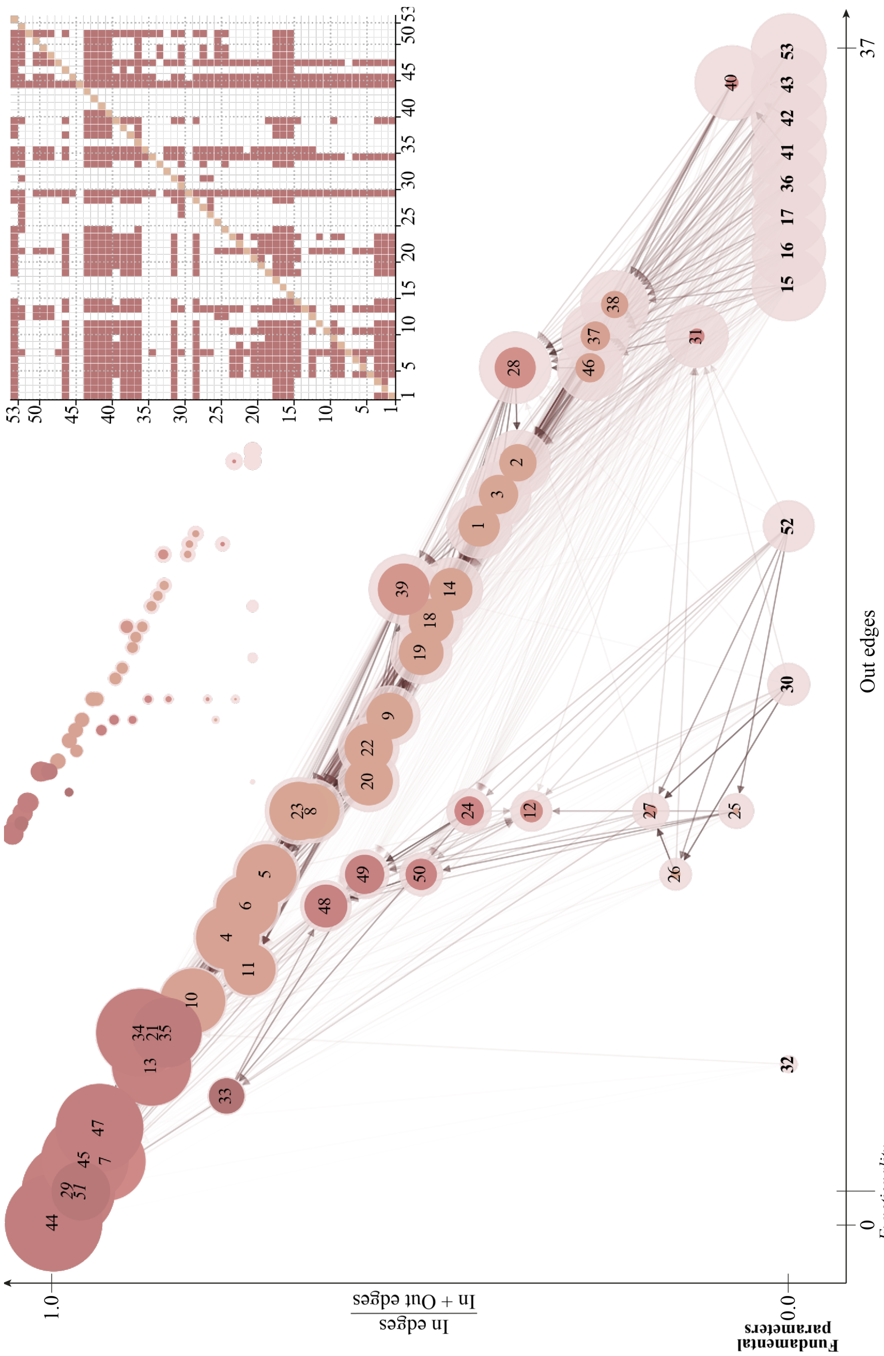

Figure caption on next page.

Fig. 3.2:
Hierarchical decomposition graph of aspects identified by Desire of Use applied on mobility of blind and low-vision individuals; the original shape of the graph: and the aspect-dependency adjacency matrix. The aspects are placed according to their ratio of dependencies over their total number of connections on the y-axis, and according to the number of aspects they affect on the x-axis. (For the sake of clarity, if a node was placed too closely to another it was shifted a small amount; the original shape of the graph can be seen in the smaller graph). Thus, high-level items like functionality and ergonomic complexity are placed in the top left, whereas the bottom-most are the set of functionality and ergonomic complexity parameters. Note for instance that the popular metric *Walking at preferred walking speed*, 7, is localized at significant height in the hierarchy. Further, node sizes increase with connection amount, their darker discs represent number of dependencies and their brighter discs represent number of affected aspects. The fundamental parameters are thus also readily identifiable through only having bright discs. Lastly, edges are drawn more prominently between nodes that are alike, where the likeness is derived based on a sum of absolute differences between the rows of the adjacency matrix. Dark pixels in the adjacency matrix denote that the row item affects the column item. Very high-level items feature columns with relatively many dark pixels, whereas proper parameters feature white columns. Figure and caption reprinted, with permission and modification, from [105], © 2020 IEEE.

TABLE 3.3
Aspects of Desire of Use applied on mobility of blind and low-vision individuals

1) Perceiving objects	9) Detecting traveling surface level changes	**16) Horizontal field-of-view**	21) Beelining	*29) Functionality*	38) Localization affordability	45) Efficiency
2) Detecting obstacles	10) Crossing straight and correcting veer	**17) Vertical field-of-view**	22) Apprehending absolute or relative direction of travel	**30) Weight**	39) Detecting objects at traveling surface level.	46) Perspicuity
3) Identifying landmarks	11) Detecting true paths	18) Apprehending nature of traveling surface	23) Constructing mental maps	31) Performance	40) Spatial resolution	47) Dependability
4) Orienting	12) Handling sighted help	19) Detecting objects to the sides	24) Sensory interference	**32) Durability**	**41) Horizontal resolution**	48) Hedonic quality
5) Orienting spatially	13) Handling public transport	20) Apprehending nature of objects to the sides	25) Physical appeal	33) Comfort	**42) Vertical resolution**	49) Stimulation
6) Orienting geographically	14) Apprehending nature of objects		26) Portability	34) Safeness	**43) Depth resolution**	50) Novelty
7) Walking at preferred walking speed	**15) Perception range**		27) Gainliness	35) Safety redundancy	44) Overall attractiveness	*51) Ergonomic complexity*
8) Detecting end of blocks			28) Skill requirement	**36) Temporal resolution**		**52) Physical design**
				37) Cognitive load requirement		**53) Functional method**

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TABLE 3.2
Aspect sources for Desire of Use on mobility of blind and low-vision individuals

Reference	**Topic**
Brambring [77] Harper and Green [75]	Locomotion process model of BLVIs.[1]
Leonard [79]	Mobility level criteria of BLVIs.
National Research Council [76]	Information needs and limitations of blind and low-vision pedestrians.
Hersh [70]	Principles of good design practice for mobility aids of BLVIs.
Chebat *et al.* [46]	Problems with contemporary sensory substitution / supplementation devices of BLVIs.
Bhowmick and Hazarika [56] Dakopoulos and Bourbakis [65] Kristjánsson *et al.* [47] Velázquez [35]	Review-based design learnings of electronic travel aids.
Dakopoulos and Bourbakis [65]	Important features of electronic travel aids.
Hassenzahl *et al.* [113] Laugwitz *et al.* [119]	User experience model.

[1] Blind or Low-vision Individuals

ciseness, unambiguousness, and consistency. The DoU terms of functionality and ergonomic complexity are added if missing.

3) All possible pairs of remaining aspects are investigated for eventual dependencies.
4) Aspects with similar dependencies are merged to remove redundancies.

Finally, the resulting aspects, shown in Table 3.3, are used to populate the DoU-MoB. By ordering them by number of dependencies — how many aspects that an aspect affect, and how many aspects that affect it, a hierarchical graph emerges, see Fig. 3.2. Aspects that are not affected by any other will be placed at the very bottom of it, these can be considered the proper DoU-MoB parameters of $\mathbf{\Phi}$ and $\mathbf{E}$ — which should entirely determine the DoU of a mobility aid of BLVIs. These are marked in bold in Table 3.3. However, the intermittent aspects are not wasted, as they still represent key items of BLVI mobility. Thus, they are excellent design guides for an ETA, tests and measures.

3.3.1 Summary

For an ETA designer, the DoU-MoB illustrates both what features of their proposal that need to be considered in the proper parameters of functionality and ergonomic complexity, and in the intermittent aspects, what those parameters need to help the users achieve and under what restrictions. As such, the DoU-MoB can be considered an overarching design tool, where a designer should aim to be able to answer how their proposal fares on each aspect, and regularly user test to provide or valide those answers.

The hierarchical organization in Fig. 3.2, suggests that the DoU-MoB aspects are at different abstraction levels, and afford different insight. For instance, the aspect *walking at preferred walking speed* is located close to *functionality*. Hence, that the measure of percentage of preferred walking speed is relatively popular for ETA assessment holds merit, though it will yield results of quite high abstraction level. Thus while a good result should be promising, neither a good or bad result will provide understanding of which features of an aid should be prioritized in further development, which might be removed, or which are currently adequate. To provide basis for such choices, lower aspects in the hierarchy should instead be evaluated.

To summarize, by employing the DoU-MoB in an ETA design process, it should benefit from leveraging the models, design learnings, and guidelines developed previously in the field and the design sciences — in both the design and evaluation stages — which in turn should result in a need-based, user-centered, and efficient development, as well as a greater likelihood of reaching a successful ETA.

3.3.2 Future work

The current DoU-MoB should be fairly comprehensive, though it could still be improved: there might still be some missing mobility or mobility aid aspects, it is likely that some sub-activities could be further sub-divided, and it could be advantageous to implement other existing frameworks to bridge various aspects. It is also probable that some dependencies would benefit to be revised, and by more contributors. However, the current state of the DoU-MoB is still deemed adequate to guide design and evaluation, so further work on the DoU-MoB is not prioritized at the moment.

Chapter 4

Desire of Use Questionnaire for Mobility of Blind and low-vision individuals

An approach to alleviate the issues from Chapter 2 of motivated and effective measures, taking the views of BLVIs into account, and comparing ETA proposals with current aids, is to employ a suitable patient-reported outcome measure (PROM). In this chapter the most relevant existing PROMs will be discussed briefly, whereafter a novel questionnaire, derived from the DoU-MoB from Chapter 3, is presented to allow for fine-grained measures with a focus on mobility of BLVIs. The proper, and more detailed, introduction of this questionnaire is in Paper III [121].

4.1 Existing patient-reported outcome measures for blind or low-vision individuals

While there are numerous available PROMs devised for BLVIs [122–124], with very few exceptions they are not developed specifically for orientation and mobility (O&M), a view corroborated by [82, 125]. Thus, any mobility measures these PROMs do provide are only of relatively high abstraction (see Chapter 3), leaving more minute measures to be wanted.

There seems to be two exceptions to this: the Independent Mobility Questionnaire (IMQ) [126], and the Orientation and Mobility Outcomes (OMO) PROM [127, 128]. Unfortunately, the former was developed for individuals with moderate vision loss, and while some work has been made to adapt it to include BLVIs [125, 129], it still might not be adequately comprehensive or fitting for such respondents, an opinion shared with [129].

This is also bolstered by that the original items of the questionnaire were derived is poorly documented; and that it is missing many of the intermittent mobility subtasks of DoU-MoB, which should be of interest. The OMO on the other hand was developed for BLVI respondents [127, 128], but it features only items of quite high abstraction levels.

As is implied in Chapter 2, no PROM has seen substantial or consistent use in ETA assessment, and given the aforementioned shortcomings with those discussed here, there is reason to develop a new PROM focusing on mobility of BLVIs, and featuring fine-grained measures to maximize learning outcomes.

4.2 Questionnaire development

4.2.1 Adopting best practices of survey design

For a questionnaire to be useful it must produce as reliable results as possible. Thus it should adhere to the best know practices in survey design. The PROM design will originate from that it will be verbally administered; this since it is convenient to administer a PROM in conjunction with user tests, it allows for longer questionnaires [130, 131], it facilitates rapid corrections of earlier responses, and it promotes clarifying questions from the respondents. The various considerations, and what is adopted in the proposed PROM is outlined in Table 4.1.

4.2.2 Development and validation

As the ambition is a PROM that facilitates sufficiently detailed and comprehensive measures of mobility of BLVIs, and the DoU-MoB aims to provide such aspects, see Chapter 3, it is quite natural to form a questionnaire with it as foundation. Hence, all items of the proposed PROM are derived from the individual aspects of the DoU-MoB. As this results in quite a sizable questionnaire, the items should have response scales to speed up its administration. To facilitate comparison between aids, the questionnaire was strived to be as aid-agnostic, i.e. generic, as possible. As to further promote such comparison, a section was made of questions directly comparing two aids in regards to functionality overall, ergonomics overall, and which aid is preferable overall. This section is also meant to act as a semi-structured interview, with the administrator asking follow-up questions on the respon-

TABLE 4.1
Questionnaire design considerations and adoptions

Consideration	Implementation	References
Agree–disagree or item-specific questions	Item-specific	[132–134]
Uni- or bipolar response scales	Bipolar	[135]
Response anchor labelling: numeric or verbal, end- or fully labelled	Fully-labelled verbal anchors	[133, 136]
Response scale length	Five anchors	[133, 135–137]
Scale direction effects	Randomized items	[138, 139]
Response anchor choice (English)	*not at all*, *slightly*, *moderately*, *very*, *extremely*	[133, 136]
Response anchor choice (Swedish)	*inte alls*, *lite*, *måttligt*, *mycket*, and *extremt*	[133, 140, 141]

dents' scale answers — allowing for collecting the most pressing opinions from the respondents, which might be missed with a strictly fixed-choice questionnaire.

The questionnaire was made to follow best practices in survey design as abridged in Table 4.1, though with the exception of the response scale. This scale was instead derived from the end-labelled, bipolar, seven-point numerical [*1..7*] scale, of the User Experience Questionnaire [119, 120], as the plan was to administer it as well, and consistency in scale types was deemed the preferable option. The result was the first version of the Desire of Use Questionnaire for Mobility of Blind or Low-vision Individuals (DoUQ-MoB).

This first version of the DoUQ-MoB was validated for face and content validity with eight O&M experts, as well as pilot-tested and validated for test–retest stability and general questionnaire issues with six BLVIs. The most obvious issues were with the test–retest stability. In many cases this caused by poor respondent or environmental stability, with some respondents claiming that a substantially different answer between sessions were due to that, since the last session, they had contemplated the questionnaire items during walks, and for some, snowy paths had become a new factor to take into account.

Though it was also clear that ambiguous instructions and questions, and the response scale, were at least partially responsible as well. Many respondents struggled with answering a large number of questions, since the answers depended on various circumstances, e.g. known–unknown area, lighting, or weather. Further, there were issues with the response scale; in a strictly verbal setting it became clear that many had trouble identifying the mid-point of the bipolar and only end-labelled scale, and thus ran the risk of erroneously answering in favor of one side when the aim was to be neutral, or vice versa. In addition, there was an excessive amount of floor or ceiling effects for many items.

The questionnaire was thus revised to a second version. First, items which were highly correlated were merged; apparently confusing or not important items, as deemed by the O&M experts, were omitted; and one item was added as suggested by one O&M expert. To make it considerably less ambiguous, the instructions were clarified so that respondents should aim to answer as for dry road conditions, and their most problematic lighting conditions. Further, a great number of items were split into two, one for known, and one for unknown areas. To better mitigate potential scale direction effects, while limiting additional cognitive load, a semi-randomization of items were implemented. Here, items regarding the same DoU-MoB aspects where kept grouped, and known–unknown versions of the same question kept paired with the known version always first. To clarify the mid-point and reduce the floor and ceiling effects, one more attempt was made on using bipolar and end-labelled numerical response scales, with a midpoint at *0*, eleven points in total [*-5..5*], and end-point modifiers exchanged from *very* to *extremely*. The scale was kept numerical as to accommodate parametrical statistical analysis, since at the time it was not realized that treating response scale data as interval — and not ordinal — is and was quite contentious.

The resulting DoUQ-MoB was employed for the first two participants in a user test, see Chapter 7. However, it became evident that the response scale still was troublesome, with confusion regarding negative numbers, as well as questions for the administrator to suggest a number that might represent verbal answers. At this time it was also clear that the time allotment needed for the DoUQ-MoB, prohibited also administering the User Experience Questionnaire (which regardless seemingly has a non-ideal response scale for a verbal setting); in addition, the debate regarding interval or ordinal data had become aware of. Thus, the scale was finally replaced with one fully adhering to the best practices as shown in Table 4.1. Eventually, after more respondents, it also became clear that some questions regarding the aesthetics of aids were ill-conceived, and did not produce any viable results. These questions were removed, leaving the current form of the DoUQ-MoB.

