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Empathetic computing for inclusive application design

Kenny CHOO TSU WEI
Singapore Management University, kenny.choo.2012@phdis.smu.edu.sg

EMPATHETIC COMPUTING FOR INCLUSIVE APPLICATION DESIGN

KENNY CHOO TSU WEI

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Empathetic Computing for Inclusive Application Design

by

Kenny CHOO Tsu Wei

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Dissertation Committee:

Rajesh Krishna BALAN (Supervisor / Chair)
Associate Professor of Information Systems
Singapore Management University

Youngki LEE (Co-supervisor)
Assistant Professor of Information Systems
Singapore Management University
(15 Mar 2013 to 15 Aug 2018)
Assistant Professor of Computer Science and Engineering
Seoul National University
(From Sep 2018 onwards)

Archan MISRA
Professor of Information Systems
Singapore Management University

JeongGil KO
Assistant Professor of Software and Computer Engineering
Ajou University

Singapore Management University

2018

I hereby declare that this PhD dissertation is my original work
and it has been written by me in its entirety.
I have duly acknowledged all the sources of information
which have been used in this dissertation.

This PhD dissertation has also not been submitted for any degree
in any university previously.

Kenny Choo Tsu Wei

05 Dec 2018

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Abstract

The explosive growth of the ecosystem of personal and ambient computing devices coupled with the proliferation of high-speed connectivity has enabled extremely powerful and varied mobile computing applications that are used everywhere. While such applications have tremendous potential to improve the lives of impaired users, most mobile applications have *impoverished designs to be inclusive–lacking support for users with specific disabilities*. Mobile app designers today have *inadequate support to design existing classes of apps to support users with specific disabilities, and more so, lack the support to design apps that specifically target these users*. One way to resolve this is to use an empathetic computing system to let designer-developers step into the shoes of impaired users and experience the impairment while evaluating the designs of mobile apps.

A key challenge to enable this is in supporting real-time naturalistic interactions in an interaction environment that maintains consistency between the user's tactile, visual and proprioceptive perceptions with no perceivable discontinuity. This has to be performed within the context of an immersive virtual environment, which allows control of any visual or auditory artefacts to simulate impairments. To achieve this, substantial considerations of the interaction experience and coordination between the various system components are required.

We designed Empath-D, an augmented virtuality system that addresses this challenge. I show in this dissertation that through the use of naturalistic interaction in augmented virtuality, the immersive simulation of impairments can better support identifying and fixing impairment specific problems in the design of mobile applications.

The dissertation was validated in the following way. I first demonstrate that the concept of immersive evaluation results in lower mental demands for designers in a design study. I then show that Empath-D despite the latencies introduced through creating the augmented virtuality, is usable, and has interaction performance closely matching physical interaction that is sufficient for most application uses, except where rapid interaction is required, such as in games. Next, I show that Empath-D is capable of simulating impairments such as to produce similar interaction performance. Finally, in an extensive user study, I demonstrate that Empath-D is able to identify more usability problems for specific impairments than with state of the art tools.

This thesis, to the best of my knowledge, is the first of its kind work to i) design and examine an augmented virtuality interface that supports naturalistic interaction with a mobile device, and ii) examine the impact of immersive simulations of impairments in evaluating the designs of mobile applications for accessibility.

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Chapter 1

Introduction

The explosive growth of the ecosystem of personal and ambient computing devices coupled with the proliferation of high-speed connectivity has enabled extremely powerful and varied mobile computing applications that are used everywhere. We now constantly interact with our personal devices and computing-enhanced ambient objects (such as televisions, washing machines, and digital directories), while engaging in everyday activities such as commuting, shopping or exercising. Given the ubiquity of such interactions, it is important to ensure that the associated computing interfaces are accessible.

From a different perspective, developers today use powerful APIs both locally and through the cloud–without needing extensive backgrounds in the subject matter–to provide access to speech recognition, natural language understanding, face recognition, emotion recognition, simultaneous localisation and mapping (SLAM) for augmented reality through the myriad applications on the smartphone. While such applications have tremendous potential to improve the lives of users–especially users with disabilities–today, *most mobile applications have impoverished designs towards inclusiveness—they lack support for users with specific disabilities*. Mobile app designers today have *inadequate support to design existing classes of apps to support users with specific disabilities*, and more so, *lack the support to design apps that specifically target these users* [107, 134, 144].

This dissertation explores the use of naturalistic interaction in an augmented virtuality and the simulation of impairments to support *evaluation* in the design of mobile applications for users with impairments. This dissertation discusses the design of naturalistic interactions and its relationship with augmented virtuality supported through a tight consistency between the user's tactile, visual, and proprioceptive perceptions with no perceivable discontinuity in the system.

Designer-developers today rely on design guidelines, and the accessibility frameworks that are provided by Android and iOS to develop applications that support *general accessibility* [4, 31]. Unfortunately, this is problematic for impaired users, because the nature of guidelines are that they exist on a higher level of abstraction in order to target a wider group of users and tailor less to the characteristics of specific impairments. This also leads to a disconnect between designer-developers and impaired app users. Without being able to empathise with the target impaired users, applications can only be created to support common functionality such as social networking or productivity. We miss out on a whole class of applications that may support specific users with impairments.

One possible way to resolve this is to let designer-developers step into the shoes of impaired users through the use of *empathetic computing*. While affective (sometimes empathic) computing uses sensor rich systems to understand, process and simulate human states (e.g., happiness, anger) in order to share these states–the use of computing systems to share the *perspectives* of others and engender empathy is termed *empathetic computing*.

To be able to experience the perspectives of impaired users is a complex problem with many different parts. The addition of mobile contexts further complicates this problem. For example, impairments are diverse in type and presentation and the representativeness of impairments for groups of users is difficult, and may vary in different contexts. In this dissertation, I discuss one possible implementation of empathetic computing. I focus on the key challenge of supporting *naturalistic interaction* using a mobile device while under immersive simulation of visual impairments so as to improve on the evaluation aspects of inclusive mobile application design.

In the rest of this chapter, I first motivate the thesis by describing the different dimensions to mobile app design and disability. Next, I describe my vision of Empath-D: how it is meant to be used in design, how it should theoretically function, and the challenges towards fulfilling this vision. I then provide an overview of my thesis. I describe the research questions, the statement, and the steps to validate it. Lastly, I provide an organising overview of this dissertation.

1.1 Motivation

The following subsections discuss the different considerations that motivate this thesis. I first explore the rationale for supporting mobile app designs. Next, I describe the definitions of disability, and how the different elements relate to design in the context of this dissertation. Finally, I describe the different facets to the problem of designing mobile applications for users with disabilities.

1.1.1 Why Support Mobile App Design?

Smartphones are increasingly used in everyday life, and have both ever *more powerful sensing and computational capabilities* and *faster network connectivity*. With smartphones being the ever present device on a user, they are well positioned to have the greatest potential to impact users–more so for users with disabilities than normal users.