Example questions of the current DoUQ-MoB are shown in Fig. 4.1, and the entirety of the DoUQ-MoB is available in Appendix I. Both are tentatively translated to English.

4.3 Questionnaire analysis

DoUQ-MoB has currently not been developed for aggregate scores, therefore the items should be analyzed individually. This makes the interval–ordinal data controversy more pressing, as the former is sometimes argued for with the central limit theorem, and by not accumulating responses over many items this becomes more difficult. This notion is aggravated further by that there is likely a limited number of respondents in a study, given the field. Therefore it is recommended to treat the data as ordinal. To draw inferences from the collected data, one could for instance investigate top or bottom bin ratios, as well as the response medians; and for comparisons use the Wilcoxon signed-rank test, which is non-parametric. It can also be elucidatory to visualize the response histograms. For examples of these analyses, see Figs. 7.14 and 7.15 of Chapter 7, where they are employed to evaluate the Audomni ETA. The analysis and visualization is currently done in the numeric computing platform Matlab [142].

4.4 Summary

The DoUQ-MoB is a generic PROM to assess mobility aids of BLVIs. By deriving questions from, aside from a few aesthetic considerations, the entirety of the DoU-MoB, it covers maybe all important mobility and mobility aid aspects through 106 aid-agnostic items. Further, it allows for and promotes the comparison of aids, in particular a proposed device with a respondent's current aid; however, this should be done in the same session, as the test-retest reliability needs to be re-evaluated with the current version of the questionnaire. Finally, the DoUQ-MoB draws from the best known design practices of fixed-choice survey design, while also offering a

Nr.	DoU[1]	Question prompt	Response scale	C[2]	T[3]
1	2	Detecting obstacles at ground level is...	not at all difficult, slightly difficult, moderately difficult, very difficult, extremely difficult		
			...		
36	15	I would like the distance from where I can detect objects and situations at to be...	shorter, longer		
37	15	—	not at all x, slightly x, moderately x, very x, extremely much x		
			...		

[1] Desire of Use aspect. [2] Current aid response. [3] Tested aid response.

Fig. 4.1: Excerpt from and typical formatting of the Desire of Use Questionnaire for Mobility of Blind and Low-Vision Individuals. Note that the questions are tentative translations of the Swedish questions. Also note the filter question *36*, in which the respondent first choose response polarity, and then in question *37* choose the corresponding strength.

section for a semi-structured interview. A tentative English translation of the questionnaire is available in Appendix I.

4.5 Future work

While the DoUQ-MoB, and the single-session administration of it, arguably supports a decent amount of insight as-is, see Chapter 7, there are a number of potential improvements that could make it more potent and versatile. First, a new validation round regarding test-retest reliability should be conducted so it can support testing over time. Such an application could be of interest both for multi-session and long-term testing. To mitigate more sources of instability of respondents and environment, the sessions of such validation should be chosen as to minimize risk of dramatic road condition changes between them, and more respondents should be recruited. Regarding validation, it would likely be advantageous to also employ survey design experts to opine on the questionnaire, to further assert abidance to good practice. Next, how the removed aspects about aid aesthetics can be reintroduced should be investigated: if careful design of the questions and responses could suffice, if they should be complemented through semi-structured interviews, or if such assessments has to be solved disjointed from the DoUQ-MoB entirely. Lastly, supporting one or several aggregate scores could be beneficial to provide easy intra- and inter-user comparison. This can typically be solved through a Rasch analysis, which could structure for instance the questions of mobility subtasks in order of difficulty. This could in turn be used to place respondent–aid combinations on a single scale, which would relate to their ability of performing all mobility subtasks.

Chapter 5

Portable virtual reality system, Parrot-VR

By employing a portable virtual reality (VR) system, it should be possible to alleviate the issues discussed in Chapter 2 of relevant methods, probing the opinions of BLVIs, and recruiting adequate numbers of blind and low-vision participants. Portability should allow for testing in the vicinity of participants, or even in their homes. This would substantially increase the number of possible candidates from the target group, as the group of BLVIs having the opportunity and the desire to travel to a specific location to test an ETA is always limited in size. Meanwhile, VR facilitates relevant, large-scale and urban scenarios wherever the test takes place. In addition, VR provides outstanding reproducibility with full control of usually external conditions, e.g. weather and traffic, as well as excellent movement data collection and safety.

Such a VR system could also be quite beneficial in the design stages of an ETA, allowing for quick and safe testing in specific and reproducible scenarios.

VR is likely especially useful in evaluating handheld or wearable ETAs with no direct physical contact with the environment, since such contact would be markedly more difficult to reproduce virtually, and particularly so in a portable setting.

While VR certainly has been utilized previously to assess ETAs, and investigate mobility aspects of BLVIs, there has seemingly been no other instance of a portable VR system being employed in the vicinity of the participants. Thus, in this chapter a novel VR system featuring such portability is presented. This chapter is based on work of Paper III [121].

5.1 Existing virtual reality systems targeting blind and low-vision users

VR has seen abundant use for many applications regarding BLVIs, see for example the review of Kreimeier and Götzelmann, which also outlines other reviews [143]. In it, they also classify VR systems according to the *scale* of the explorable space (small, medium, large), as well as identify shared parameters among them, e.g. the *exploration interface* (control method), *positioning* (absolute or relative), and *perspective* (ego- or exocentric).

An egocentric perspective means that the user is the frame of reference, consider for instance a camera; while an exocentric (aka allocentric) perspective has an external frame of reference, e.g. an overhead map of an area. (Note, however, that e.g. overhead maps with live GPS tracking of the user most often use an egocentric perspective.)

Meanwhile, positioning can be split into two parts: rotation and translation (movement). Absolute rotation or translation in this context means that there is an unambiguous mapping of the input method to the user-controlled character, the VR avatar. I.e. the same direction input would always yield the same heading, and the same translational input the same location. A touch screen is a non-VR example of absolute translation, and a compass of absolute rotation. On the other hand, keyboard arrows are example of relative translation, as a cursor or avatar will end up at different locations depending on its original position; and a steering wheel performs relative rotation, as the resulting heading also depends on original rotation and speed.

For the current application of a primary mobility aid, which is held by or worn on the user, and is used to navigate routes possibly hundreds of meters long, it is clear that for most ETAs an egocentric and large-scale VR system is of interest; though the choice of absolute or relative positioning is more uncertain. Such VR systems that have also been used for evaluating ETAs are listed in Table 5.1. Of these, the most frequent positioning scheme is a hybrid of absolute rotation and relative translation. It is reasonable to assume that absolute positioning is the most intuitive for users, at least when the input are the users' natural movements, so the choice of a hybrid method is most probably a compromise. First, absolute rotation is both relatively easy to track and requires little space. Meanwhile, absolute translation is very much the opposite, with the only solution likely

TABLE 5.1

Electronic travel aid assessments using large-scale, egocentric virtual reality systems

Year	Reference	Rotation	Translation	Participants
2022	Ricci *et al.* [144]	Absolute, head-tracking	Relative, joystick	1 sighted[1]
Computer vision obstacle detection with multidimensional abdominal haptic feedback.				
2021	Real and Araujo [145]	Absolute, head-tracking	Absolute, open space AR[2]	23 sighted
2020	Real and Araujo [146]	—	—	16 sighted
The vOICe: head-mounted visuo-auditory SSD[3] through greyscale images, see [147]; PVAS/VAS: head-mounted visuo-auditory SSD through distance; hand-held visuo-tactile SSD through distance.				
2020	Lupu *et al.* [148]	Absolute, head-tracking	Relative, keyboard/joystick	15 BLVIs
2017	Dascalu *et al.* [149]	—	—	7 sighted 8 BLVIs
2017	Moldoveanu *et al.* [150]	—	—	4 BLVIs
Sound of Vision: head-mounted visuo-auditory/tactile SSD through distance and with multidimensional abdominal haptic feedback.				
2019	Maidenbaum and Amedi [151]	Relative, keyboard	Relative, keyboard	40 sighted 8 BLVIs
EyeMusic: head-mounted visuo-auditory SSD through RGB images.				
2018	Massiceti *et al.* [152]	Absolute, head-tracking	Absolute, open space AR	18 sighted
Head-mounted visuo-auditory SSD through distance.				

Publications in the same segment of the ten listed use the same VR system. They evaluate the electronic travel aids summarized in text; the summary is based on the most recent work in the cell.

[1] Most likely. [2] Augmented reality. [3] Sensory supplementation / substitution device.

Table continued on next page.

being using augmented reality methods and a very large open space to allow for large-scale exploration, see e.g. [146, 152, 162]. If the aim is to test near participants, finding suitable places that are large enough, close enough, provide good augmented reality tracking, and are not subject to weather conditions, quickly becomes a portability issue. Next, as luck would have it, absolute rotation is arguably the more important of the two, as a proper global sense of direction is critical when traversing toward a destination. A global sense of place is important in real-life, but in an evaluation setting with a greater focus on local (near-field) navigation, a lacking one should be acceptable. However, it is advantageous if at least a local sense of place, in relation to detected nearby obstacles for instance, could be achieved.

TABLE 5.1
Contd.

Year	Reference	Rotation	Translation	Participants
2016	Levy-Tzedek *et al.* [153]	Relative, keyboard	Relative, keyboard	29 sighted
2017	Chebat *et al.* [154]	—	—	36 sighted 20 BLVIs
2015	Chebat *et al.* [93]	—	—	—
2014	Maidenbaum *et al.* [155]	—	—	7 sighted
2013	Maidenbaum *et al.* [156]	—	—	20 sighted 3 BLVIs
EyeCane: hand-held distance perception with auditory feedback.				
2016	Maidenbaum *et al.* [157]	Relative, keyboard	Relative, keyboard	29 sighted 9 BLVIs
2015	Maidenbaum *et al.* [158]	—	—	10 sighted 5 BLVIs
EyeMusic: head-mounted visuo-auditory SSD through RGB images.				
2014	Sanz *et al.* [159]	Absolute, head-tracking	Relative, verbal command	13 sighted 15 BLVIs
Head-mounted visuo-auditory SSD through distance.				
2013	Lun Khoo *et al.* [160]	Absolute, mouse	Relative, joystick[1]	18 sighted[1]
Arm-mounted distance perception with haptic feedback on arms.				
2012	Bujacz *et al.* [161]	Absolute, head-tracking	Relative, keyboard[1]	10 sighted
Naviton: Head-mounted visuo-auditory SSD through distance.				

Publications in the same segment of the ten listed use the same VR system. They evaluate the electronic travel aids summarized in text; the summary is based on the most recent work in the cell.

[1] Most likely. [2] Augmented reality. [3] Sensory supplementation / substitution device.

Table reprinted from [121].

Beside positioning, from Table 5.1 it is clear that the issue of BLVI inclusion is also prevalent in ETA works using VR. This highlights that, while some systems could feasibly be employed in a portable manner, portability has not been a reason behind opting for a VR methodology previously.

5.2 The Parrot-VR system

Due to the aforementioned reasons regarding positioning, the Parrot-VR system features a hybrid positioning scheme with absolute rotation and relative translation. In contrast to other systems of the field, it was also designed with portability in mind, effectively restricting how it can be implemented. These features also gives the name of the system: Portable, Absolute Rotation, Relative (O) Translation VR — Parrot-VR.

It is plausible that a commercial VR system could be adopted, most likely one consisting of a stand-alone headset for the portability consideration. However, as the priority was to evaluate the Audomni system, which was integrated in a physical prototype already, see Chapter 7, further factors became relevant. For one, it was unclear how time consuming or restrictive it would be to either port the Audomni software to such a device, or to extract the relevant information from the device to the Audomni prototype with a low enough latency. Further, an off-the-shelf solution could color the assessment of a proposed ETA, as in the worst case a participant might have difficulty in ignoring how the system fits, feels, and handles when assessing the ETA, and in any case a proposed physical design can not be tested during use at all. Moreover, the Audomni prototype already featured enough computational power and much of the control hardware needed for a VR system, both providing a more certain time frame and ensuring adequate portability.

A side note is that, by constructing the VR system from the Audomni prototype, it has the added benefit of aiding in rapid prototyping of algorithms, as well as can potentially provide fast and safe training for users in the future.

The absolute rotation is provided by a head-mounted inertial measurement unit. By virtue of its internal calibration (its orientation in relation to the real-world), and a bespoke external calibration (its measure of the orientational axes of the user's head), as well as its accurate and timely measurements, the current orientation of the user's head is mapped to that of the player-controlled VR avatar. A side-effect to this is that, since there is only one inertial measurement unit, the horizontal rotations of the VR avatar body and head are tied together. Therefore the user should make efforts to always have their head and body aligned, otherwise the actual walking direction might not be the expected one.

The relative translation is implemented through a commercial video game controller, because while an omnidirectional treadmill should provide the most intuitive solution, it would also be prohibitively large. The controller have additional benefits as it can be expected that the company developing it put much effort in making it both ergonomic and durable, and since it can provide vibrational feedback which can convey both move-

Fig. 5.1: Virtual reality system, Parrot-VR, hardware. *Clockwise from left*: bone-conductive headphones; embedded computer and audio interface; headband with inertial measurement unit; controller. Figure and caption reprinted from [163].

ment and collisions. A user simply pushes the directional button for up to walk forward in their current heading at a set speed, or down to walk backward. While walking, the controller vibrates softly for each footstep, while collisions produce strong vibrations.

During operation, the system produces data according to a virtual sensor mounted on the VR avatar, which is fed to the feedback system of a virtual ETA. (Currently the only integrated virtual ETA is Audomni, see Chapter 7.) Further, the avatar positioning and any collisions occurring, as well as the audio feedback, is recorded continuously for use in subsequent movement analysis.

In an evaluation setting, the system also provides real-time data of the VR avatar positioning, along with if any collisions occur; this can be read from an external computer to provide a live visual display of a test. Meanwhile, the audio feedback can be mirrored to the administrator through an external audio card. Together, this grants the administrator an ideal overview of exactly where the participant is, and what feedback they receive, at any given time.

The VR hardware is shown in Fig. 5.1 and a typical test setup in Fig. 5.2. The hardware and software used is listed in Tables 5.2 and 5.3.

Fig. 5.2: Virtual reality system, Parrot-VR, test setup: *1*) inertial measurement unit; *2*) bone-conductive headphones; *3*) controller; and *4*) embedded computer. Auxiliary equipment: *5*) audio interface; *6*) laptop; *7*) bone-conductive headphones; and *8*) audio recording device. Figure and caption reprinted from [163].

TABLE 5.2
Hardware of the Parrot-VR system

System proper	
Embedded computer	Jetson Nano Developer Kit. Nvidia.
Inertial measurement unit	BNO055 Absolute Orientation Sensor. Adafruit.
Controller	Dualshock 4 V2 Controller. Sony.
Headphones	Sportz Titanium. Aftershokz.
Audio interface	Pmod I2S. Digilent.
Auxiliary	
Laptop	MacBook Pro 13-inch 2017. Apple.
Headphones	Sportz Titanium. Aftershokz.
Audio USB interface	Volt 2. Universal Audio.
Audio recording device	iPhone 6s. Apple.

Table reprinted from [121].

5.2.1 Virtual environments

To display virtual environments, Parrot-VR uses 3D models with accompanying collision data which denotes where the VR avatar cannot walk. Both environments and collision data can be constructed in the 3D-creation software suite Blender [182]. The environments can be designed from real counterparts through satellite imagery and crowd sourced data from

TABLE 5.3
Software of the Parrot-VR system

Programming and software environment	
Operating system	Ubuntu [164][1]
Programming language	C++ [165]
Compiler	GCC [166]
External libraries	
Inertial measurement unit	BNO055 sensor driver [167]
Window and controller	GLFW [168][2]
Graphics and 3D	OpenGL [169]
Math	GLM [170]
3D model import	Assimp [171]
OpenGL instancing	Glad [172]
Image loading	Stb_image [173]
Electronic travel aid	Audomni [174][3]
Audomni compatability	OpenCV 4.4 [175]
Additional code	
OpenGL, additional	Code by J. de Vries [176–180][3]

[1] Slightly modified kernel to allow for controller haptic feedback.
[2] Slightly modified source-code to allow for controller haptic feedback as per [181].
[3] Modified.

Table reprinted from [121].

e.g. [183–185], along with physical visits. To aid in this process, the Blender add-on Blender-OSM [186] may be used to directly import data from OpenStreetMaps [185]. A number of custom scripts has been developed to expedite the corresponding collision data. Example virtual environments that were deployed in user tests can be seen in Fig. 7.10 of Chapter 7.

5.2.2 Virtual avatar

Since the positioning of the sensor on a user's body, the movement of the body, and the body itself can affect the field-of-view (FoV) of the sensor, see Fig. 5.3, the virtual avatar should be designed with care. As basing it on each individual participant could be sensitive to some, be time consuming, and would result in only one observation of a particular body type, a generic avatar is beneficial. Lastly, because it is of interest to produce an aid useful for as a many users as possible, the generic avatar should represent the body type which would be the most unfavorable regarding the sensor FoV, or the feedback method of a proposed ETA. Thus, a female user avatar, with the most disadvantageous 95th percentile of relevant anatomical features, was produced through the anthropometric data of [187] and some ad-hoc measurements. (A male avatar was also produced in the same manner, but

Fig. 5.3: Virtual reality avatar in default positioning, from the side and front. White spheres are head and body, and red their pivot points, blue cone is the sensor field-of-view (not visible on the right). The body can affect the sound feedback by occluding this, which happens for many possible head rotations. All sizes and relative positions that might affect this are based on a hypothetical female user with relevant features at the most disadvantageous 95th percentile of anthropometric data. Figure and caption reprinted from [163].

TABLE 5.4
Anthropometric data of the VR-avatar in cm

Stature	179	**Shoulder (bideltoid) breadth**	47
Eye height	167	**Thorax depth at the nipple**	30
Head length	20	**Chest frontal translation**[1]	6.5
Head vertical translation[1]	8.8	**Nipple height**[2]	130
Head frontal translation[1]	1.5		

[1] From its pivot point. Based on ad hoc measurements.
[2] Approximated as midpoint between shoulder and elbow height.

Table reprinted from [121].

it turned out that the effect on the sensor FoV was quite similar as for the female avatar, so only using the latter was opted for.) The resulting avatar is shown in Fig. 5.3, and the used measurements in Table 5.4.

5.3 Summary

Parrot-VR is a portable, ego-centric, large-scale VR system. It has a hybrid control scheme of absolute rotation and relative translation, utilizing a head-mounted inertial measurement unit, and two buttons on a video game controller. This should strike a reasonable balance between intuitiveness and realism on one hand, and portability and large-scale traversal on the other. It supports audio feedback through headphones, which currently the Audomni system has been integrated for, and vibrational feedback via the controller. The portability facilitates testing in proximity of the participants — dramatically increasing the number of potential blind and low-vision test candidates — while the large-scale exploration made possible by the control scheme, makes relevant urban environments possible as testing scenarios. In addition, Parrot-VR aids in ETA development as design iterations of the software can be rapidly tested in pertinent and specific scenarios.

5.4 Future work

The system can at present aid in both ETA evaluation and development, as demonstrated in Chapter 7, though it could be improved further. At this time, there is no way to include ambient sounds in the virtual environments, effectively removing a powerful existing tool for both a local and global sense of direction and place. Moreover, today only the VR avatar is unfixed in place, so issues due to moving traffic, pedestrians, or animals, or their possible reactions to the avatar, cannot be encountered. Lastly, the head of the avatar moves exclusively in the direction of travel, i.e. there is no up-and-down, or side-to-side movement when walking, which could affect the ETA feedback in real-life. In future tests with the Parrot-VR, these issues should be addressed to facilitate more realistic scenarios.

Chapter 6
Long-term studies

The only way to improve the scarcity of long-term studies in the field, as noted in Chapter 2, is to endeavor for such. Dakopoulos and Bourbakis made note of their importance in their ETA review, stating that the lack of successful systems could be due to that long-term tests with the target group has not been performed [65]. Indeed, the Audomni project, see Chapter 7, is aimed toward long-term O&M outcome assessment, as such are deemed necessary for claiming that an ETA might actually increase the mobility of blind and low-vision users. Reasons for this are that participants should have time to: 1) learn a new aid; 2) experience functionality close to that of an experienced user; 3) let the novelty of a new aid wear off; and 4) form new habits.

However, such studies are substantial undertakings, requiring both that the safety of the ETA has been ascertained to as a high degree as possible, and that the studies themselves have been adequately designed for reliability and robustness. While the former is challenging enough, this chapter addresses the studies. Since long-term tests are exceedingly rare — with seemingly almost all conducted in the 1980's or earlier [84] — no proved, and certainly no established methods can be relied on, and so this chapter takes an initial step to develop such. This chapter is predominantly work that was originally part of Papers III and IV, but was omitted due to the scope of those papers, and is not planned to be published elsewhere.[1]

[1] Thus, Tomas Jansson, and Johan Nilsson (see copyright page for affiliations) can be considered co-authors to this chapter. I have contributed with the literature review, the implementation of the ADL-I and COPM questionnaire, the graphical content, and the writing.

6.1 Previous long-term studies

Ironically, even back in the 1980's, both Simon in 1984 and Blasch *et al.* in 1989 note how few studies had performed follow-up evaluations to assess ETA usefulness [188, 189]. Unsurprisingly, Blasch *et al.* also found considerable variation in methodology of those that had been performed by then. Nevertheless, they themselves conducted a commendable survey, administering a self-developed and externally reviewed up-to-308-item questionnaire to 298 respondents who had received ETA training. Regrettably, beside mentioning some items, they gave no further disclosure of their seemingly substantial instrument, nor gave any suggestion that it is, or ever was, available.

A few recent examples worth mentioning do exist, if nothing else since these works by themselves represent a substantial portion of the entire corpus of long-term assessment. In one of these, Hersh and Ramírez administered a questionnaire to 18 users with between one month and three years experience with their electronic cane [101]. Regrettably, the questionnaire was self-developed as the authors wanted items specific to their ETA; further, beside stating that it was not piloted, information is scant of how it was developed, or if it was validated in any other way.

Other recent examples employ repeated-measures designs to assess long-term O&M outcomes of technical interventions. A PROM was used by Edwards *et al.* in [190], where a modified version of the IMQ of [126] was employed to assess the Alpha AMS retinal implant. First a baseline was collected before an implant, and a second measurement was collected two months postimplantation. In [191] and [192], Geruschat *et al.* employed their Functional Low-Vision Observer Rated Assessment (FLORA) instrument to evaluate the Argus II retinal implant. Observers made measurements with the device turned on and off to produce their evaluation data. While this on–off procedure has no inherent long-term aspect, such instead would stem from that the users had 18–44 months of experience with the device. The IMQ was briefly discussed in Chapter 4. Meanwhile, the FLORA is a visual functioning questionnaire which include many strictly vision-dependent items, e.g. "Locate lights in the environment" not necessarily relevant for BLVI mobility; further is does not focus on mobility, and was potentially too committed to evaluation of the Argus II in particular.

6.2 Outcome measures in clinical use in Sweden

While arguably no established tool offers the granularity needed for ETA development, see Chapter 4, making use of already established tools from O&M practice could both serve as long-term outcome measures, while also provide good communicability with O&M professionals and decision makers. Also, while the DoUQ-MoB (also in Chapter 4) with further work could be suitable for long-term use, employing a well-established instrument alongside it might grant more robust results overall.

To limit the scope of an initial review of tools used by O&M professionals, this will focus on such in common use in Sweden, where Audomni currently is developed. During the interviews with the eight (Swedish) O&M experts mentioned in Chapter 4, they were also asked what instruments they might use to assess BLVI mobility today. There was little consensus, but a few mentioned standardized tools: the ADL taxonomy [193], the COPM [194], and the National standard for the vision centers in Sweden in O&M [195]. This standard is actually a framework to achieve a set quality goal of independent O&M in the home, as well as in known, and unknown environments with white canes, and it defines the COPM as its outcome measure.

Meanwhile, Svenskt Kvalitetsregister för Rehabilitering vid Synnedsättning [Swedish quality register for rehabilitation when visually impaired] (SKRS), lists four validated tool for O&M professionals in Sweden [196]: ICF [197], ADL taxonomy [193], Upplevd säkerhet [Perceived security] [198], and COPM [194] — which also encompasses the expert answers.

6.2.1 International Classification of Functioning, Disability and Health, ICF

The International Classification of Functioning, Disability and Health (ICF) is a framework developed by the World Health Organization (WHO) [197, 199]. It provides a standardized classification utilizing hierarchical codes for an extensive set of categories regarding body functions and structures, activities and participation, as well as environmental factors. This should facilitate for different professions, fields, and languages to communicate efficiently and unambiguously. In practice, ICF is structured as follows.

ICF practical details
For a given patient, a domain of interest is registered with one or multiple qualifiers. The generic qualifier is a single number [*0..4*, *8*, *9*], where [*0..4*] denotes *no*, *mild*, *moderate*, *severe* and *complete problem*, respectively, *8 not specified*, and *9 not applicable*. A registration for a patient might look like *d4602.24*, where *d4602* denotes "Moving around outside the home and other buildings" which is in the "Activities and participation" component [199]; *xxxx.2x* is the first qualifier, corresponding to a performance (context dependent) of *moderate difficulty*; and *xxxx.x4* the second qualifier, corresponding to a capacity (context independent) of *complete difficulty* [197, Appendix 2].

WHO does not specify how these codes should be assessed in the ICF proper, but in [200] they suggests that existing instruments in a field might be mapped to them, or to use an instrument originally developed to use ICF.

The aim of SKRS is that all vision centrals should use a specific utilization of ICF called "Mäta effekter [Measure outcomes]" as an outcome measure by mid-2024 [196]. Further they show that the use of ICF-based tools has increased dramatically in recent years, and they are now used in 41 % of all assessments. However, as the ICF itself does not specify how its qualifiers are to be assessed, it is unclear which standardized tools that are actually used, or the number of assessments performed without such a tool. Likewise, it is at this time unclear if the qualifiers in the SKRS's "Mäta effekter" are assessed by O&M professionals or as a PROM, which could affect its utility for ETA assessment.

6.2.2 ADL taxonomy and ADL-Interview, ADL-I

Activities of daily living (ADL) are recurring activities of self-care, or relating to one's home or communications, and the ADL taxonomy is one of the most well-established instruments among Swedish occupational therapists [193]. (Norwegian and Danish versions are also available.) It is a generic tool for occupational therapists to evaluate a patient's ability to manage twelve important ADLs, e.g. *Eating and drinking*, or *Mobility*, each divided into various sub-activities.

The ADL taxonomy has gone through several iterations, as described in [193]. It was initially derived from an expert panel consisting of its original authors, and trialled with practicing and teaching occupational therapists [201]. Subsequently, it has been revised once following feedback from occupational therapists using it clinically [201]; and once after an analysis if the tool exhibited an ordered and categorial structure [202].

A few demographic-specific versions have been produced for the ADL taxonomy, including one for BLVIs. This version was developed in conjunction with personell and representatives of the Swedish advocacy group for BLVIs, Synskadades Riksförbund [193]. It heavily modifies the *Mobility* activity of the standard version (among other activities), into an *Orientation and mobility* activity. It is defined as to purposefully move from one place to another, with the subactivities: “in known environments”; “in outdoor known environments”; and “in unknown environments”.

Beside clinical use, the ADL-taxonomy has been employed in research as well. [193] provides a review of such, for instance listing uses as an outcome measure, ADL ability assessment, and as a PROM. The latter of which will be expanded upon later in this section.

The ADL taxonomy was mapped to ICF in 2015 [193]:

ADL taxonomy ICF mapping
Mobility sub-activities “In known environments” where mapped to ICF code *d4600* — “Moving around within the home”, and both “In outdoor known environments” and “In unknown environments” to *d4602* — “Moving around outside the home and other buildings” [193, 199]. For the first two mappings, the source items were regarded more specific than the ICF term, and the last mapping was deemed identical to the ICF term.

The ADL taxonomy was used in 23 % of O&M assessments in Sweden in 2021 according to [196]. However, it is not a PROM, and requires an O&M professional for assessing the various activities. This makes it prohibitive to use the ADL taxonomy proper for ETA development.

In [203], Wæhrens and Fisher performed a Rasch analysis on the ADL-taxonomy in order to yield a linear scale that could facilitate outcome research. This work was expanded in [204] and [205] to produce and evaluate the ADL questionnaire (ADL-Q) and ADL interview (ADL-I). The workings of ADL-I are expanded on below.

ADL-I practical details
ADL-I requests a respondent to report which of seven response categories are applicable to the activities from the ADL taxonomy: “I perform the task independently without use of extra time or effort and without risk”; “I perform the task independently but I use helping aids”; “I perform

the task independently but it takes me extra time"; "I perform the task independently but I use extra effort / get tired"; "I perform the task independently but there is a risk that I might injure myself"; "I need assistance from someone but do participate"; and "The task is performed by others for me — I cannot participate actively". For a given activity, the latest reported applicable response determines an ordinal score of [*1..4*]. These scores are thereafter converted into a logit (aka log-odds) based on the previously estimated difficulty of the ADL activities, to yield a single linear ADL score per respondent.

ADL-I has been applied in a number of research studies, spanning multiple fields [206]. However, as it appears it has not been employed for BLVIs, and an ADL-I version based on the ADL taxonomy for BLVIs is not available. Further, for the sake of ETA evaluation, it is excessive to assess all categories of the ADL taxonomy and ADL-I.

6.2.3 Perceived security in daily activities

Upplevd säkerhet i dagliga aktiviteter [Perceived security in daily activities] is a PROM for patients with age-related macular degeneration [198]. It was developed to be used in conjunction with the therapeutic program *Finna nya vägar* [*Find new ways*], though it can be used in a standalone fashion as well. Perceived security in daily activities assesses perceived security in 30 ADLs. Three of these are listed under mobility and one other can also be considered mobility-related. These, and the operation of the tools are as follows.

Perceived security in daily activities practical details
The mobility(-related) items of Perceived security in daily activities are "Gå till din närbutik" ["Walk to your convenience store"], "Gå över gatan vid ett bevakat övergångsställe" ["Cross the street at a crossing with traffic signals"], "Urskilja ojämnheter i underlag, t.ex. trottoarkant [sic]" ["Detect irregularities in the traveling surface, for example curb [sic]"], and "Hitta i din närbutik" ["Find in your convenience store"]. For each item, the leading phrase "How secure do you feel in..." followed by the item is asked, whereafter the respondent chooses one of the following response categories: *säker* [*secure*], *någorlunda säker* [*somewhat secure*], *osäker* [*insecure*], *mycket osäker* [*very insecure*], or *utför ej* [*do not perform*].

The PROM has been validated for test–retest reliability and responsiveness [207], and a mapping to ICF was made in 2014 [198, Appendix E]:

Perceived security in daily activities ICF mapping
The Perceived security in daily activities item "Detect irregularities in the traveling surface, for example curb [sic]" was mapped to ICF *d4502* — "Walking on different surfaces", and "Walk to your convenience store" to *d4602* — "Moving around outside the home and other buildings", both of which mappings were deemed identical; and both "Cross the street at a crossing with traffic signals" and "Find in your convenience store" were mapped to *d4503* — "Walking around obstacles", for which the source items was deemed more specific than the ICF term [198, 199].

According to [196] the instrument is used in 2 % of all O&M assessments in Sweden, a number that has been declining in recent years. Due to this, along with that any use in research is unknown; the comparatively low number of validity studies; and that the exhibited mobility items can be regarded both arbitrary and inconsistent in abstraction level; this tool is not considered further.

6.2.4 Canadian occupational performance measure, COPM

The Canadian occupational performance measure (COPM) is a PROM widely used clinically by occupational therapists, as well as in research [194]. It is administered as per below.

COPM practical details
The COPM is designed so that a given patient imparts a number of activities that they struggle with through an interview with the administrator. These activities are then graded by the patient according to their importance on an end-labelled scale [*not at all important 1..10 extremely important*]. This in turn helps the patient to, in conjunction with the administrator, choose and prioritize possible interventions. Subsequently, the activities that the patient is to receive interventions for are again graded, but for ability and satisfaction by the patient on the end-labelled scales [*cannot at all perform it 1..10 can perform it extremely well*] and [*not at all satisfied 1..10 extremely satisfied*], respectively. After the interventions, and a set time, these two gradings are repeated by the patient. The old scores are then subtracted from the new scores, and if the mean difference of all ability-scores, or satisfied-scores are 2 or more, this indicates a clinically important difference [194].

The COPM enjoys a substantial body of research regarding reliability, validity, and sensitivity, and has seen use in investigating and developing interventions in various fields as per reviews in [194].

Despite being the specified outcome measure in the Swedish national standard [195], and that in 2013, a survey found that 9 of 15 responding vision centrals used this standard (though it was noted that several vision centrals had individually modified it) [208], COPM was used in just 1 of 670 reported O&M assessments in Sweden 2021 [196]. The report comments "The instrument is widespread and might have been replaced by ICF-based assessments".

Regardless of popularity, the COPM is by its nature very adaptable to a given field of inquiry, as well as is time effective. This in combination with its excellent record of validation and reliability studies, can make it advantageous to complement other tools with.