Global smartphone penetration today is approximately 34.7%, and is poised to grow to 40% by 2021 [57]. The same pattern of growth is seen in different regions of the world. Today's smartphone penetration by region shows North America at 66.5%, Latin America at 43.2%, Asia Pacific at 34.9%, and Middle East & Africa at 14.8%. Even in developing countries such as Nigeria and Ethiopia, smartphone penetration as of Sep 2018 is at 13% and 11.2% [62].

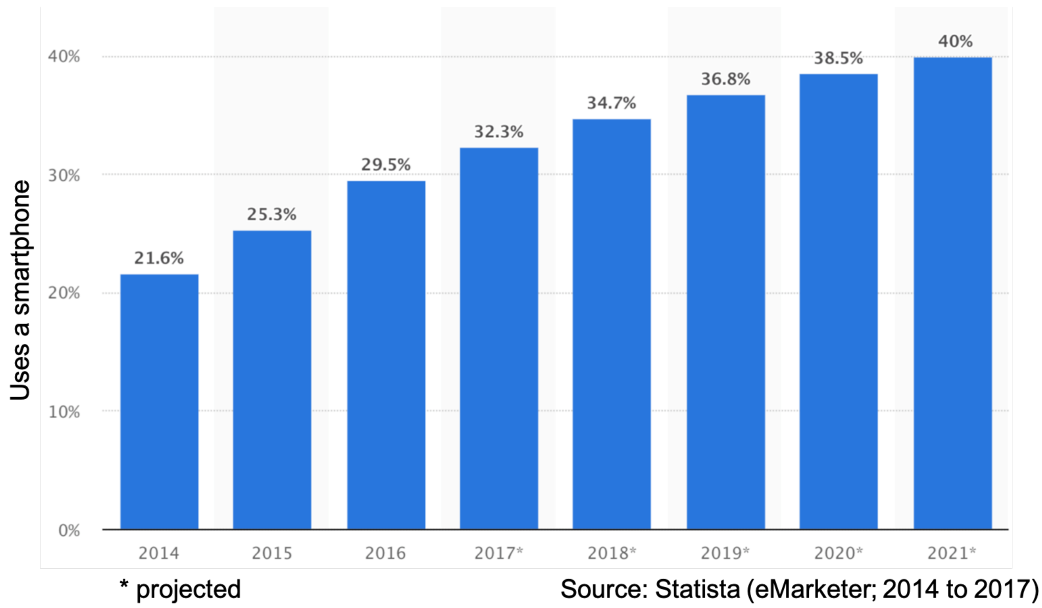

Figure 1.1: Actual and projected growth of worldwide smartphone penetration.

The World Health Organisation (WHO) using 2004 data, estimates that some 15.3% (978 million) of the world population were afflicted with moderate to severe disability. In 2010, there were approximately 18.7% (56.7 million) in the US [87] and 17.6% (aged 15 and above; 70 million) in Europe [75] with a disability. This gives us a lower bound of approximately 340 million moderate to severe disability users globally, who may benefit from better app designs–*designs that account for specific impairments* (redesign), and better, apps that are developed for the disability (innovation).

1.1.2 Disability and Design

Disability, refers to difficulties encountered in human functioning: (1) *body functions and structures* (i.e., *impairment*), (2) *activity limitations* (e.g., walking, eating), and (3) *participation restrictions*, and their interaction with environmental and personal contexts [30, 74] (see Figure 1.2). Incorporating these factors is key to designing for disability.

Consider this in the context of an elderly user who has **primary open-angle glaucoma** (one of the main forms of glaucoma; all subsequent references of glau-

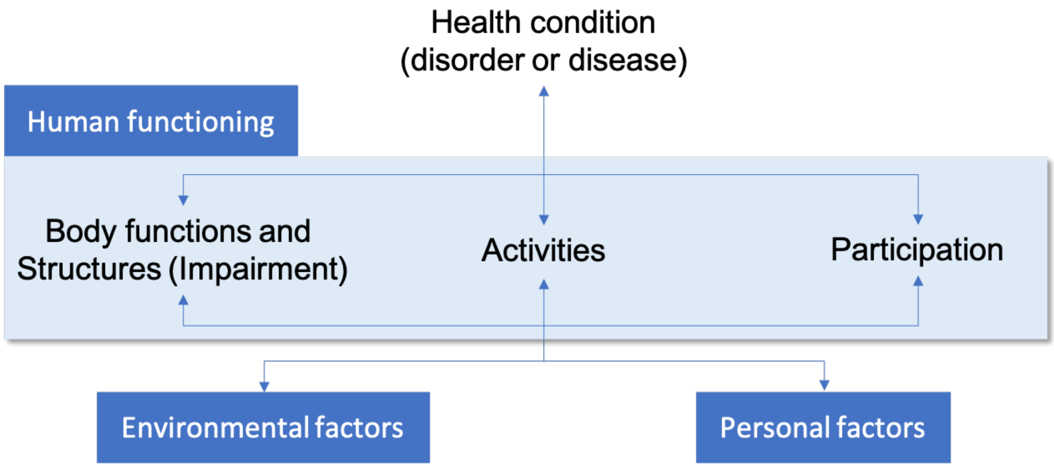

Figure 1.2: Representation of the International Classification of Functioning, Disability and Health. *Adapted from [74]*

coma mean this form), and also suffers from **cataracts**:

Impairment: Glaucoma is a disease that damages the eye's optic nerve can occur in one or both eyes. It primarily presents itself as gradual loss of peripheral vision, until no vision remains [76]. Glacuoma can have varying presentations, which may also include nerve damage on the areas of central vision (see Figure 1.3). Cataracts is mainly an age related disease, presenting as a general loss of visual acuity.

Normal Vision | Glaucoma | Glaucoma–with damage in central vision

Figure 1.3: Images showing the differences between presentations of glaucoma. (L-R) Normal vision, glaucoma with loss in peripheral vision, and glaucoma with both peripheral and central vision loss

Activities and the Environment: How would this user *navigate on the streets*? An informed guess, would be that the user is likely to only be able to navigate with much difficulty. With reduced peripheral vision, users may slow their pace of walking, scan his surroundings more often in order to acquire the same visual field as a normal user. With reduced visual acuity, the user will likely have to walk closer to signage in order to read text. In a *crowded setting*, the user is likely to bump into people more often. In the *night*, the *lights from street lamps* or *cars* are likely to cause discomfort to the user due to the glare.

I have described an archetype of disability over the aspects of impairment, activities, and the environment. While participation and personal factors are also important to disability, this thesis is only concerned with the aspects that may be generalised to support design. How might mobile applications be designed to address these impairments? I examine the different approaches to support such impairments and activities, for mobile application design in the next section.

1.1.3 The Need for Mobile Application Design Support Tools

1.1.3.1 Design guidelines: General Accessibility vs Specific Impairments

Despite greater awareness and research efforts in accessibility, design guidelines remain the primary means by which designers design for accessibility [4, 31, 79, 92]. Design guidelines are often general, and are not directly linked to their specific or grouped end-user impairment pathologies [144]. This is by design. By abstracting at a functional level, it maximises the coverage of accessibility problems. For example, the WCAG 2.0 guideline *1.4.1 Use of Colour* states that *"Colour is not used as the only visual means of conveying information, indicating an action, prompting a response, or distinguishing a visual element* [92]. The committed reader may, delve deeper into this resource, and note that it states some of the specific benefits of *1.4.1* that allude to the **impairment** faced. Two of the example benefits are given below:

- Some **older users may not be able to see colour well**.
- Users who have **colour-blindness** benefit when information conveyed by colour is available in other visual ways.