6.3 Piloting potential long-term outcome measures

As an exploratory study of suitable long-term outcome measures, as well as to further investigate BLVIs' O&M needs from self-reported O&M ability, we utilize two of the aforementioned tools designed for occupational therapists: the ADL taxonomy through the ADL-I [193, 205], as well as the COPM [194].

6.3.1 Method

The response categories from the ADL-I, ad-hoc translated to Swedish, as well as the COPM procedure, were adapted to the definition of the *Orientation and mobility* activity of the ADL taxonomy for BLVIs, and its related sub-activities. During an interview, for each sub-activity, the respondent is verbally instructed to answer yes or no to all response categories of the ADL-I, followed by the *importance*, *ability*, and *satisfaction* rating scales of the COPM. As for the ADL-I, the latest reported category determines the score, but since there is no logit conversion for these sub-activities, the simple scale of [*0..6*], as per [204], is used. The COPM scores are used as is.

The ADL-I and COPM questionnaire were administered in conjunction with the most recent user tests of the Audomni system, see Chapter 7, with 19 BLVIs, 14 that used a cane as their primary mobility aid, and 5 that used a dog. See Table 6.1 for the respondent distribution of e.g. gender, education, and visual impairment.

TABLE 6.1
Participants of the latest user test

Gender	*Female*			*Male*		
	8			11		
Vision impairment	*Effectively total blindness*			*Low vision*		
	9			10		
Current prim. mob. aid[1]	*Guide dog*			*White cane*		
	5			14		
Used prim. mob. aid	*0-5 years*		*> 10 years*		*Congenital*	
	4		7		8	
Hearing imp.[2]	*No imp.*		*Uneven L–R*[3] *sensitivity*		*Imp. and uneven L–R sensitivity*	
	17		1		1	
Education	*Primary*	*Upper sec.*[4]	*Post-sec. non-tert.*[5]	*Bachelor's or eq.*[6]	*Master's or eq.*	
	1	4	6	6	2	
Age	*30-40*	*40-50*	*50-60*	*60-70*	*70-80*	*80-90*
	3	0	7	4	4	1

[1]Primary mobility aid. [2]Impairment. [3]Left–right. [4]Secondary. [5]Tertiary. [6]Equivalent.

Table reprinted, with slight modification, from [163].

6.3.2 Result

The ADL-I and COPM questionnaire results are visualized through box plots in Fig. 6.1.

6.3.3 Discussion

The COPM results show that all activities were generally deemed highly important, with a slight movement downward on the scale for "Unknown areas". *Ability*-wise, respondents trended downward from high scores at "Known indoor areas", through "Known outdoor areas", to "Unknown areas" where more than 50 % of all respondents gave low scores, between *1–3*. This was also mirrored in the satisfaction score. The same trend can be seen for the ADL-I, where almost 75 % of all respondents got a score of *1–2* for "Known outdoor areas", and only a score of *1* for "Unknown areas'. As a score of *2* is interpreted as that a respondent cannot perform the activity without risk of injury, and a score of *1* that they cannot perform the activity independently at all. This clearly indicates that an ETA which increases blind and low-vision users' ability to navigate in unknown environments

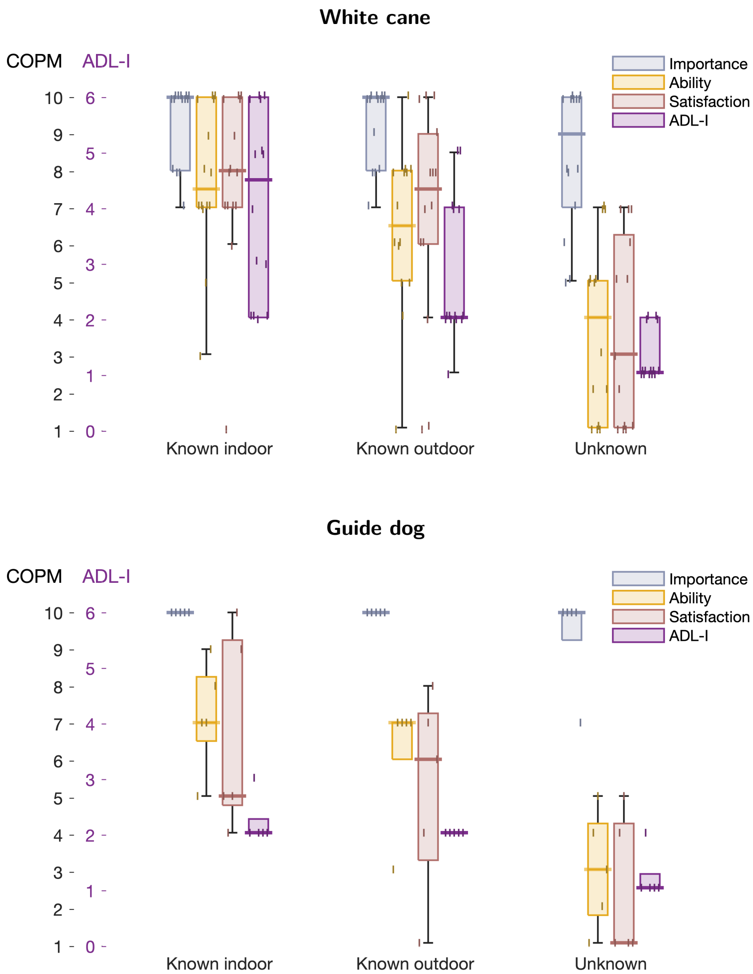


Fig. 6.1: Results from the COPM and ADL-I questionnaires, grouped by primarily used aid (cane $n = 14$, dog $n = 5$). Tick marks denote individual responses. All activities are predominantly deemed very important, whereas the users' ability and satisfaction generally decrease from "Known indoor [areas]", through "Known outdoor [areas]", to "Unknown [areas]". For ADL-I, answers *0–1* mean that the activity is not performed independently, and *5–6* that the activity can be performed without extra time or effort taken, and with no risk of injury.

would be most beneficial; one increasing it in known outdoor environments would be less, but still considerably, beneficial; whereas one increasing it in known indoor environments might yield limited benefit.

The apparent discrepancy between the scores of the COPM and the ADL-I for "Known outdoor areas" is interesting. Possible explanations might be that some users interpret "there is a risk that I might injure myself" conservatively, e.g. "there is always a risk"; that they use a different baseline; or both.

As a measure, both ADL-I and COPM provide measures of very high abstraction levels. As such, they cannot reveal the driving forces behind a particular score, but they can and usually serve as tools to compare relevant activities before and after an intervention. They benefit from having robust backgrounds when it comes to theory, validation, and being relatively prevalent in assessing ADLs. Furthermore, they take little time to conduct. In this study they proved useful in illustrating the most pressing navigation activities by some BLVIs. In future works, they could be used for before–after comparisons of ETAs in long-term studies.

6.4 Summary

Adopting adequate methods and measures for long-term studies of ETA outcomes is essential for reliable results. While the DoUQ-MoB is a comprehensive tool, using additional instruments should be beneficial for robustness and reliability of the results, additionally so if they are already established in the O&M community. In Sweden, the ADL-I stems from the popular ADL taxonomy, and COPM has at least previously been advocated for use by O&M professionals. Employing them in the manner described in this pilot study provided easy and time-efficient measures, albeit at high abstraction levels, and could prove useful for long-term tests.

6.5 Future work

Before the DoUQ-MoB, the ADL-I, or the COPM are deployed as long-term measures, they first need to be trialled for that objective, for instance to ensure test–retest reliability over a period of time (see Chapter 4 for further discussion regarding DoUQ-MoB). Further, any used long-term measure should be reconciled with measures already in use, or planned future measures, by O&M professionals.

This chapter can be regarded as an introductory investigation into long-term outcome measures, and not much have been discussed regarding methodology. Before long-term studies are performed, naturally a robust method would need to be in place as well, which is left for future work.

Chapter 7
Primary mobility aid, Audomni

This chapter outlines the Audomni system — an ongoing effort toward an ETA that is helpful and that blind and low-vision users want to use. This includes project aim, development, physical design, functionality, evaluations, and future plans. The descriptions of the physical design, functional method, and evaluations originate from Papers II [174], and IV [163].

7.1 Project aim

DoU is a function of the functionality and ergonomical complexity of an aid, see Chapter 3. If a new aid, alone or in a setup with other aids, yields a higher DoU, the user will choose it over their current aid (setup). With that in mind, the following assumptions are made:

Project assumptions

A1: Increased mobility increases BLVIs' quality of life and decreases their associated socioeconomic costs.

A2: An aid increases users' mobility if used *and* the functionality result is much greater than that of a current aid (setup).

A3: An aid is used if the joined functionality and ergonomical complexity result is better than that of a current aid (setup).

Box reprinted from [163].

These in turn produce the hypotheses, and overarching design goals:

Project hypotheses / design goals

H1: The aid results in a functionality much greater than that of a current aid (setup).

H2: The aid results in a joined functionality and ergonomical complexity better than that of a current aid (setup).

Box reprinted from [163].

Producing evidence supporting that Audomni has such functionality and ergonomical complexity so that **H1** and **H2** are plausible, is a formidable challenge. It effectively requires:

1) Long-term user tests to show both that testers' mobility increase, and that they keep on using a prototype after a novelty period.
2) A prototype very close to an imagined end-product, as it needs to be quite safe, and because a prototype that is ungainly, unintuitive, unattractive, or has issues in its functionality, most likely will affect tester behavior and perception.
3) A heterogeneous and large set of blind and low-vision testers.

While performing long-term tests with a diverse set of participants from the target group might technically be attempted at any given time, it takes great effort, considerable time, and inherently exposes the participants to hazardous environments. Thus, it is essential that the methods and measures of such tests are apt, see Chapter 6; as well as that a prototype is fit — especially considering the safety aspect — before initiating such an endeavor. Reaching that stage of development is the current aim of the project.

7.2 Design outset

Arguably, there are two possible general approaches when developing an ETA: guide the user through the environment, or show the user the environment. The guide dog is an excellent example of the former, and the white cane of the latter. "Show" can further be divided into two sub-approaches, either provide as little information as possible while allowing for safe travel, or provide as much information as possible without it becoming overwhelming. Both guiding and "show as little as possible" approaches are quite the design problems, as both what is necessary information, and when to provide it, is highly individual [72, 73]. Further, both approaches can be technologically prohibitive, as if any classification algorithm is to be used, they must be very robust. Consider for instance the challenges of self-driving cars, and exacerbate them with that the technology must be wearable; algorithms need to take into account that beside roads, various sidewalks, paths, curbs, stairs and steps are also traversable; there are a more types of possible obstacles for the algorithms to consider; and pedestrians are more probable to get hurt in accidents than car passengers. Thus, it might be beneficial to design with a "show as much as possible"-approach if the aim is to maximize the chances of reaching a successful ETA.

A likely presumption is that vision allows for sufficient independent mobility; therefore, an ETA design rooted in vision affordances could provide for adequate functionality. Transforming one modality into another is commonly referred to as sensory substitution or sensory supplementation. In the ETA field, this either means a visuo-auditory (aka sonification), a visuo-tactile, or a hybrid sensory substitution / supplementation device (SSD). Though there are various theories regarding as to why vision affords mobility [209], possible advantageous low-level traits are a large FoV, high resolution, and low latency. In combination, this produces a considerable amount of data per time unit. Since the auditory system normally provides greater bandwidth than that of haptic perception [47], utilizing audio feedback could be favorable for SSD design.

A common reservation against visuo-auditory SSDs are that they can block important — often especially for BLVIs — environmental sounds. However, such concerns should be mitigated with the recent arrival of accessible open-ear headphones, e.g. bone-conduction headphones and headphones with active transparency modes, in conjunction with deliberate sonification algorithms.

The general idea of Audomni is that of a visuo-auditory SSD, that transforms relevant visual information from a user's immediate environments into continuous sound, with as a wide FoV, high spatial resolution, and low latency as possible. This conforms to the above discussion, arguably heightening the chances of becoming helpful for blind and low-vision users.

Continuous sound of low latency can warrant further discussion, as most well-known visuo-auditory SSDs with relatively high spatial resolution, instead choose to temporally sequence the feedback, e.g. the vOICe [147,210], EyeMusic [211], Naviton [90], and in one mode of Sound of Vision [148]. This is probably a popular choice as it can reduce cognitive load and hearing fatigue. However, continuous feedback provide more timely information about new objects entering the FoV — which could be crucial for safety and user perception of reliability. It is also probable that rapid iterations of the sensorimotor loop of an SSD helps in distal attribution, or externalization, of perceived objects [46], which in turn should lower its learning curve and make it more approachable. Lastly, a sequenced sonificaiton algorithm

Fig. 7.1: Video capture from Wissler's blindfolded challenge run of the video game *The Legend of Zelda*: *Ocarina of Time* [212], used with permission.

makes it necessary to sometimes wait for demanded information, which may actually increase cognitive load.

7.3 2014–2017 — Audomni before the PhD-studies

Audomni started out as a hobby project by me in 2014, alongside my engineering studies, originally by the name of Navigation by Sound. The project was inspired by Wissler's blindfolded challenge run of the video game *The Legend of Zelda*: *Ocarina of Time* [212], see Fig. 7.1. In the game, there is a hand-held tool which can shoot out a hook at a fixed speed and in a perfectly straight trajectory. The tool can be shot in any direction from a first-person perspective, and when it hits something it makes a distinctive audible clang. When unsure of his surroundings, by shooting the tool systematically at incremental angles and listening for the delay of the clang, Wissler could perform what was essentially a form of echolocation. He could do this both horizontally and vertically, and effectively produce rudimentary cognitive maps of where walls, objects, and walkways where located from an egocentric perspective. While this could take substantial time and effort, with this understanding he could then often navigate various rooms of the game safely. Thus, the original idea of Navigation by Sound was to provide the same functionality in real-life, but as if there was a considerable quantity of such tools firing simultaneously, in order to accelerate the process.

Between 2014 and 2017, the first software sonification algorithms were explored, a rudimentary VR simulation was made, the first physical prototype (which only worked indoors and was not battery powered) was

Fig. 7.2: Physical design of the first Audomni prototype, at the time called Navigation by Sound. Photograph: Nordic Innovation.

Fig. 7.3: Test of the first Audomni prototype. Note that it was not battery-powered, and only worked indoors.

constructed and implemented, see Figs. 7.2 and 7.3, and the first contacts with the target group were made.

Since the project was worked on as a pastime, it was more start-up focused as to potentially arrive at an end-product. To this end, the project was entered in a number of start-up-related activities, among them: Leapfrog innovation scholarships and the VentureLab student start-up incubator of the innovation branch of Lund University, LU Innovation; the University

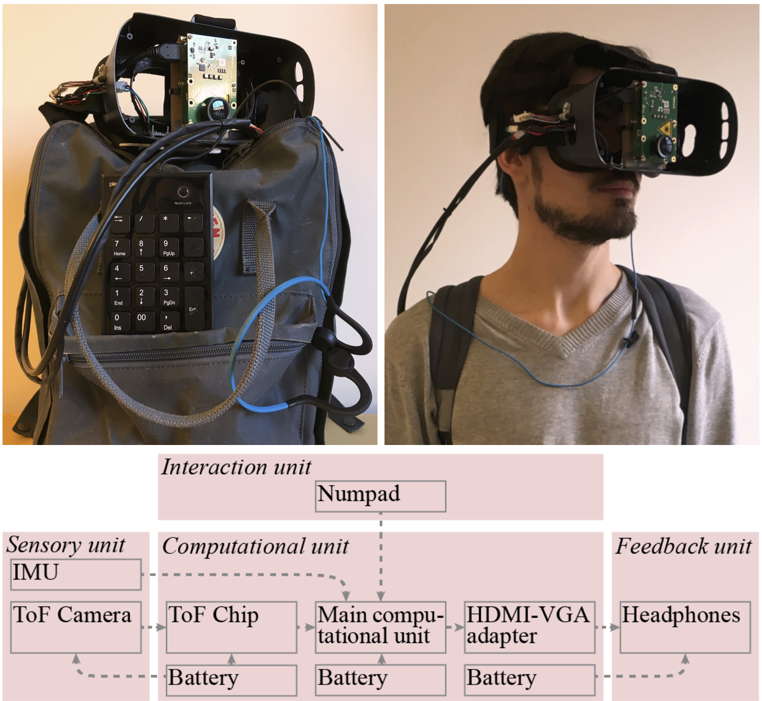
Fig. 7.4: Attempted, and later abandoned, prototype for a sensor solution utilizing stereo-vision in 2017.

Start-Up World Cup; and the Nordic Independent Living Challenge. While all aided the project substantially, the latter was especially notable as it lead to the first considerable funding of the project, granted from the Swedish Governmental Agency for Innovation Systems, Vinnova.