The choice of how to address this is left up to the designer and his interpretation. Common methods at this level of generality are to utilise redundant coding (e.g., adding text to indicate the colour), or to adopt patterns instead of colours to differentiate colours.

A well-informed designer who is trying to design applications *specifically for colour blind users* may adopt a different approach to this problem. Rather than adopt the approaches (e.g., redundant coding) above, she may instead allow the user to choose his *form* and *severity* of colour blindness either through interface options, or known tests (e.g., using an Ishihara test [126]). This calibration may allow for more suitable colour schemes that may be applied consistently throughout the application.

1.1.3.2 Tools for accessibility checking

There are myriad accessibility checking tools available for web content, all of which take reference from the WCAG [92]. Automated accessibility checking tools such as aChecker [113], WAVE [68], and DynoMapper [13] have been developed to ensure designs meet these guidelines. These tools check for compliance with WCAG guidelines, which are grouped into A, AA, or AAA with more As indicating a higher level of requirement and encompassing the requirement before it (e.g., AA compliance satisfies both A and AA compliance). However, this can lull designers into a false sense that they have catered to their desired end-users, since it is entirely possible to design a *compliant* web page that is hard to use, or has bad aesthetics [150, 154]. As they are based on the accessibility guidelines such as the WCAG, they suffer similarly from the previously described problem of targeting general accessibility.

1.1.3.3 The Developer-Designer

The typical developer-designer (henceforth referred to simply as designers) in the mobile app development industry is young, averaging 33 years old. They are mainly independent developers (47%) or work in small teams (33% in teams of 2–5) [78], with limited resources–necessitating the take up of multiple roles in app development, including design. They design and develop applications for broad appeal (41% of developed games, and 32% developed entertainment apps) [78], which often ignore being inclusive [152].

1.1.3.4 Safely testing mobile apps that are used everywhere

Mobile apps are used everywhere, and in many different contexts. They differ from desktop computing, which is generally used in the safe confines of office settings. Mobile app users often encounter problems with dividing attention between safely navigating their environment, and using their phones [119,143]. The problems faced by impaired users in the mobile setting are even more pronounced. The designer thus faces the problem of safely and ethically testing a mobile app with end-users– particularly if it is an early prototype and may not support its full functionality that may help mitigate some of the issues.

1.1.3.5 Access and consistency of impaired users

To compound the issue of safe testing above, impaired users are extremely hard to recruit and sustain [173]. Impairments are diverse in nature, even within the same type of impairment. This exponentially increases the difficulty of recruiting such users. One either implements a strict selection criteria (resulting in few participants), or accept the diversity that is presented in the participant pool and make concessions about that outcomes of usability testing. While the latter is more "realistic", it is also difficult to draw conclusions if the sample is representative of that demographic [144, 156]. This narrow set of users, consequently renders user testing more sensitive to dropouts since replacements are hard to find as compared to unimpaired user testing.

1.2 The Empath-D Vision

To address the above problems identified in the previous chapter, I propose an empathetic computing solution, Empath-D. The key to Empath-D lies in supporting naturalistic interactions in an immersive environment that maintains consistency between the user's tactile, visual and proprioceptive perceptions with no perceivable discontinuity. This has to be performed within the context of a an immersive virtual environment, which allows for control of any visual or auditory artefacts to support the simulation of impairments. To support this, Empath-D is an augmented virtuality solution, where the real-time intermeshing of real (such as one's fingers which are normally not visible in virtual environments) and virtual artefacts helps to maintain the perceptual consistency. To achieve this, substantial coordination between the various system components are required.

Empath-D is able to support naturalistic interactions in the augmented virtuality to support better performance in identifying and fixing impairment specific problems in the design of mobile applications.

The following subsections describe my vision for how Empath-D will be employed to help with fast immersive evaluations of designs.

1.2.1 Fast Immersive Evaluations in a Modified Iterative Design Process

Empath-D supports *fast immersive evaluations* of prototypes, supporting mini design-prototype-evaluate cycles in standard iterative design cycles (See Figure 1.4). Immersive evaluations allow designers to experience the problems that their target users experience.

There are two distinct advantages to this. First, the designer can rapidly create multiple "good-enough" prototypes without having to involve actual impaired users in the design cycle. This is especially important given the limited access that app designers may have with impaired users. Second, even with access to impaired

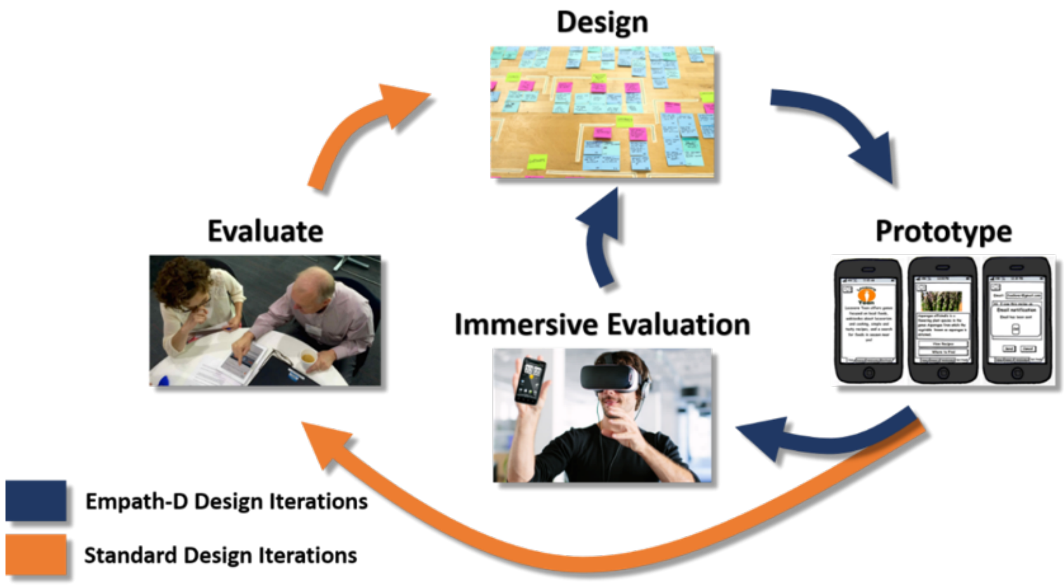

Figure 1.4: Iterative Design Cycles in Empath-D

users, a designer may not be able to fully understand the disability of impaired users. As discussed previously in Section 1.1.2, disability requires context. It is also unlikely that the designer may consistently and repeatedly subject impaired users to the contexts of use or have access to them. Empath-D allows designers to directly experience the disabilities in their environmental contexts. With greater research in this area, impairment profiles representing certain demographics may be generated and ensure that designers are testing with a representative set of impairments.

It is key to note here that **Empath-D is not meant to supplant testing with actual impaired users**, but rather aims to support the *creative and usability evaluation processes in app development*.

1.2.2 Motivating Scenarios

The following scenarios showcase my vision for Empath-D.

Scenario 1: Designing for Visual Impairment. Alice is a young mobile app developer who is trying to innovate on mobile applications that may help improve the quality of life for users who suffer from cataracts. With her initial background search on this condition, she notes that a primary visual impairment pathology in cataracts is reduced visual acuity. To understand this problem, Alice starts Empath-D, and is presented with a web interface that allows her to choose impairment profiles. She picks out a profile for users with cataracts, and customises the impairments to reflect age group, severity, and other aspects she is designing for. She then selects a realistic pre-built street environment setting and customises the environment such that there are cars and people moving around.

Alice clicks in the Empath-D web interface to compile the environment to the VR display. She then explores the virtual environment and immediately notices that it is near impossible to make out text such as that on street signs without being extremely near. Alice surmises that people afflicted with cataracts often find it annoying to have walk up to street signs only to realise they had gone the wrong way. She comes up with an initial prototype of the application that utilises digital zooming on a video stream from the camera to magnify all content. She connects the application binaries (e.g., Android apk) and a physical phone with Empath-D and starts Empath-D once again. She then experiences the environment, with a virtual phone showing up in the virtual environment that tracks the real-world motion of the physical phone. Empath-D mapped the physical camera to the virtual camera, allowing her to use the same digital zooming features in the virtual environment.

To test her app's zooming feature, she hold up her phone and interacts to zoom in and attempts to read the road signs and other text content in the world around her. She quickly realises that while zooming in on content helped with reading text, the mobile app obscures her view, which results in the inability to maintain awareness of her surroundings such as cars or pedestrians (see Figure 1.5).

Alice redesigns her application to be an augmented reality application that only extracts and magnifies text that can be seen through the images from the camera. With the magnified text only partially obscuring the top of the phone screen, and the rest being non-magnified environmental content, Alice is satisfied that she has come up with a satisfactory design. She then continues to iteratively and rapidly modify her designs using Empath-D until she is satisfied that it is ready to test with

Figure 1.5: A design flaw identified through Empath-D: Reduced peripheral awareness due to the phone obscuring VR display view

cataract impaired users. Finally she tests the app with impaired users.

Scenario 2: Designing for Motor Impairment. Bob is designing a mobile application for users with Parkinson's disease, which causes tremors in the hand. He configures the impairment model in Empath-D for Parkinson's and straps on electromyographic sensor bands (e.g., *Myo* [41]) on both arms. Bob then interacts with the application prototype in Empath-D's immersive reality environment–which simulates the home environment where the app is meant to run. Empath-D presents Bob with a first-person perspective situating him as an avatar in the virtual environment and creates a virtualised phone (running Bobs app) that is placed in the simulated home environment. Empath-D modifies the sensor and touch inputs of the sensor bands and the output of Bob's virtual representation of his limbs to produce a jittered output that accurately simulates hand motion with tremors. Bob notices that the apps buttons are not large enough for him to press accurately and adjusts his design.

Scenario 3: Designing for Auditory Impairment Eve is designing a lifestyle application that helps users with high frequency hearing loss (HFHL) enjoy movies. Users with HFHL often have a hard time following conversations when multiple people speak at a time. Using Empath-D, Eve is able to test her movie audio refinement application in an immersive environment where a movie is being played to a user sitting about ten meters away. The audio output from the speakers simulate the sound heard by a HFHL sufferer at a distance of ten meters. Eve realises that her application produces uneven volume levels due to possible errors in her logic for modifying the power levels of specific audio frequencies. The immersive environment helps to clearly identify the portions of the audio track that are not audible enough; giving her enough data to modify her frequency compensation logic.

Each of these scenarios focuses on a single modality of impairment. With Empath-D, I envision scenarios where multiple impairments are combined and tested together. This highlights the true power of Empath-D as it is designed to allow (a) modelling and simulation of multi-modal impairments, (b) recreate rich environmental contexts, that may include multiple sensors and input/output devices (e.g., phones, watches, tablets, TVs). Empath-D also allows designers to experience for themselves the potentially non-additive effects that result from such multiple impairments. As impairments vary greatly in nature, the focus of this thesis will be on **visual impairments** (Scenario 1).

1.2.3 Challenges

To realise my vision of empathetic design for Empath-D, numerous challenges need to be addressed. In this section, I describe some of these challenges as it relates to the scenarios described in Section 1.2.2.

1. **Supporting Naturalistic Interaction**: Naturalistic interaction is predicated on real-time mirroring of the physical interaction with a real-world smartphone, while perceiving (visual, auditory) the virtual interaction seen through the VR interface. This split-interaction paradigm requires tight time coupling comparable to direct interactions with a standalone physical smart-

phone. This is particularly difficult given the multi-device nature (computer, physical smartphone, VR headset) of Empath-D's vision. In addition, to be able to mirror as described, we must be able to perform *real-time tracking* of 1) the physical smartphone (e.g., swinging the phone around), and 2) a suitable virtual analogue for physical interaction–all of which are sensitive to latency.

2. **Diversity of Impairments and Simulation**: Impairments are diverse in type and presentation. They also span different modalities (e.g., visual, auditory, motor). A fundamental principle to the simulation of impairments as is reflected by past impairment simulators [42, 63, 82, 96, 110, 115] physical and virtual, is that simulations need to reflect the functional aspects of impairment. For instance, cataracts is functionally modelled as a loss in visual acuity. Yet, functional models can be hard to represent, and are unique to each impairment, and to users. While each impairment may be modelled on its own, users may have multiple impairments, and the system needs to support the simultaneous presentation of impairments, across the different modalities, which may not be supported. While VR can likely support both visual and auditory modalities, motor impairments are harder to represent, as they may need additional physical devices to produce the right synchronous motor perturbations.

3. **Supporting Evaluation in Design**: The most important challenge is over how and if the system will support evaluation in design. There are three parts to this. First, while impairment simulation has been previously studied to examine its simulation fidelity, the direct impact on designs is unclear [140]. Second, Empath-D's split interaction paradigm to support mobile application design is a novel one. Since no previous systems support impairment simulation with naturalistic interactions for mobile applications, it is unclear how a designer may use Empath-D to 1) *redesign existing classes of applications*,

and 2) *explore and design a whole new class of applications that are meant to support the user with impairments*. Third, let us assume that the system can simulate any impairment. This allows us to infinitely customise an application's design so that an individual user may gain the most benefits. However, this does not maximise the cost-benefit tradeoff to support a wider range of users. The challenge here is to be able to establish *representative groups* of users, that allow the designer to better target them. This is a difficult thing to do given the diversity of impairments. It requires large cohort studies of impaired users.