This funding was used to finance an employment for a year at Lund University with the project, and thus it became academically tied in 2017. During that year, the technological solutions of a new physical prototype were investigated, e.g. a stereo-vision-based sensor solution, see Fig. 7.4, though a solution using time-of-flight was later opted for instead, see Fig. 7.5; and a new computational platform to support both sensor and algorithm computations. The algorithms were also overhauled to make use of the new sensor and computational capabilities. Finally, the first formal pilot tests of the new prototype with blind and low-vision participants were designed and prepared for.

While the funding from Vinnova covered 2017, funding was subsequently granted by the Promobilia Foundation to continue the project in the first half of 2018. In spring 2018, the hardware, software, and test preparations could be concluded, while the pilot tests were finished before that summer. These tests are expanded on later in this chapter.

During that spring, the Promobilia Foundation contributed with further funding to the project through a PhD-student grant, which allowed for my PhD studies to commence, which they did in the latter half of 2018. It was



IMU — Inertial measurement unit **ToF** — Time-of-Flight

Fig. 7.5: Two images of the physical design of the Audomni prototype in 2018 and a flowchart of interrelations of the system units. In the top left image, the sensor is resting on top of the backpack, which houses the computational unit. The numpad and the headphones are the interaction and feedback units, respectively. Figure and caption reprinted, with permission and slight modification, from [174], © 2020 IEEE.

not until that point that the first proper literature reviews of the research field of ETAs were made, the shortcomings of the field were identified as per Chapter 2, and DoU was developed to answer some of them, see Chapter 3. I.e. the first pilot tests were performed before knowing the shortcomings or how to avoid them, which might explain why many are effectively reproduced in those tests.

7.4 2018 — Audomni at the onset of the PhD-studies

The aim of the hardware is to gather depth data from the environment, feed it into the computational platform which conducts the sonification, and then present it through headphones. As discussed earlier in this chapter, the idea is to enable as a large FoV, spatial resolution, and low latency as feasible, while keeping the price point reasonable, and outdoor and portable

TABLE 7.1
Model names of the various parts in the physical design of Audomni in 2018

Time-of-flight camera	Melexis EVK75123
Inertial measurement unit	Adafruit BNO055 Absolute Orientation Sensor
Main computational unit	Jetson TX2 Developer Kit
Batteries	Kjell & Company 18650 Li-ion, 3.7 V, 2600 mAh
Headphones	Aftershokz Sportz Titanium
Backpack	Fjällräven Kånken Laptop 17”
Numpad	Plexgear N-18

Table reprinted, with permission, from [174], © 2020 IEEE.

TABLE 7.2
Functional method sonification parameters of Audomni in 2018

Horizontal field-of-view	99.3°
Vertical field-of-view	70.6°
Horizontal resolution	80 px
Vertical resolution	60 px
Max sonification depth, r_m	4000 mm
Distance curve parameters	
Linear fraction, l	0.3
Maximum descent, d_m	0.5001
Point of maximum descent, d_d	800 mm
Max tremolo rate	4 Hz
Tone interval	220-7040 Hz
Tone increment (half step)	$2^{(1/12)}$
Warning depth, d_w	300 mm

Orientation filter note – For a given pixel, a quotient q is computed:

$$q = \begin{cases} (1 - angle/45), & angle > 0 \\ 0, & angle \leq 0 \end{cases}$$

A distance limit d_l is introduced as $d_l = q * (r_m - d_w) + d_w$. If the pixel depth is larger than this limit, the pixel is muted.

Table reprinted, with permission, from [174], © 2020 IEEE.

use possible. In mid-2018, the most promising sensor possibility seemed to be camera-based stereo vision. This was tentatively attempted, see Fig. 7.4, but was abandoned when a time-of-flight (ToF) camera evaluation kit that complied with the aforementioned requirements became available. The computational platform had initially been chosen to enable the demanding stereo-vision computations, but the choice was then also beneficial for the similarly demanding sonification scheme.

The physical design and a flowchart of Audomni in 2018 is shown in Fig. 7.5, with the various model parts presented in Table 7.1.

For the sonification scheme, the pixels of the depth image were mapped to audio as follows. Horizontally, the aim was to map the volumes for

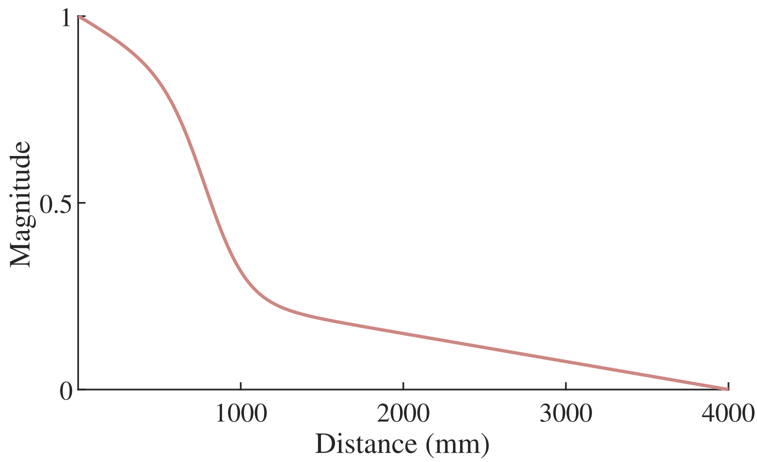


Fig. 7.6: Volume and tremolo mapping curve for Audomni in 2018. For a given distance of a pixel, the corresponding magnitude is multiplied with the set maximum volume and frequency to produce the end volume and tremolo frequency, respectively. Note how the maximum descent happens at 800 mm, and thus should provide for an easily differentiable cue for the user that an object is getting very close. Figure and caption reprinted, with permission and slight modification, from [174], © 2020 IEEE.

the left and right stereo channels according to the corresponding pixel angles. This was done by measuring what horizontal angles users associated various left–right stereo pans with, which should allow for intuitive horizontal differentiation for users. The vertical angles of pixels were mapped to different tones of a relatively wide frequency range, to aid in discerning neighboring vertical pixels, see Table 7.2. Lastly, for depth, volume and a tremolo frequency were mapped with the following function.

Depth curve equation

$$v = (l + \frac{s_m}{1 + e^{-s_e*(\delta - d_p)}}) * (1 - \frac{\delta}{r_m}) \tag{7.1}$$

where v is volume, l is the linear term fraction, δ is distance, d_m determines the maximum descent rate, r_m is the maximum sonification range, and s_m and s_e are constants which are computed as:

$$s_m = 2 * d_m - l, \quad s_e = \frac{ln(2 * d_m - 1)}{d_d} \tag{7.2}$$

where d_d is the distance of the maximum descent rate.

Equation and description reprinted, with permission, from [174], © 2020 IEEE.

The parameters are shown in Table 7.2, and the resulting curve in Fig. 7.6. The objective of this mapping was to both prioritize closer objects, and emphasize objects that are getting into very close range. The tremolo effect had the additional benefit of arguably making the sound more pleasant.

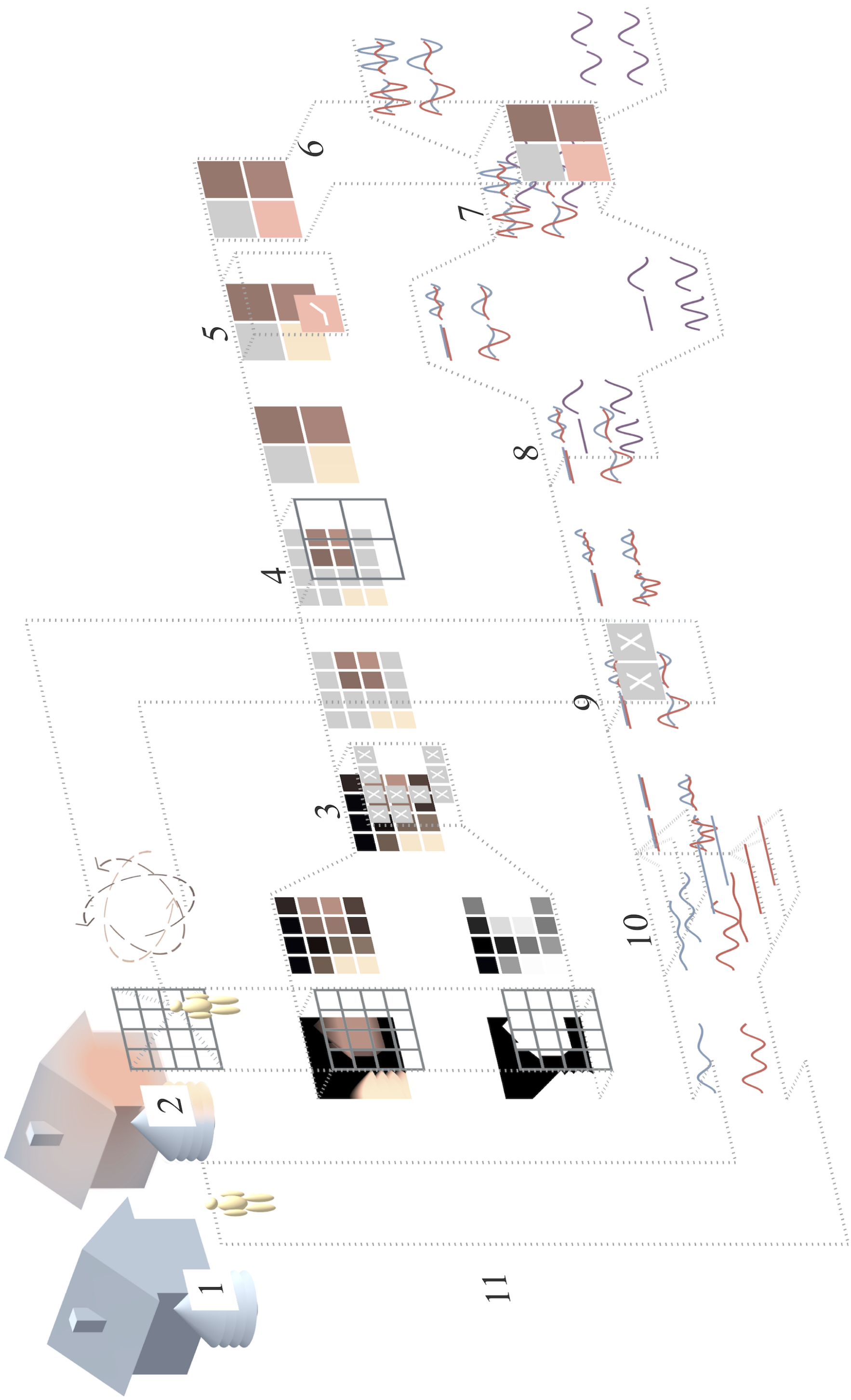


Figure caption on next page.

Fig. 7.7: Functional method of Audomni in 2018:
1 *Initial state*
2 *Data acquisition — Scene illumination and capture*
The environment is illuminated by the time-of-flight camera, and a depth (top) as well as a confidence (bottom) image is captured. The inertial measurement unit orientation is also read.
3 *Data acquisition — Confidence filtering*
The depth image is filtered with the confidence image by disabling values of pixels with a corresponding confidence value below a set threshold.
4 *Data acquisition — Downsampling*
The filtered depth image is downsampled by averaging neighboring pixels.
5 *Data acquisition — Truncation*
The downsampled depth image is truncated by setting pixels below a set minimum value to that minimum value.
2–5 *Data acquisition — Loop*
Steps 2–5 are looped continuously. The most recent final depth image is stored in memory until a more recent final depth image is produced.
6 *Sonification — Initial state*
Each pixel on the most recent final depth image has three sine waves ascribed to it: one of left sound samples (top waves in orange), one of right sound samples (top waves in blue) and one of a tremolo effect (bottom waves in purple). The "left" and "right" waves of each pixel have a set amplitude as a function of its horizontal angle, and a set frequency as a function of its vertical angle. The "tremolo" waves have a set amplitude and frequency.
7 *Sonification — Depth application*
The pixel values of the depth image are transformed via a set function, see Fig. 7.6. The result is applied to the three waves of each pixel. The amplitudes of the left and right wave are multiplied with it, as is the frequency of the tremolo wave.
8 *Sonification — Tremolo application*
The amplified left and right waves are multiplied with their respective frequency modulated tremolo wave.
9 *Sonification — Orientation filter*
The orientation of the IMU is used to compute the real world angle of each pixel. If the given pixel depth is too large compared to its vertical angle, the corresponding left and right waves are muted, see Table 7.2.
6–9 *Sonification — Loop*
Steps 6–9 are looped continuously. The final set of waves are held in memory until a more recent set of final waves are produced.
10 *Presentation — Sampling*
The most recent set of final left and right waves are added together, respectively, producing the left and right audio waves to be presented.
11 *Presentation — Output*
The audio is sent to the speakers and user.
10-.11 *Presentation — Loop*
Steps 10 and 11 are looped continuously.
Figure and caption reprinted, with permission and slight modification, from [174], © 2020 IEEE.

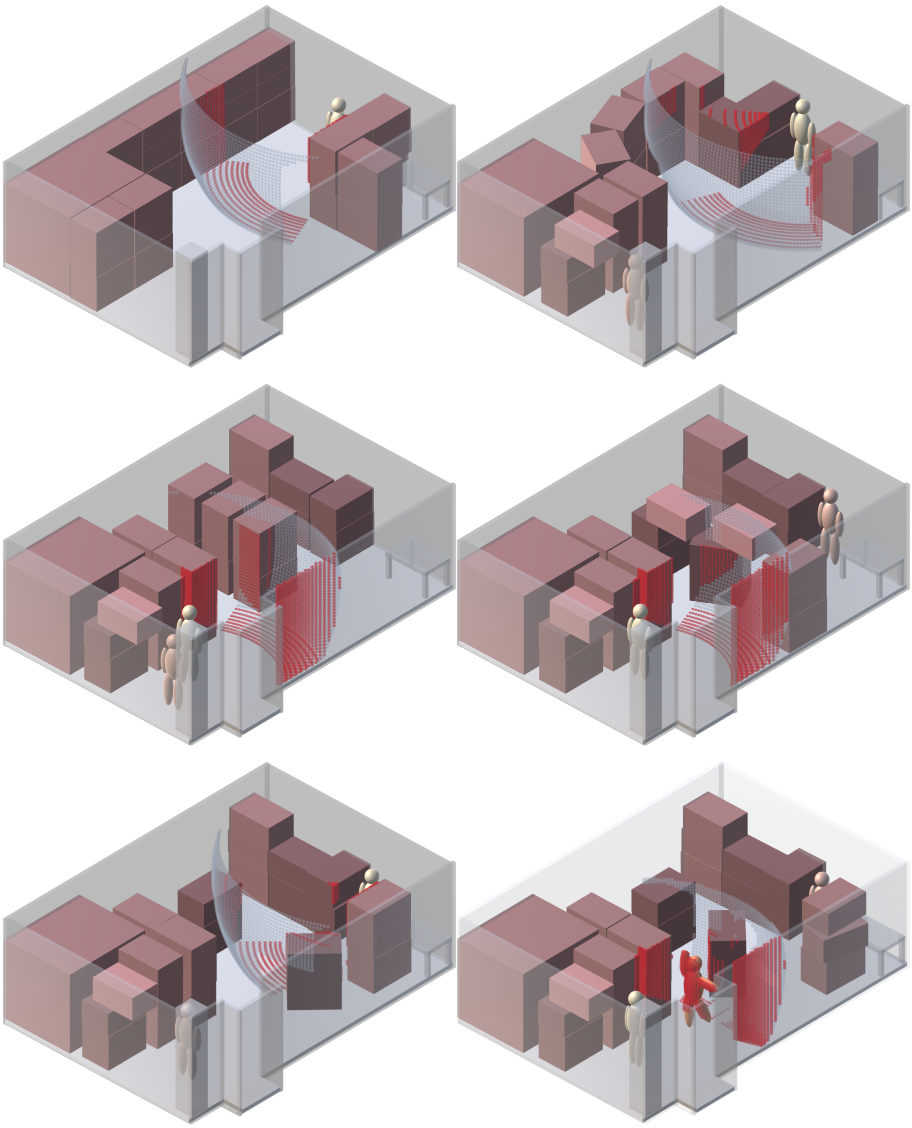


Fig. 7.8: Visualizations of the tests scenarios used in the pilot tests of 2018. The bright characters denote starting positions, and the dark ending positions. The points of the point fields (which might resemble lines due to the densely packed points) represent pixels of the sensor projected into the environment, with a max range which also represents that of the sensor. Red points are in range and are pixels that would be sonified. The posing character in the bottom-right scene denotes a test instructor that the participant is to follow in that scene. Figures reprinted, with permission, from [174], © 2020 IEEE.

Fig. 7.9: Example images for the pilot tests of 2018 with the two blind or low-vision participants. Figures reprinted, with permission, from supplemental material of [174], © 2020 IEEE.