In this dissertation, I addressed a subset of the challenges above that are key to enabling the vision of Empath-D. I focused on enabling naturalistic interaction (Challenge 1; See Section 2.2.2, 3.2 and 3.3) in augmented virtuality–demonstrating its interaction performance in user studies. I also demonstrate the ability to simulate individual visual impairments as calibrated with existing physical impairment simulators and standardised tests [160]. While more impairments (auditory, motor) were developed (See Figure A.6 in Appendix A.4), these remain untested. Similarly, while Empath-D supports the incorporation of environmental contexts, this dissertation does not explore the effects of environmental simulation. This dissertation focused on visual impairments, and partially addresses Challenge 2. Finally, I partially address Challenge 3 by examining the impact of using Empath-D for design work, demonstrating that it is superior to existing tools commonly used by developers and is able to identify more usability problems.

1.3 Thesis Overview

In this thesis, I design and study our novel augmented virtuality interface–Empath-D. I present the considerations that were made in developing Empath-D, and show in four validation studies its performance to support naturalistic interaction and its effects on design.

The validation studies answer the following main research questions:

1. How can we support designers to design for impaired users on mobile devices?

2. How do we design and develop a VR system that supports naturalistic interaction and assessments of mobile apps with simulated impairments?

3. How does such a system outperform existing methods for mobile app design?

The thesis statement can thus be stated as follows:

The use of a novel augmented virtuality interface that supports naturalistic interactions with a mobile device and immersive simulations of impairments will improve on existing methods of evaluating mobile application designs for accessibility.

This dissertation establishes the thesis via the following steps:

- First, it identifies the salient characteristics of designing mobile applications for disability, and clearly outlines the need to address this problem.

- It then defines the vision for Empath-D, a general solution that supports addressing the problems identified for visual, auditory and motor impairments.

- Next, it presents the design requirements and solution, Empath-D, that uses a combination of augmented virtuality interaction design and implementation to achieve these requirements.

- Finally, it demonstrates through a series of user studies that Empath-D is able to achieve naturalistic interaction and immersive simulation, and it is superior to existing methods to evaluate mobile application designs for accessibility.

This thesis, to the best of my knowledge, is the first of its kind work to i) design and examine an augmented virtuality interface that supports naturalistic interaction with a mobile device, and ii) examine the impact of immersive simulations of impairments in evaluating the designs of mobile applications for accessibility.

1.4 Dissertation Organisation

This dissertation is organised into five chapters and two appendices as follows:

Chapter 2 describes the Empath-D augmented virtuality impairment simulation system that allows developers to rapidly and iteratively evaluate their designs. It describes the design goals and their implications, and the design iterations examined to develop the final augmented virtuality solution.

Chapter 3 presents the validation for this dissertation. It details four sets of studies that demonstrates that Empath-D: 1) requires less effort to use than design guidelines, 2) is sufficiently low latency to support perceptual-cognitive fidelity, 3) can provide accurate performance comparable to physical impairment simulators and reality, and 4) can better support mobile app designers to identify design issues and fix them for specific impairments.

Chapter 4 presents the related work for this dissertation. It examines the related concepts in designing for accessibility and how application accessibility is supported today. It provides an overview of the different means to provide

Finally, Chapter 5 presents the dissertation conclusion. It summarises the main contributions of the thesis, and provides a discussion over future work related to this disseration, and the concluding remarks.

The dissertation also has two appendices. Appendix A describes the implementation of Empath-D, detailing how the physical smartphone is tracked and mapped, how hand segmentation is performed to supported an augmented virtuality view, and how we performed impairment simulation. Appendix B provides the materials used in the user studies to validate this thesis.

Chapter 2

Augmented Virtuality Impairment Simulation for Design

In this chapter, I describe the Empath-D augmented virtuality impairment simulation system that allows developers to rapidly and iteratively evaluate their designs. I provide an overview of the key design goals and their implications, and our iterations towards developing Empath-D.

First, I examine the concept of *augmented virtuality*. I describe the *Reality-Virtuality* continuum on which augmented virtuality sits, and explain the key advantages and disadvantages that solutions on the range provide. This motivates the choice of augmented virtuality for Empath-D. Next, I describe the key design goals and implications in developing Empath-D, and explore the iterations that we went through to finally enable naturalistic interaction. I then give an overview of the Empath-D's ideal system architecture. Finally, I describe how augmented virtuality interaction works in Empath-D.

The design and development of Empath-D was a collaborative effort. While I focused on interaction design, a fellow student focused on the implementation, with inputs from all the faculty involved. For completeness, the implementation details–including the algorithms used–have been included in Appendix A.

2.1 Why Augmented Virtuality?

What is *augmented virtuality*? It is useful to describe this with respect to two common related concepts of augmented and virtual reality. Augmented reality is the experience of a *real-world* environment *augmented* by computer generated information. Virtual reality on the other hand is the experience of a completely *computer generated* environment. Milgram and Kishino [142] first succinctly describe the relation between the two concepts in a *Reality-Virtuality* (RV) continuum (See Figure 2.1). *Augmented virtuality* is a form of mixed reality, where the surrounding environment is principally virtual, but augmented with real information.

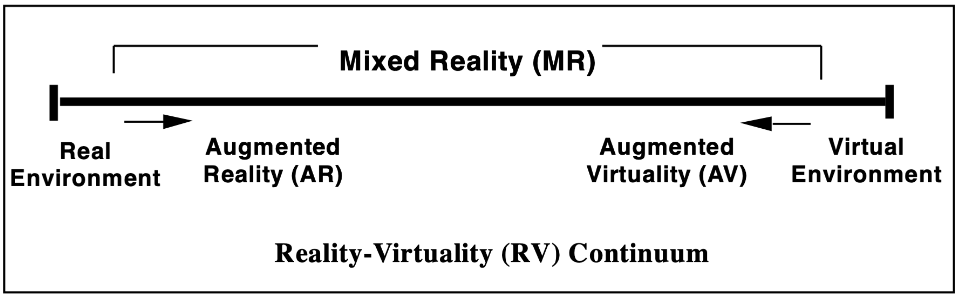

Figure 2.1: The Reality-Virtuality Continuum [142]

The main advantage of using AR, is its *implementation simplicity*. With AR, apps can be developed and deployed to the smartphone as in standard development processes. Developers then experience the physical environment with the impairments provided by Empath-D and interact naturally with their smartphones. However, the very advantage that AR provides–real environments–is also its limitation. Mobile apps by nature are used in diverse contexts and environments. AR is limited by a designer's ability to access the required environmental contexts, and to simultaneously ensure safe usage in higher risk environments (e.g., crossing a street). This risk is particularly pronounced for disabled users, who already suffer from impairments that may reduce their ability to perceive their surroundings (See Section 1.1.3).

VR on the other hand allows for the *full customisability of virtual environments*. This customisability allows the risks of real environments to be mapped to game-like feedback (e.g., game engine physics supporting virtual avatar being knocked aside by cars) to supporting user testing that would not happen otherwise. VR also supports the possibility for *higher cognitive fidelity in simulating impairments*. Take for example the simulation of hand tremors in Parkinson's disease in which the touch event registers a point that is jittered from where one physically touched. An AR solution would fail since one may observe the actual landing point of the finger. VR on the other hand immerses one in the virtual world and can support virtual finger jittering to match the visual expectations of the landing point.

Empath-D is an **augmented virtuality** system. As described in Section 1.1.2, designing for disability requires consideration of the impairment, activities and the environment. To support an iterative design process for designer-developers, the system needs to support an easily run, naturalistic means of interacting and assessing mobile app designs in the activities and environments of use. This would provide for strong ecological validity in usability testing. This translates to the following usability requirements:

1. Having minimal or no instrumentation with a designer's hands and fingers.
2. Support the grasping of a physical mobile device (or semblance of, then virtually simulated).
3. Reconfigurable impairments, environments and activity contexts.
4. Provide appropriate feedback for environment interactions

Requirement 3 and 4 (R3 and R4) are easily achieved using a virtual reality display. The desired physical environments and physics can be generated using resources that are widely available (e.g., through Unity's Asset Store [65]). While requirements 1 and 2 may simply be fulfilled by the use of a physical smartphone, the use of a virtual reality display, as imposed by R3 and R4, means that users would not be able to see the physical smartphones that they are holding, their hands and fingers–no part of themselves. Augmented virtuality is thus needed. A representation using screens from the smartphone can be virtually generated, with movements in physicality being mirrored to the the virtual world to maintain the functional realism of smartphone use.

2.2 Developing Empath-D

In the previous section, I discussed the need to develop an augmented virtuality solution from the perspective of designing for disability and to support ecological validity. In Section 1.2, I described my vision for Empath-D, with scenarios that help to show how the system may work across three modalities of impairments–visual, auditory and haptic. However, to reduce this to a tractable research problem, Empath-D cannot currently support all of these scenarios. For instance, Empath-D currently does not support *virtual camera emulation* (as described in Scenario 1; See Section 1.2.2), nor does it currently utilise 3D spatial audio libraries to provide sound source spatialisation as described in Scenario 3 (See Section 1.2.2)).

In this section, I discuss the system requirements and the iterations that were taken in developing the current incarnation of Empath-D.

2.2.1 Design Goals and Implications

1. **Holistic emulation of impairments**. For a truly empathetic experience, the app designer must perceive the effects of impairments not just while using the mobile app, but throughout her immersion in the virtual world. Consider a user, suffering from cataracts, who is interacting with her smartphone while attending a dimly dit dinner gathering. Simply blurring the phone display, while leaving the background illumination and focus unchanged, might not replicate challenges in visual contrast that an impaired user would face in reality. This requirement precludes the straightforward use of IO redirection techniques such as Rio [81], which can potentially perturb the IO streams of only the mobile device. Instead, the impairment must be

applied holistically, to the entire virtual world.

2. **Realistic emulation of smartphone and mobile apps in the virtual world**. Empath-D aims at realistically emulating mobile apps within the virtual world rendered by a commodity VR headset. Realistic emulation of mobile apps imposes two requirements: (a) First, the virtual smartphone should have sufficient visual resolution, corresponding to typical usage where the smartphone is held $\approx$30cm away from the eyes. This requirement, coupled with differences in display resolutions between smartphones and VR devices, requires careful magnification of the virtual smartphone to provide legibility without hampering usage fidelity. (b) Second, the user should not perceive any lag between her user input and the rendered view of the app, seen through the VR device. Quantitatively, we thus require that the task completion time, experienced by a user interacting with the emulated application in the virtual world, should be comparable to real-world app usage on a real smartphone.

3. **Use of an unmodified app**. For easy and low-overhead adoption by app designers, Empath-D should support the emulation of mobile applications using the original, unmodified binaries (e.g., .apks for Android). Empath-D's requirement to support empathetic emulation without app modifications implies that app designers would be able to adopt Empath-D with minimal impact to existing development practices.

4. **Low-latency, accurate finger tracking**. This goal is an extension of the holistic emulation objective. In the real-world, users utilise instantaneous visual feedback and proprioception to move their fingers around the smartphone display, even when they are hovering but not actually touch- ing the display. To ensure consistency between the users tactile, visual and proprioceptive perceptions of her hand movement, Empath-D should also realistically render, in the virtual world, the users hand movements and any changes in the position/orientation of the real-world smartphone, without any perceptible lag.

5. **Lightweight, effective emulation of impairments**. Empath-D will need to

emulate impairments, at different levels of severity. For high-fidelity empathetic emulation, the insertion of such impairments in the IO streams of the smartphone should not add generate any additional artefacts (e.g., increased latency, reduction in display refresh rate, etc.).

2.2.2 Design Iterations Towards Naturalistic Interaction in VR

I describe in the following section the two most key components that were iterated over in designing Empath-D.

VR and Hand & Finger Tracking. Supporting naturalistic interaction with a *physical mobile phone* as a *virtual mobile phone* in a VR display is extremely hard. Empath-D must run in real-time and maintain consistency between the user's tactile, visual and proprioceptive perceptions without perceptible lag. A tethered VR device that utilises high-end desktop graphics processing would ideally provide a lag-free VR experience. The VR device should also come with low latency tracked input devices.

For the first iteration, we explored using the HTC Vive. However, commercial devices like the wands from the HTC Vive [24,37,44,56,66] are generally designed to enable VR experiences. These support the interaction with *virtual* and not physical objects. They often require the entire hand to manipulate the physical controller controls, which prevent the reasonable use of a smartphone (see Figure 2.2).

For the second iteration, to explore more natural forms of interaction that may allow natural smartphone use, we attached a Leap Motion Controller [34] to the front of the HTC Vive (See Figure 2.3). This allowed for a relatively accurate means of tracking hands and fingers (See Figure 2.4). However, when the smartphone is held, the occlusion of fingers resulted in inaccuracy in tracking the hands and fingers, often mixing up left and right hands in tracking. Additionally, one had to be familiar with using the skeletal representation to be adequately proficient in manipulation.

HTC Vive Wand | Oculus Touch

Figure 2.2: Two commercial interaction devices requiring whole hand manipulation. *Left*: HTC Vive Wand, *Right*: Oculus Touch

[Source: Left: "DSC_0041" by psutlt / CC BY 2.0]

Figure 2.3: HTC Vive with Leap Motion Controller

[Source: "Leap Motion VR Mount + HTC Vive" by Leap Motion / CC]

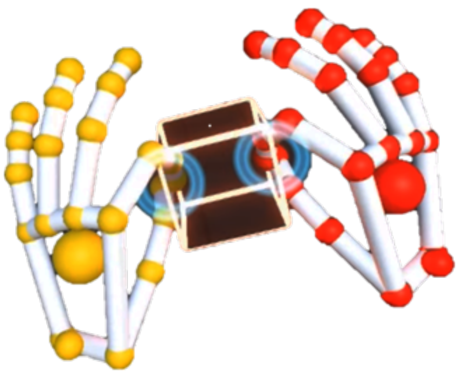

Figure 2.4: Skeletal model of the hand and finger tracking using the Leap Motion Controller

For the third iteration, to overcome the problems of occlusion and natural representation (of the hand), we replaced the Leap Motion Controller with the Intel RealSense SR300 depth camera [29]. However, the HTC Vive and Intel RealSense SR300 are infrared (IR) systems. The HTC Vive uses two base stations to emit pulsed IR lasers in order to perform headset and controller tracking. The Intel RealSense SR300 projects IR patterns on surfaces, and captures the reflected patterns in order to perform depth sensing. The emissions from the HTC Vive base stations interfered with the IR patterns from the SR300, resulting in inaccurate and unreliable depth sensing.