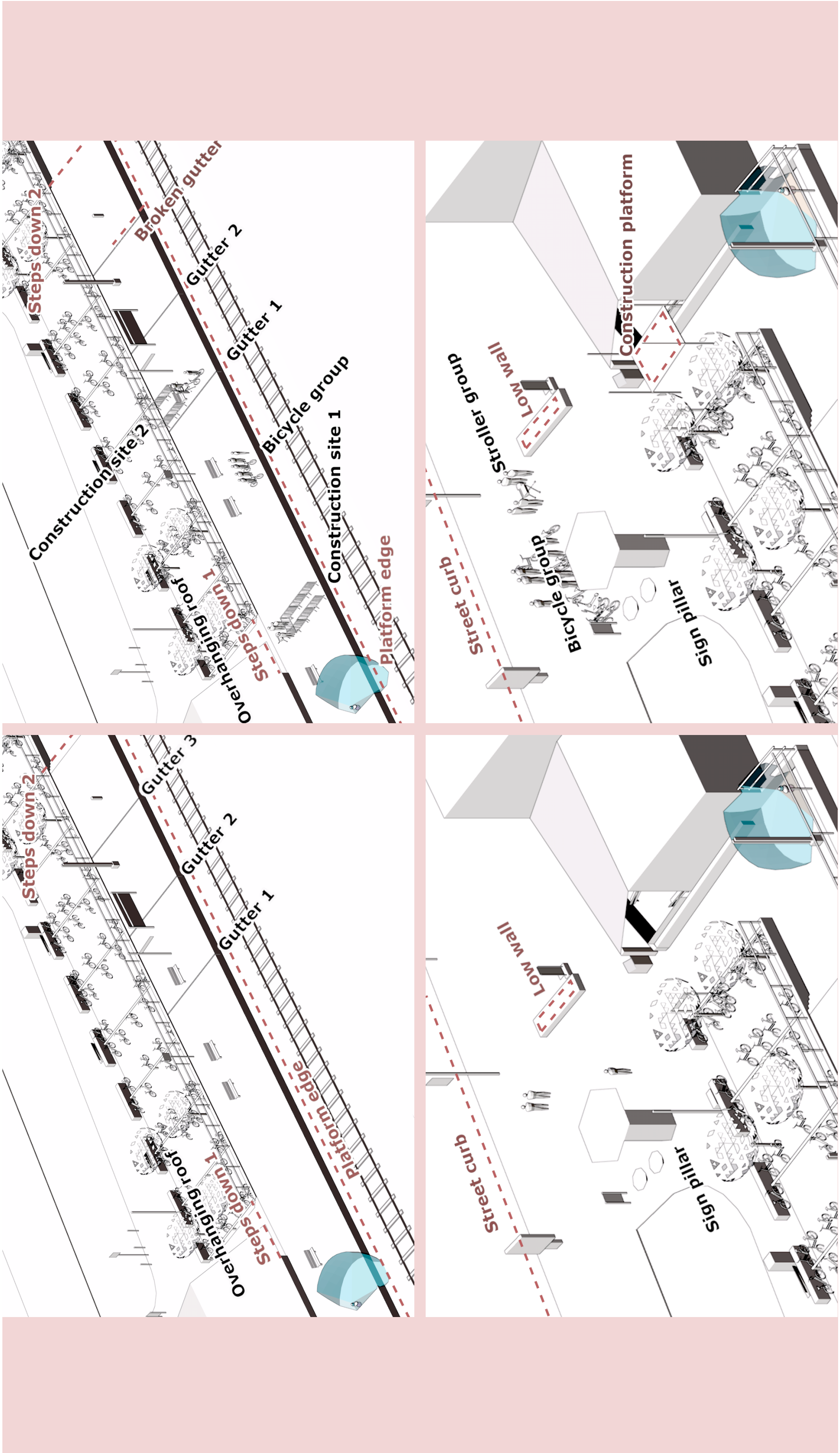
The functional method, i.e. the signal processing chain and sonification scheme, of Audomni in 2018 is outlined in Fig. 7.7, and an abridged set of relevant parameters in Table 7.2.

7.4.1 User tests I — Pilot tests

Audomni, as it was in 2018, was evaluated through pilot user tests with two blind or low-vision participants: both were male and used white canes as primary mobility aids; Participant 1 was congenitally blind with total vision loss, and was in his sixties; and Participant 2 had a contracted condition of severe vision loss and was between 18 and 30 years old.

The test objective was to take stock of Audomni, as well as to produce initial user tests which could act as a starting point for future tests. Recall that these tests were designed before the PhD studies, and thus before a proper literature review and the development of DoU — indeed, the motivation behind DoU was much due to the experiences of developing the tests, and the analysis of them, which often felt ineffective and unsatisfactorily grounded in real mobility of BLVIs. This resulted in methods and measures which in retrospect could have provided more insight. The tests took place indoors in a controlled environment, utilizing cardboard boxes to produce various scenes. A test session was split into four introductory scenes, and six testing scenes, see Fig. 7.8, which each participant performed in succession. There was also an introductory and a final semi-structured interview with each participant. Example images from the tests are shown in Fig. 7.9.

With only two participants, and quite an artificial setting, conclusions about the functionality of an ETA should be made with care. However, a few tentative inferences could be made: that both participants at least once failed in detecting obstacles at head-height warranted concern; they had



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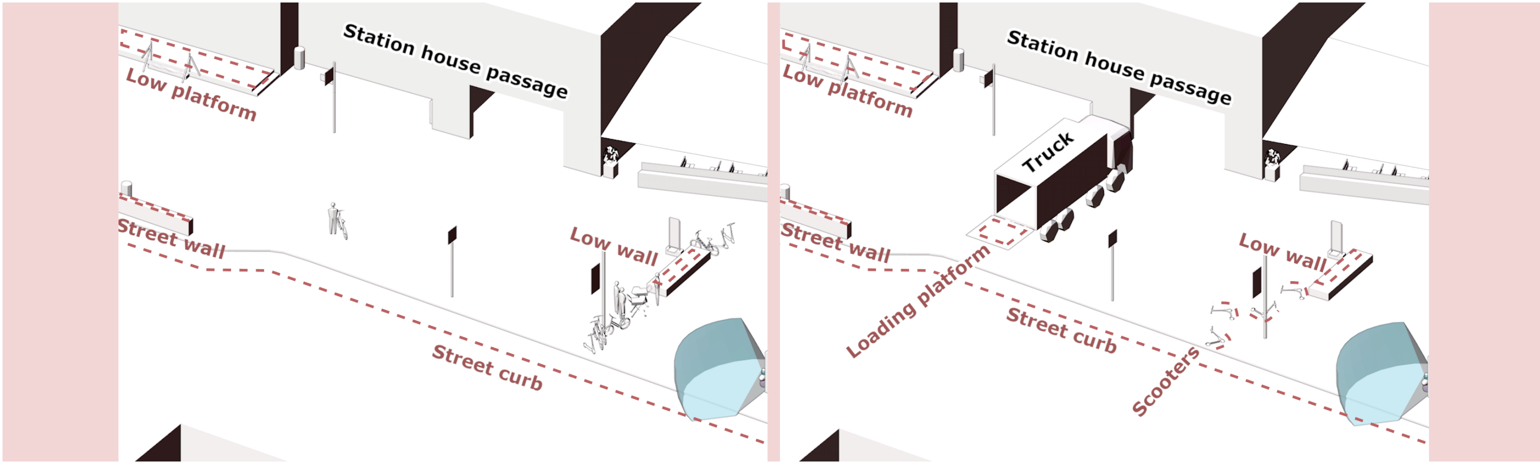

Fig. 7.10:
Virtual training and testing scenes used in the latest user tests, to the left and right respectively (slightly edited for clarity). Blue fields denote the field-of-view and the starting positioning, red dotted lines severe obstacles. The goal in the top scenes is "Steps down 2" by coastlining "Platform edge"; in the middle scenes "Street curb" by beelining; and in the bottom scenes the far edge of "Street wall" and then face "Street curb" by coastlining "Street curb". Figure and caption reprinted, with slight modification, from [163].

TABLE 7.3
DoU-MoB parameter values and discussion summaries of Audomni in 2018

Perception range — 4 m The range should afford adequate stationary obstacle detection, though an increase could be beneficial for comfortable detection of other pedestrians. It should be increased if possible.

Horizontal field-of-view — 99.3° The horizontal FoV covers a substantial portion of the FoV of a person with normal sight, though a larger horizontal FoV would afford better landmark identification, as well as spatial orientation, as objects to users' sides would be more readily perceived. It would also help in detecting moving objects. It should be increased if possible.

Vertical field-of-view — 70.6° The vertical FoV does not cover the entire ground area from the feet and forward when a user's head is at a neutral angle. Thus it should be increased, or tilted toward the ground.

Weight — *Mask*: 0.33 kg; *Backpack*: 2.27 kg The mask and backpack weight should not be too prohibitive, though the mask might prove taxing after long sessions or for some users. It should be reduced if possible.

Durability The durability is very low and must be increased.

Temporal resolution — 160 ms The device latency is noticeable and could affect user perception. Efforts at reducing it should be made.

Spatial resolution — *Horizontal*: 80 px, 1.24°; *Vertical*: 60 px, 1.18°; *Depth*: 1-2 % at 4 m The perceived spatial resolutions are largely unknown, though edges and walls seems to be localizable within 10 cm at arm's length. Efforts should be made to both increase them, and measure them more methodically.

Functional method Methods that provide horizontal, vertical, and depth differentiation seem fairly intuitive and allow for some of the important mobility tasks; though, efforts should still be made to improve them to make those tasks easier, as well as make more tasks possible.

Interacting with the device from a user's perspective is currently close-to impossible and must be improved.

The sensory comfort seems decent for such short-term tests, but efforts can be made to improve it.

Physical design The prototype is hardly physically appealing, and whereas both the mask and backpack are decently comfortable, they are quite large and could be considered bulky. The device is also considerably ungainly. Efforts should be made to reduce the size of the mask and backpack, as well as make it more gainly.

Table reprinted, with permission and slight modification, from [174], © 2020 IEEE.

consistent trouble with horizontal differentiation in cluttered scenarios; it was apparent that the test methodology had many issues; and the interviews provided minor learnings. With that said both participants, with no prior experience, managed to perform a number of relevant DoU-MoB aspects; this at the very least showed some potential of Audomni. How the state of Audomni in regards to the proper DoU-MoB parameters was reasoned is shown in Table 7.3.

7.5 2018–2023 — Audomni development during the PhD-studies

To mitigate the issues identified in the initial pilot tests, numerous iterations were made consisting of moderate adjustments of the sonification parameters and informal internal tests. However, it quickly became clear that such modifications would not be enough to sufficiently alleviate those issues, as well as other known issues the sonification had in real urban environments. Thus, considerable effort went into overhauling the algorithms, where various scripts and software were developed in order to explore and experiment with different sonification schemes. Once a scheme that was deemed adequately promising had been found, efforts were directed toward the design and preparation of the next round of user tests. This resulted in the DoUQ-MoB questionnaire and the Parrot-VR system described in Chapters 4 and 5. The new sonification was again internally tested and adjusted, leveraging the rapid iterations made possible by Parrot-VR and various simple but purposeful virtual environments. Eventually, a final sonification scheme that allowed novice internal testers to perform many of the various troublesome aspects of the DoU-MoB was achieved.[1]

7.5.1 User test II — Virtual tests

In 2022, the current sonification scheme of Audomni was evaluated in VR, with methodology and measures designed with the learnings of Chapters 2 and 3, and the DoUQ-MoB questionnaire and the Parrot-VR system (Chapters 4 and 5). The participants were the same 19 BLVIs of various backgrounds as in the pilot tests of the ADL-I and COPM in Chapter 6, see Table 6.1, as those were administered as part of the same test sessions.

For fruitful tests, relevant large-scale and urban test settings should be used; moreover, it should afford the evaluation of as many DoU-MoB aspects as possible, as well as a realistic navigation scenario for the participants. Train

[1] Toward maximizing the likelihood of reaching an end-product that can aid independent mobility of BLVIs, the current sonification scheme is unfortunately not described in detail. This is a decision reached through input from the innovation branch of Lund University, LU Innovation, along with personal experience with the start-up scene; as probably the likeliest route to a product is commercial, through either a start-up or an established company, where safety in terms of IP can be crucial for eventual investors and the company.

stations in general fulfill these criteria, and the easiest to reproduce for Parrot-VR is likely the Lund Central station, Sweden, due to its proximity to Lund University. A navigation scenario was constructed as so: a participant had arrived to a platform by train, they were to follow the platform (ideally by coastlining the edge) to the end; then walk in a straight path toward a street (without coastlining opportunity) until they reach the curb; and lastly follow the curb (ideally by coastlining it) until they reach a pedestrian crossing. Two versions of the scenario were developed, one for introducing the Parrot-VR, the Audomni sonification scheme, and navigation strategies; and one for the actual tests, featuring more obstacles and narrow paths, many of which force participants away from their coastlining edge or their straight path, see Fig. 7.10. The aim with the testing scenes was that few participants should manage them without issue, as to elucidate the limits of the sonification (for novice users at least), and also to expose the participants to a difficult scenario, which could promote more critical responses regarding the aid during the DoUQ-MoB.

Since VR facilitates excellent recording of the avatar movement, and all participants traversed the same environments, an aggregate movement analysis could be performed. In these, all instances where participants collided with anything (walking off a ledge counted as a collision as well), or needed help in any capacity were registered. This could then be visualized on trace maps, for an example see Fig. 7.11, as well as broke down to common underlying reasons in river charts, see Figs. 7.12 and 7.13. The trace maps effectively illustrate what sections were relatively easy and hard for all participants, and the river charts illustrate what reasons behind collisions or interventions were most common.

Because the participants had been subject to a relevant navigation scenario in real-life-like environments, they could also answer the DoUQ-MoB questionnaire meaningfully. The interview analysis is shown in Table 7.4, the ten most notable paired items in Fig. 7.14, and the comparison items in Fig. 7.15

The movement analysis, with the event breakdowns and the trace maps, provided many insights. For instance, there might exist some externalization and differentiation issues with the current sonification, and some specific obstacles and passages were quite problematic. However, in general most participants were able to effectively utilize the concept in VR to follow edges, and detect and avoid obstacles, after only about 40 minutes of training.

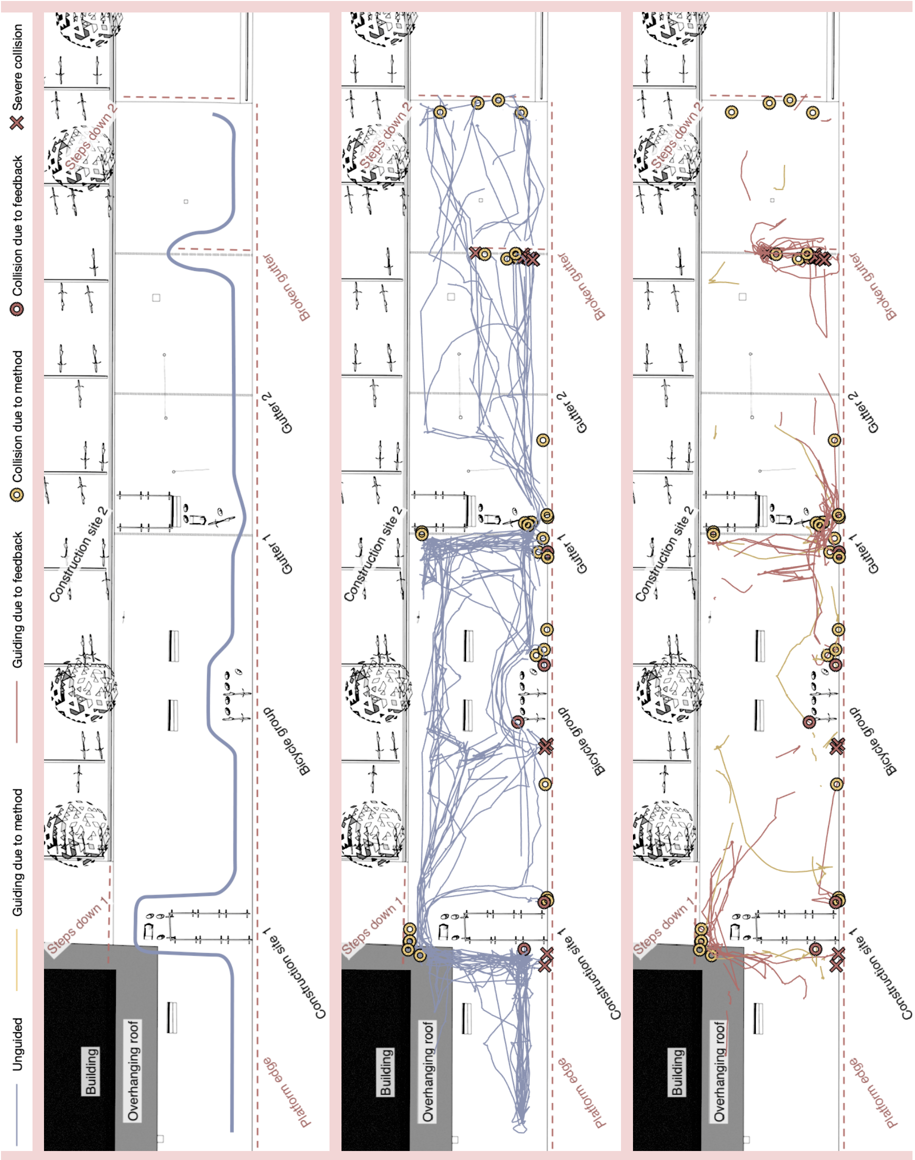

Fig. 7.11: From left to right, ideal, unguided, and guided movement traces for the first testing scene in the latest user tests. "Broken gutter", as well as at the passages "Construction site 1"–"Steps down 1" and "Platform edge"–"Construction site 2" are clearly troublesome, yet note that a few participants cleared even the latter. Figure and caption reprinted, with slight modification from [163].

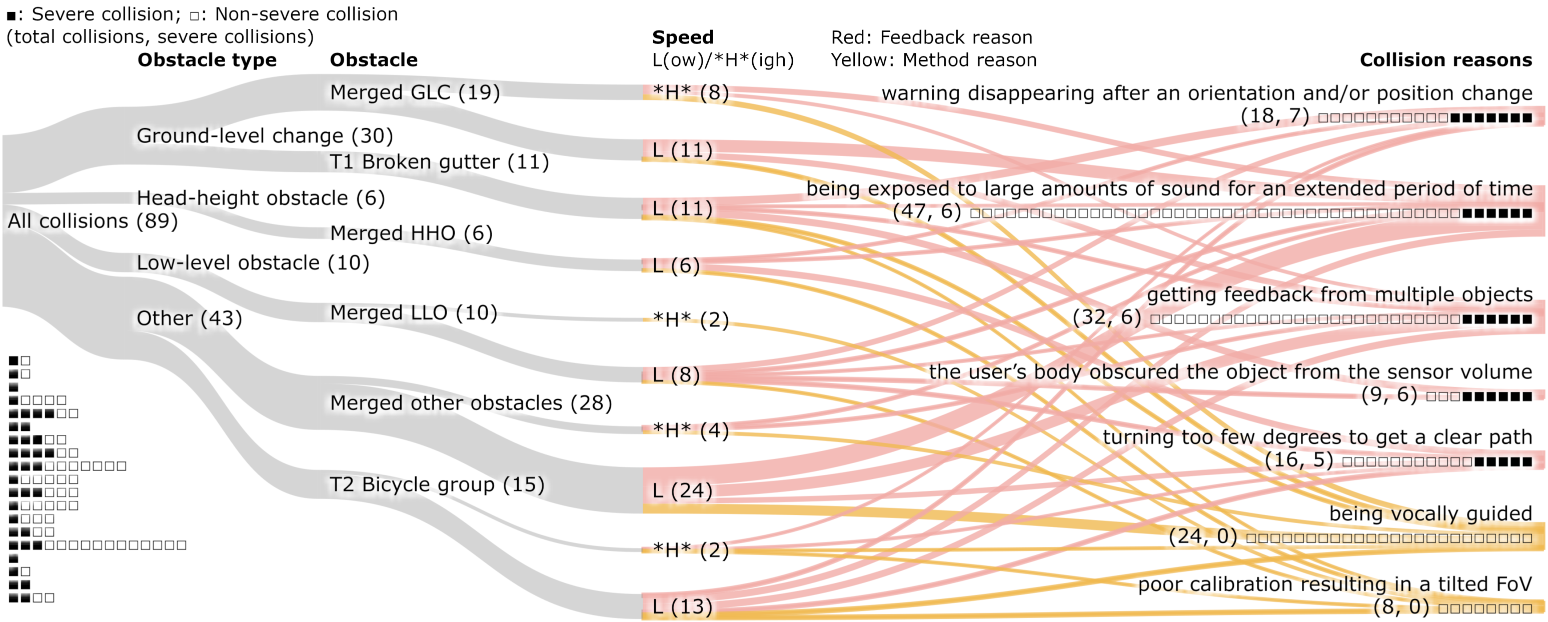

Fig. 7.12:
Condensed collisions breakdown of the latest user tests, split from the left by type, obstacle and speed; and merged into reasons to the right. These are sorted based on: 1) feedback or method; 2) severe collision amount; and 3) collision amount. A severe collision is a collision at high speed, or with a ground-level change, head-height obstacle or low-level obstacle. One collision can have multiple reasons. The most prominent reasons due to the Audomni feedback are to the top right. For clarity, all obstacles with < 3 collisions are merged, and reasons with < 8 collisions are excluded. Figure and caption reprinted, with slight modification, from [163].

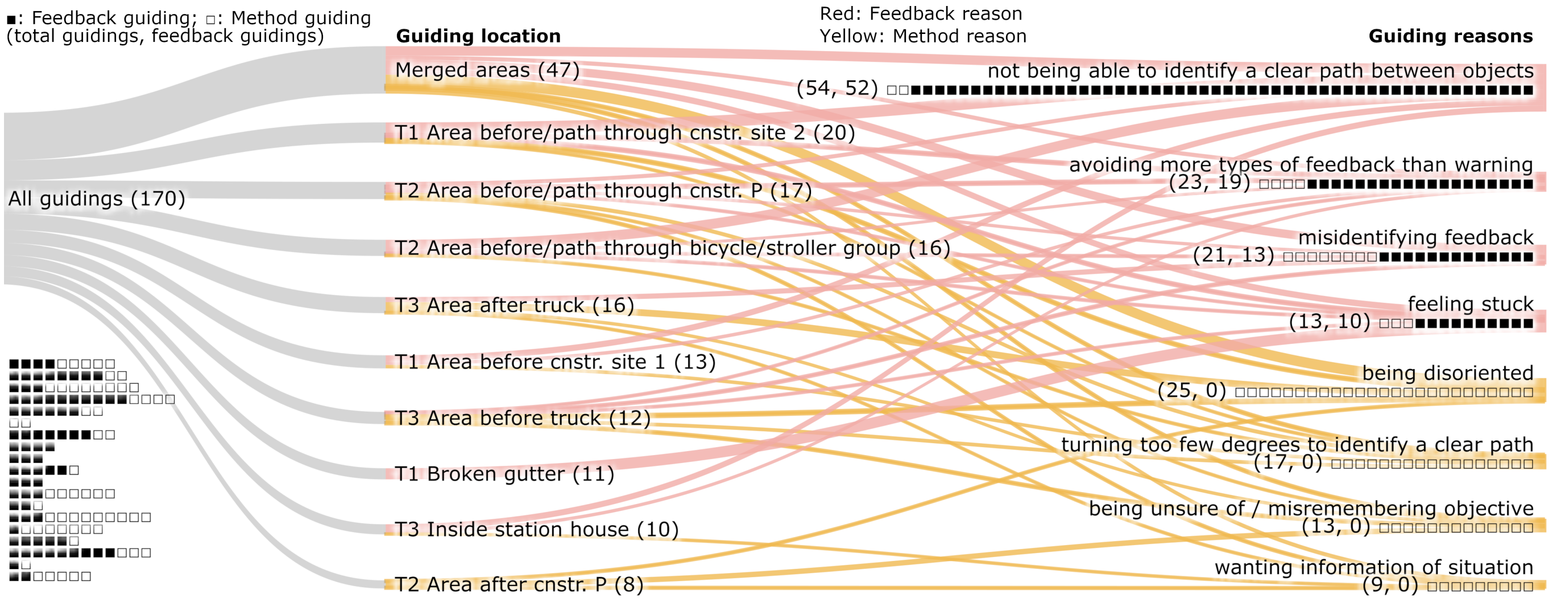

Fig. 7.13:

Condensed "guidings" breakdown of the latest user tests, split from the left by location and merged into reasons to the right. These are sorted based on: 1) feedback or method; 2) feedback guiding amount; and 3) method guiding amount. A guiding is any time, besides collisions, that a participant was intervened with. A guiding can have multiple reasons. The most prominent reasons due to the Audomni feedback are to the top right. For clarity, all locations with < 3 guidings are merged, and reasons with < 8 guidings are excluded. Figure and caption reprinted, with slight modification, from [163].

The responses to the DoUQ-MoB likewise yielded numerous results, e.g. regarding difficulty in detecting obstacles at head-height respondents' attitudes were that Audomni was significantly ($\alpha = 0.05$) easier than the cane; and the opposite was found for understanding the feedback of each device, with the median answer for Audomni being that it was *moderately difficult* to understand. However, the most striking result of the test was that 79 % of cane users, and 76 % (13 / 17) of all responders, answered that it was *very* or *extremely likely* that they would want to use the aid simultaneously with their current aid; further, of two participants that answered either *a little*, or *not at all likely*, one had previously answered that they *much rather* would use Audomni over their cane, and the other commented "I would not have them [turned] on simultaneously, but I would easily have both [dog and Audomni] with me."

Regarding the test methodology and measures, the portability of Parrot-VR enabled an adequately sized and heterogeneous set of participants from the target group, while still offering a relevant test setting. The movement analysis clearly illustrated what should be focused on next in the Audomni development. Meanwhile, DoUQ-MoB produced a considerable number of data points on how blind and low-vision participants themselves feel and think about Audomni, which both confirm the aptness of some design choices, and will help guide the design process going forward.

7.6 Future work

7.6.1 User tests III — Real-life tests

The next step is to attempt to reproduce the positive results in real-life user tests. A subgoal is to also start evaluating the physical design of prototypes, so for these tests a new, smaller, and relatively user-friendly physical prototype needs to be designed. This requires new solutions for the computing platform, battery, and sensor. The computing platform was possibly already solved when the Parrot-VR development commenced, where the comparatively bulky Jetson TX2 Developer Kit of the last physical prototype, had been replaced with the considerably smaller and more cost effective Jetson Nano Developer Kit, both of Nvidia. Also, a new battery system has been investigated, where the aim was to leverage already existing durable batteries with corresponding and user-friendly chargers. To this end, the off-the-shelf Bosch ProCORE18V battery pack and charger were chosen.

TABLE 7.4
Interview analysis and example comments of the latest user tests

Category (unique respondent–code pairs)	Code (unique respondents)	
Audomni disadvantages (36)	Mentally/physically more difficult	(12)
	Symbolic value	(8)
	Hearing gives just an idea	(8)
	Learning curve steeper/longer	(5)
	Sound is an issue	(3)
"The sounds from the aid requires concentration and listening, while you also have to listen to the environment – and I have no clue how exhausting that is." "When you have a cane and hit something, then you know that you really are that close." "The symbolic value of crossing a street and having cane in front of you cannot be beaten."		
Audomni advantages (27)	Perception volume/speed	(16)
	Physically easier	(11)
"[You] can get told a few meters before anything happens. That can be really reassuring." "The cane manages a lot, but not the entire volume I am in as an individual."		
Complement (20)	Complement	(14)
	Unprompted desire for both	(6)
"[With a cane and the aid simultaneously] I think I would manage very very well." "In practice you would need both together. That would not be twice as good, it would be three times as good."		
General interest (16)	Positive about aid in general	(11)
	Desire to skip/avoid the cane	(5)
"I see terribly good potential, and this is missing." "It would be nice to get rid of that cane, that is actually quite valuable."		
Methodology issues (22)	Familiarity	(12)
	Test procedure	(10)
"Of course [Audomni] would be worse. I do not know it." "I think that question cannot be asked unless you have run the tests in a live setting."		
Audomni suggestions (11)	Suggestions/other solutions	(11)
"If you would have a talking GPS navigation built in — that was good — then we would be in a completely different league." "[Another proposed aid] was with glasses, and a camera on the glasses which gave readings, but I could not even imagine walking like that... They were large, and there was a camera sticking out."		
Situation differences (5)	Situation differences	(5)
"Give [Audomni] an unknown environment and [it] would probably be of greater help, than if you would fumble about with the [cane]... It would be a little excessive amount of information that you would not need in a known environment."		
Dog considerations (4)	Dog comments	(4)
"You feel incredibly safe with the dog." "[Audomni] is an aid I can turn off and turn on when I need it. A dog always needs to be taken care of, and I need to walk her. Now while at work I still need to get out."		

Table reprinted from [163].

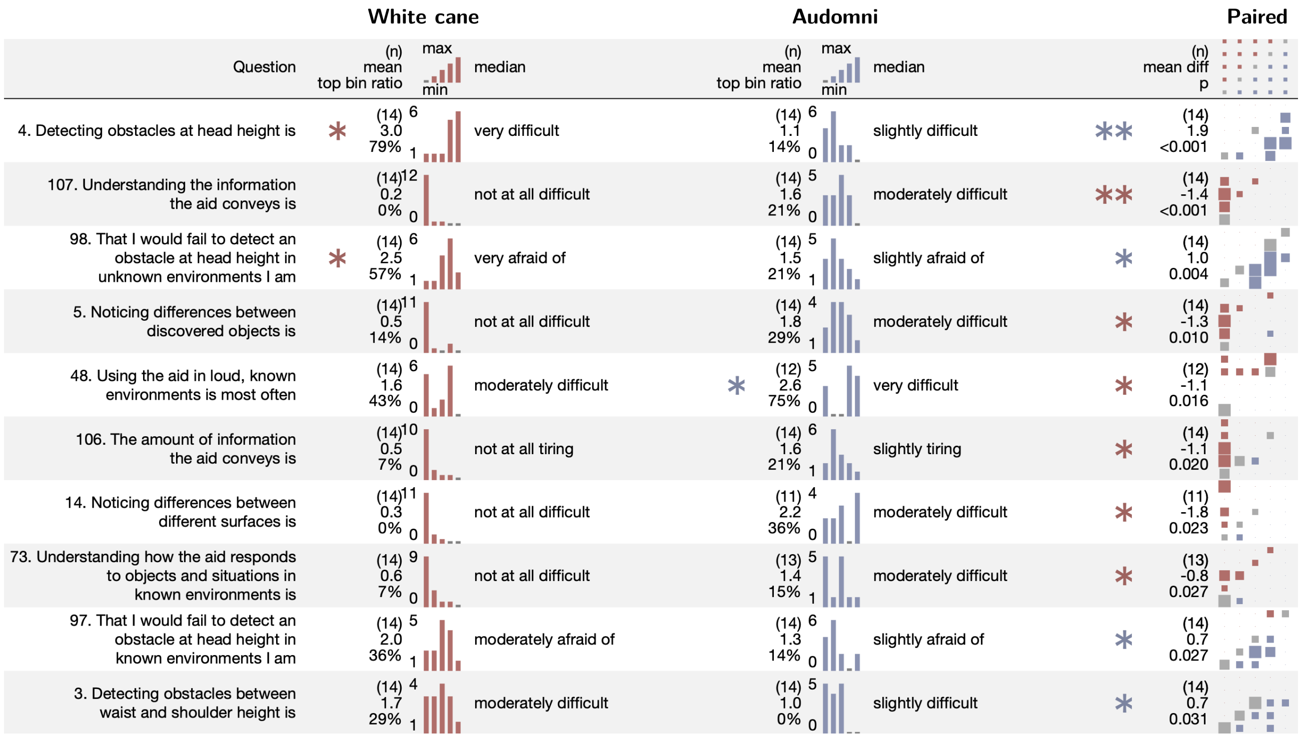

Fig. 7.14:
Results of the ten most notable paired items for cane users from the Desire of Use Questionnaire for Mobility of BLVIs, based on lowest p-value. Asterisks in the left and middle column denote a top bins ratio greater than 50 %. In the right column, a single asterisk denote significance ($\alpha = 0.05$), and two asterisks denote significance after a Holm-Bonferroni control for the family-wise error rate. Figure and caption reprinted, with slight modification, from [163].