Consequently, for the fourth and final iteration, the HTC Vive was swopped out for the Samsung Gear VR [54] (See Figure 2.5). The Samsung Gear VR utilises IMU-based (inertial measurement unit-based) sensing to provide head tracking for virtual environments, allowing the SR300 to be utilised.

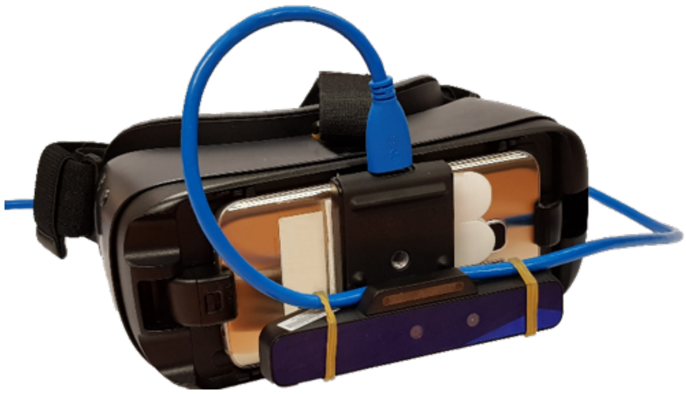

Figure 2.5: Final version of Empath-D's VR and tracking interface–the Samsung Gear VR with the Intel RealSense SR300

2.3 System Overview

Using Empath-D. To immersively evaluate the application, the designer starts by installing her developed application binaries (i.e., Android apks) to run on the emulated smartphone. The developer then adjusts the profile settings for the impairment using Empath-D's web dashboard and selects a use case scenario (e.g., in the

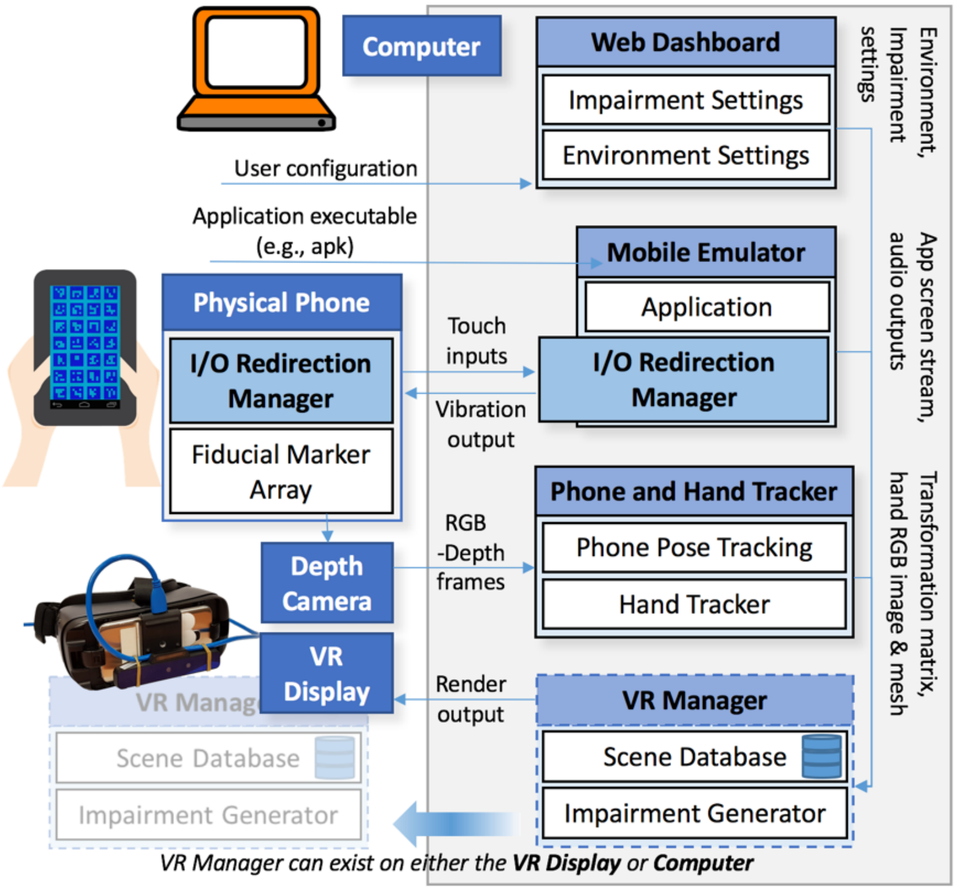

Figure 2.6: Empath-D architecture

office, street). She holds her physical smartphone and puts on the VR headset, earphones (when hearing impairments are involved) and experiences the immersive reality (where she can use the app–now mapped onto the physical smartphone–with the configured impairment under the designated use case scenario) that Empath-D generates. She then tests out various interfaces and functionalities of the app in the immersive VR environments.

Components of Empath-D. Empath-D runs across three different physical devices: a physical smartphone, a computer, and a VR device (See Figure 2.6).

Smartphone. The user interacts with the app using a real smartphone held in her hand. Interestingly, this smartphone does not run the app itself, but functions as a tracking device, with the touch and feedback of an actual smartphone helping to preserve the user's realistic sense of smartphone interaction. The smartphone simply *redirects* the user interaction events (e.g., touch events such as clicks and swipes on the display and motion events captured by inertial sensors) to the computer, which is in charge of the app emulation. This smartphone also displays a fiducial marker array on its display, to help in efficient, real-time tracking of the phone's location and orientation in 3D space [112].

Computer. The computer is at the heart of Empath-D's ability to fuse the real and virtual world. It consists of two major components: *Phone and Hand Tracker* and *Mobile Emulator*, as well as a *Web Dashboard*, which allows the user to select the impairment profile to be applied. In addition, this computer *may* run an Impairment Generator cum Virtual World Renderer.

- The *Phone and Hand Tracker*, uses images captured by the VR headset-mounted camera to track the position and pose of the smartphone (relative to the VR device), and create the virtual phone image at the correct position in the virtual world. It also uses the same camera to track and segment the user's hand as it interacts with the smartphone, and then renders it in the virtual world.

- The *Mobile Emulator* executes the app being tested, using the redirected stream of user interaction events transmitted by the smartphone. The resulting visual output of the app is then transmitted as a sequence of images to the VR device, where these images will be integrated into the virtual phone object; likewise, audio output, if any, is directly streamed to the VR device.

The overall Empath-D framework includes an Impairment Generator that is typically applied as one or more filters over the Virtual World Renderer (an engine such as Unity [64]), which is responsible for combining various virtual objects and rendering the virtual world). The *Impairment Generator* effectively perturbs/modifies the audio/video feeds of the virtual world, before they are displayed on the VR device. For example, to emulate cataracts, it applies an appropriate "blurring/dimming" filter on the video feed; similarly to emulate high-frequency hearing loss (an auditory impairment), this generator will apply a low-pass filter on the output audio stream. These two components are placed inside a dotted-line rectangle in Figure 2.6 to reflect the reality that these components run on *either* the Computer or the VR device, depending on whether the VR device is *tethered* or not. In untethered VR devices (such as the Samsung Gear VR), the Impairment Generator and the Virtual World Renderer run on the VR device itself. In contrast, tethered devices such as the HTC Vive will run on the computer, and typically offer higher graphics quality, frame rates, and faster execution.