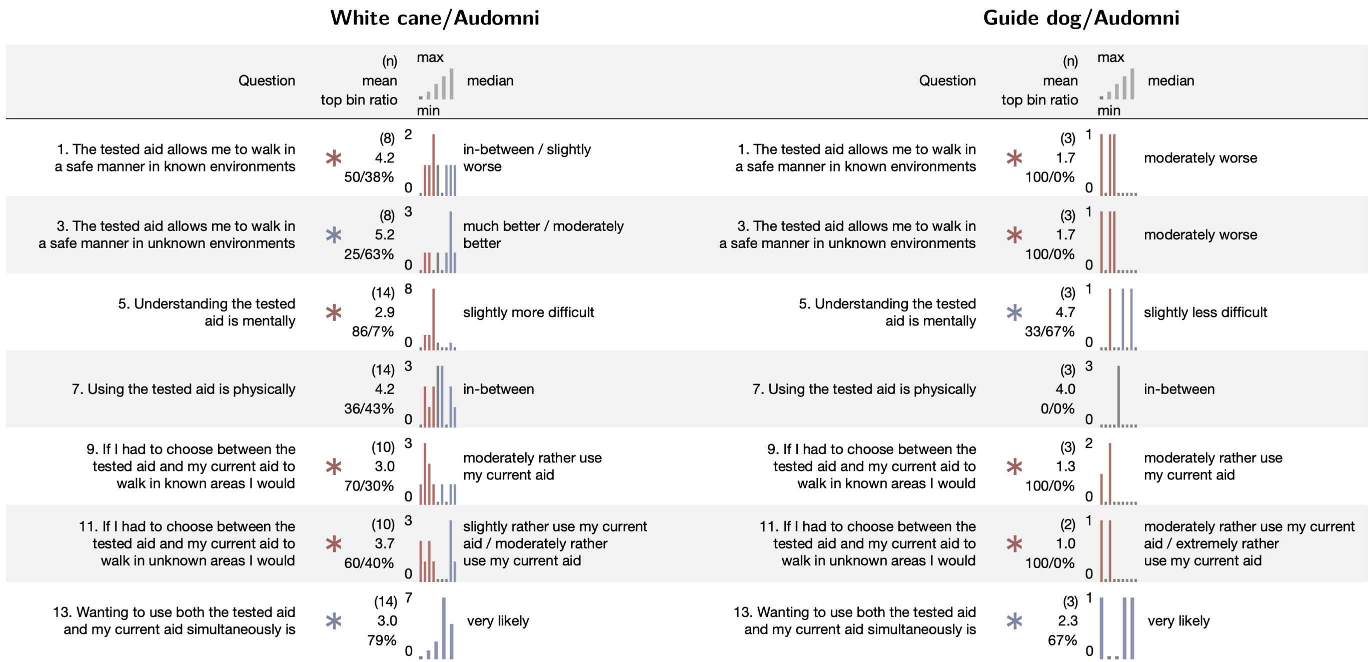

Fig. 7.15:
Comparison item results from the latest user tests of the Desire of Use Questionnaire for Mobility of BLVIs. Asterisks denote a top bins ratio greater than 50 %, and when applicable, blue and red are for Audomni or current aid advantage, respectively. The cane holds advantage for all items except for "...walk in a safe manner in unknown environments". Notable, however, is that the great majority of all respondents deem it *very* or *extremely likely* that they would want to use Audomni simultaneously with their current aid. Figure and caption reprinted, with slight modification, from [163].

Lastly, a new sensor has been implemented, with a special order of Melexis EVK75123 evaluation kits fitted with their newer ToF sensor MLX75027. A proof-of-concept system has been constructed which integrates all these parts, where the computational platform and the sensor is powered from the battery with corresponding DC-DC converters; the sensor communicates with the computational platform through a custom interface PCB; and custom drivers have been written for the computational platform to handle the sensor data.

Now, a physical design is to be produced that accommodates this solution, which should also allow for assessing physical ergonomics. Once in place, the current Audomni sonification will be tested internally to investigate if the identified issues in VR are also issues in real-life, as well as if any new potenital issues might have arisen.

When these are considered adequately solved, it is time for the next user evaluation. In order to recruit a decent number of BLVIs as participants again, as well as to provide them access to Audomni in their real environments, the tests will likely consist of the participants traversing known routes close to their homes. While this have negative impact on reproducibility, it should be compensated for with a better participant understanding how Audomni might function and feel for them, which again will be probed for using DoUQ-MoB. As these tests will be the first taking place in real urban environments, efforts will be made to ensure as a safe procedure as possible, including a single-session design again, and stress-testing the new prototype in various circumstances beforehand.

Depending on the results, the physical design, the sonification, or both might need iteration and, if substantial, more short-term tests might be needed. These could also be interleaved with sequential single-session testing to investigate potential learning effects of the prototype.

As starting points of various aspects that might become relevant in the future development, I have also supervised three Bachelor's theses, and a project in a Master's level project-course, for works that could solve potential issues with the sensor technology [213], aid in VR testing [214], and help in the overall design of the aid [215, 216].

7.6.2 User tests IV — Long-term tests

Ultimately, once short-term user tests with BLVIs have shown apt safety, as well as promising functionality and ergonomics, long-term tests should ensue. A discussion regarding these is given in Chapter 6. If these do not show an increased mobility of the participants, further iterations on either physical design, sonification, or both, lies ahead; otherwise, if they do show increased mobility, Audomni should likely be developed into an end-product.

7.6.3 Additional remarks

While Audomni so far strictly has been developed and evaluated with the sensor being head-mounted, eventually the sensor should allow for various configurations, e.g. glasses-mounted, worn on the body, or cane-mounted, in order to accommodate various user preferences. Along these lines, while the ambition for Audomni is that it can suffice as a primary mobility aid by itself, it is recognized that many likely will still want to use or bring their current aid (or just bring Audomni), due to familiarity, extra safety, or for the symbolic value provided by the guide dog and, especially, the white cane. On the other hand, many desperately want to avoid the cane for its symbolic value due to perceived stigma. Thus Audomni should be designed to be useful both by itself, and in conjunction with other primary mobility aids.

7.7 Summary

Audomni is a visuo-auditory SSD developed toward a primary mobility aid for BLVIs. DoU is leveraged in both its design and evaluation to keep them user-centered, and maximize the likelihood of achieving an end-product with functionality that helps the users, and ergonomics so that users wants to use it. In the latest user tests, 76 % of responders (13 / 17) said that it was *very* or *extremely likely* that they would want to use it along with their current aid. This might be the first result of a majority of blind and low-vision participants claiming that they actually want to use a new ETA. The overarching project aim is to reach long-term tests which can show an increase in the mobility of blind and low-vision users, as this would indicate that Audomni can and should take steps toward an end-product.

Chapter 8

Summary of included papers

This chapter provides brief summaries of the papers this thesis primarily is built upon. Papers I and II are published articles, and Papers III and IV are manuscripts to be published.

The first two papers were worked on in parallel; indeed, at first a single manuscript accounted for the historical background of the field, the shortcomings of it, the design and development of DoU, the functional method and physical design of Audomni in 2018, as well as the pilot tests. As DoU could and arguably should stand on its own (and somewhat due to the substantial length of it) the manuscript was split into Papers I and II. Here, the former represents the theoretical frameworks of, and the motivation for, the latter. Paper II thus needed Paper I, and Paper I benefitted from a work that already utilized its results, and so they were aimed at being published together — in the same number of the same journal.

This process was roughly repeated for Papers III and IV, which also were part of the same manuscript initially (along with Chapter 6), which reported on the motivation and background of DoUQ-MoB and Parrot-VR, as well as the latest user tests. Since the tools could and arguably should stand on their own (and somewhat due to the substantial length of it) this work was also split into two. Again, Paper IV needed the background provided by Paper III, whereas Paper III benefits from that the tools already has seen successful deployment. The aim is once more to publish them simultaneously in the same journal.

Paper I — Desire of Use: A Hierarchical Decomposition of Activities and Its Application on Mobility of Blind and Low-Vision Individuals

Paper I gives an introduction to why new ETAs need to be strived for and gives a brief account of the history of ETAs. It then argues that the lack of an adequate ETA is largely due to various shortcomings of design and evaluation in the field, and that by adopting a design model focused on mobility of BLVIs, these might be overcome. Since seemingly no existing model was sufficiently fitting, as it main results it introduces the generalizable DoU model, as well as the application of it to the current objective in form of the DoU-MoB.

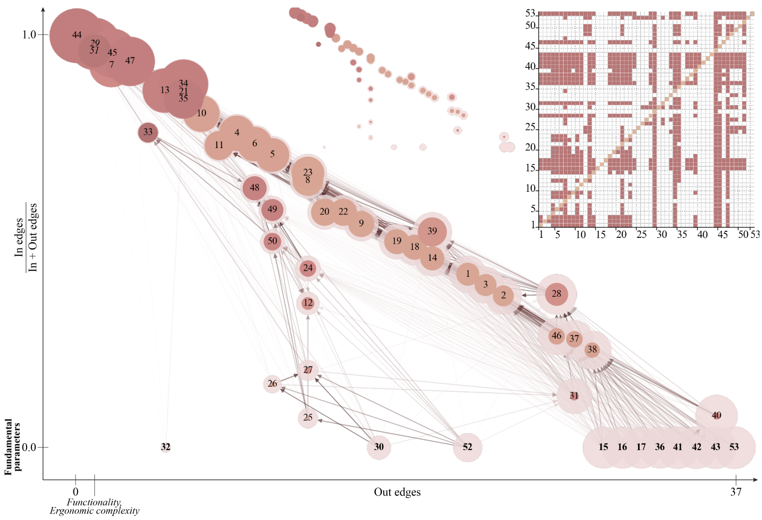

Fig. 8.1: Hieararchical decomposition of the aspects of Desire of Use applied on blind and low-vision mobility, as done in Paper I. Figure reprinted, with permission, from [105], © 2020 IEEE.

Paper II — Audomni: Super Scale Sensory Supplementation to Increase the Mobility of Blind and Low-Vision Individuals — A Pilot Study

Paper II introduces the Audomni system, as it was in 2018, giving a detailed description of the physical design and functional method of the prototype. It also outlines the current state of methods and measures of the field, and in what ways they might be lacking. The paper then gives a report on a pilot test performed with two BLVIs to evaluate the prototype, and assesses it in terms of DoU-MoB. The results show substantial issues in the proposed test method, underlining the need of well-motivated test procedures that also afford a high amount of learning; as well as some potential issues in Audomni. However, the results also show some promise in Audomni as an ETA, since two BLVIs with little training could use it to carry out some important mobility subtasks.

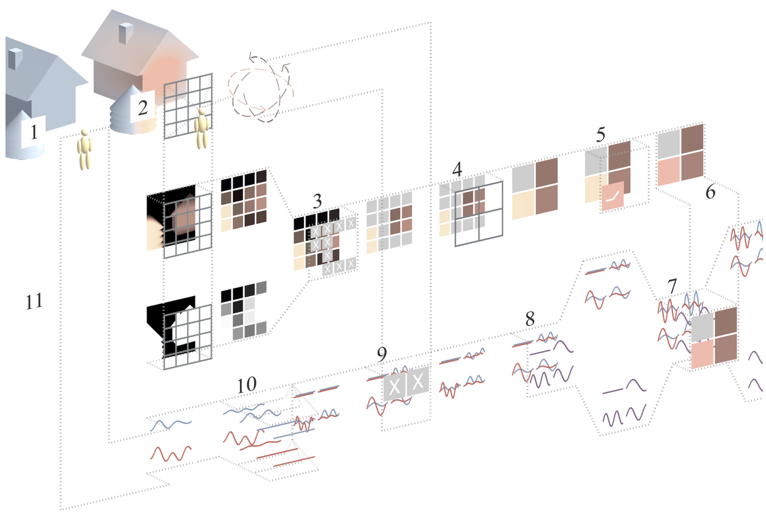

Fig. 8.2: Sonification scheme of Audomni as in 2018, described in Paper II. Figure reprinted, with permission, from [174], © 2020 IEEE.

Paper III — Assessing Mobility of Blind and Low-Vision Individuals through a Portable Virtual Reality System and a Comprehensive Questionnaire

Paper III spring from the discussions regarding the shortcomings of the field of Paper I and II, and in an attempt to mitigate some of them, it introduces the Parrot-VR system and the DoUQ-MoB questionnaire, which are the main results of the work. For Parrot-VR, it provides the reasoning for a portable VR system, previous VR systems used for ETA evaluation, as well as a detailed presentation of Parrot-VR, including its design choices and its function. For DoUQ-MoB, it gives account of other PROMs in the field, best known survey design practice, as well as the development process, validation, and design choices of the questionnaire.

Fig. 8.3: Test setup of the Parrot-VR system introduced in Paper III. Figure reprinted from [121].

Paper IV — Using Portable Virtual Reality to Assess Mobility of Blind and Low-Vision Individuals with the Audomni Sensory Supplementation Feedback

Paper IV reports the latest user tests performed to evaluate Audomni. These were performed with 19 BLVIs, and utilized both the DoUQ-MoB questionnaire and Parrot-VR system from Paper III for testing and evaluating the current sonification scheme, as well as the proposed test methodology. Parrot-VR was found to facilitate both the recruitment of participants from the target group due to its portability, and an aggregate movement analysis of the participants. DoUQ-MoB granted numerous results regarding Audomni, and in relation to current aids, according to what potential end-users think. While there were plentiful results from both the movement analysis and the DoUQ-MoB, the most noteworthy is that a majority claimed that it was very or extremely likely that they would want to use Audomni along with their current aid — which might be the first result in the field showing that a majority of blind and low-vision participants want to use an aid.

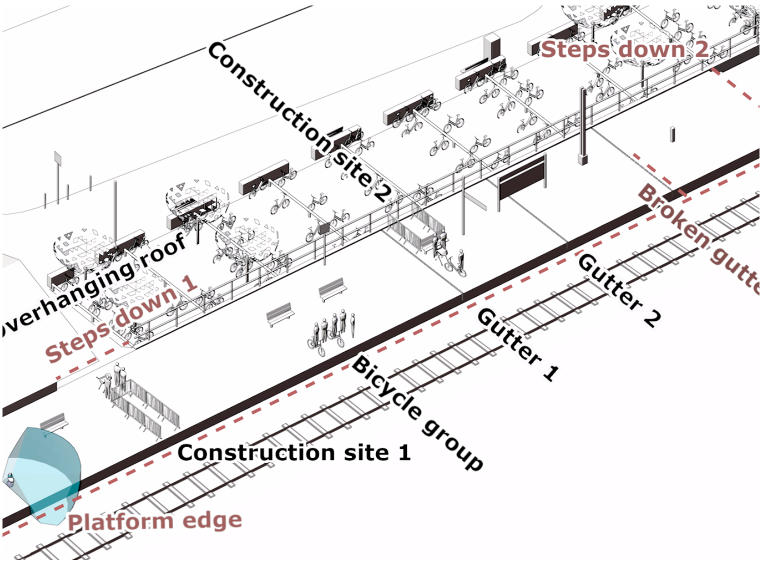

Fig. 8.4: Virtual environment from the user tests of Paper IV. Figure reprinted from [163].

Chapter 9
Final statement

To conclude this thesis, its aims as outlined in Chapter 1 have plausibly been reached. Why a widely adopted ETA, that significantly increase the mobility of blind and low-vision users, is yet to emerge has much to do with the shortcomings of the field, as discussed in Chapters 1 and 6, as well as in Papers I and II. To mitigate the shortcomings, the three tools of the DoU-MoB design model, the DoUQ-MoB questionnaire, and the Parrot-VR system, have been presented in Chapters 3–5, and are introduced in detail in Papers I and III; also an initial study has been performed with potential long-term outcome measures in Chapter 6. Finally, the design and evaluation of the Audomni ETA, utilizing the DoU-MoB, the DoUQ-MoB, the Parrot-VR, and with plans for long-term studies, have been presented in Chapter 7, and also thoroughly in Papers II and IV.

I argue that by leveraging the tools and methods presented in this thesis, the chances of achieving an ETA fulfilling both a high enough functionality increase, and a low enough ergonomic complexity, are considerably improved. The Audomni project adheres to this view, and at this time there is reason to believe that almost complete novices can use its feedback to perform many important subtasks of mobility, and that the great majority of BLVIs that have tried it actually want to use it. This shows promise of Audomni to eventually become the sought-after ETA, an aid that would reduce societal cost and burden on family and friends — and for users, increase their independence and quality of life.

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Acronyms and Abbreviations

ADL	Activities of Daily Life
ADL-I	Activities of Daily Life-Interview
BLVI	Blind or Low-Vision Individual
COPM	Canadian Occupational Performance Measure
DoU	Desire of Use
DoU-MoB	Desire of Use for Mobility of Blind and low-vision individuals
DoUQ-MoB	Desire of Use Questionnaire for Mobility of Blind or low-vision individuals
ETA	Electronic Travel Aid
FoV	Field-of-View
ICF	International Classification of Functioning, Disability and Health
IMU	Inertial Measurement Unit
IMQ	Independent Mobility Questionnaire
O&M	Orientation and Mobility [of blind and low-vision individuals]
OMO	Orientation and Mobility Outcomes
PROM	Patient-Reported Outcome Measure
SKRS	Svenskt Kvalitetsregister för Rehabilitering vid Synnedsättning. [Swedish quality register for rehabilitation when visually impaired]
SSD	Sensory Substitution / Supplementation Device
ToF	Time-of-Flight
VE	Virtual Environment
VR	Virtual Reality
WHO	World Health Organization