VR Device. Finally, the VR device is used to display the synthesised virtual world to the user. This synthesis involves the fusion of the virtual smartphone, the user's hand and the ambient virtual world, all subject to the impairment filter. Figure 2.7 shows an overview of how impaired views are composed with the various system components in Empath-D.

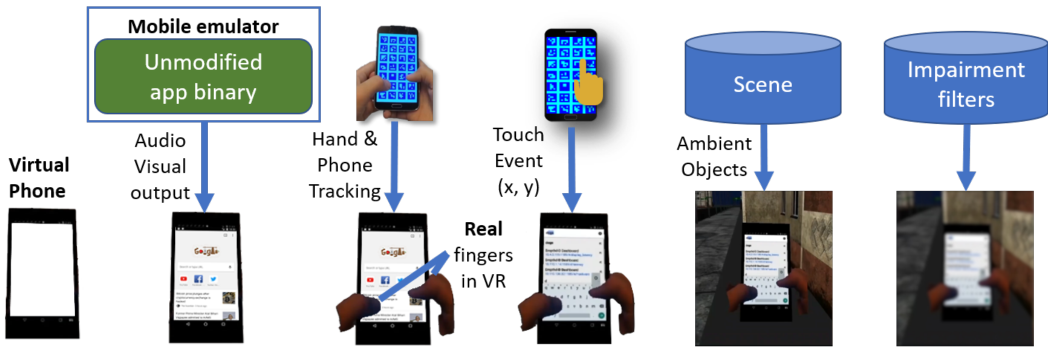

Figure 2.7: Composing Impaired Views in Empath-D

2.4 Supporting Augmented Virtuality Interaction

Empath-D follows an *augmented virtuality* split interaction paradigm: for realistic immersion, Empath-D renders the visual and audio output of the target app in the virtual world (i.e., via the VR headset's display and speakers), while allowing the user to interact naturalistically with a real-world physical phone. A major challenge in this paradigm is to enable natural, low-latency tracking and display of the real-world motion of both the phone and the user's hands, so as to ensure consistency across the user's visual, tactile, and proprioceptive experience. This is achieved by performing three distinct steps: (a) smartphone tracking, (b) hand tracking, and (c) hand rendering in VR, using an RGBD camera (Intel SR300) mounted on the VR headset. Empath-D first tracks the position and orientation of the physical smartphone and synchronises the position of the virtual phone to the physical smartphone. Separately, Empath-D also captures the fingers in the real world and displays them at the correct position (relative to the virtual smartphone) in the virtual world.

Empath-D uses the headset mounted RGBD camera to capture the colour and depth images, relative to the camera. Since the camera is affixed to the VR display, the camera's position is also fixed, relative to the user's head. Its three axes are thus aligned to a user's head: z-axis to the user's forward (gaze) direction, and x and y axes capturing the vertical and horizontal displacement. Full implementation details can be found in the Appendix A.

Chapter 3

Validation Studies

To validate my dissertation, it is key to examine the usability of Empath-D from multiple perspectives. In this chapter, I describe the four groups of studies that contribute towards this validation.

In the first study, I examine the feasibility of impairment simulation for design. As pointed out in Section 1.2.3, past work in the area of impairment simulation for design, has either focused on the simulation aspects of design [140], or described the empathetic aspects of using impairment simulation [82]. Study 1 demonstrates the feasibility of the approach by examining impairment simulation–using an early augmented reality version of Empath-D–as it is used by designers [98].

Study 2A and Study 2B are two experiments that stem from our work in studying the augmented virtuality prototype of Empath-D [131]. Study 2A are micro-benchmark studies of Empath-D to examine the latencies that are introduced through implementing Empath-D as an augmented virtuality system. Study 2B is a study constructed to examine the usability (e.g., touch accuracy) of Empath-D as it relates to real-world tasks and controlled pointing by users, and under different impairment simulations (none vs physical vs virtual:Empath-D).

Study 3 examines the most key research question: is Empath-D a useful tool to design mobile applications for impairment-specific accessibility? It comprises two studies; the first study examines the usability challenges that cataract-impaired users experience, and the second study examines the effects of utilising the most current tools for design vs using Empath-D.

3.1 Study 1. Feasibility of Impairment Simulation for Design

To examine the effects of impairment simulation on design, a proof-of-concept AR prototype of Empath-D was built. A cataract vision impairment was simulated to guide the design of more accessible webpages for the elderly. Web content accessibility is one of the most active areas of work, both through the Web Accessibility Initiative (WAI) [71], and by accessibility researchers [134, 150]. Worldwide, the mobile phone internet user penetration in 2015 stands at 52.7% [18], and is estimated to grow to 63.4% in 2019. Understanding this, the WAI has developed their standards/guidelines such that mobile accessibility is also covered [40]. The WCAG content guidelines are thus well suited to be a study analogue for mobile application accessibility.

While past work has qualitatively examined the usability of an AR interface to do impairment simulation [82], their evaluation of the tool only examined the simulation aspects of visual impairments, but not its use in *design*. Other earlier work focused on desktop-based simulation experiences [140], or on control panel designs [122], both of which do not perform head-tracking and correspondingly do not head-track transform visual impairments. The following describes the early experiences of using this Empath-D prototype with six users. This work was reported in [98].

A video of the prototype is available at `https://is.gd/empathd`.

3.1.1 Experiment Design

Participants. I recruited six male participants, ages 27–41, with no pre-existing uncorrected vision impairments (e.g., short-sightedness corrected by spectacles was acceptable, but colour-blindness was not). All participants have experience in designing webpages, and have working knowledge of HTML/CSS.

Task. Participants were asked to redesign two stripped-down webpages (See Figure 3.1; for source code, See Appendix B.4.1) for elderly users suffering from cataracts, a vision impairment that is mainly experienced as *reduced visual acuity*. The webpages are based off WebMD's Symptom Checker [61]. We asked participants to focus on supporting vision in their designs. Participants were free to use the Internet to research methods for implementing their designs. To reduce the individual differences in skill and to focus participants on design, I also provided help on *implementation* (HTML-CSS) to fulfil the designs that the participants came up with.

Conditions. I conducted a within subjects experiment. The participants were split into two groups to balance for ordering effects. The first group designed using guidelines only (Condition 1; C1) first, then AR+guidelines (Condition 2; C2). The second group designed with C2 first, then C1. Each design session of the 2 stripped down webpages was 45 mins long. To mitigate the effects of learning and fatigue, I conducted each experimental condition in a separate session, with one night's rest between. The NASA-TLX [73] was administered upon the completion of each condition. Participants were asked to complete the NASA-TLX with reference to the condition they had just completed. At the end of C2 sessions, I conducted a semi-structured interview to understand the participant's experiences with using the AR prototype.

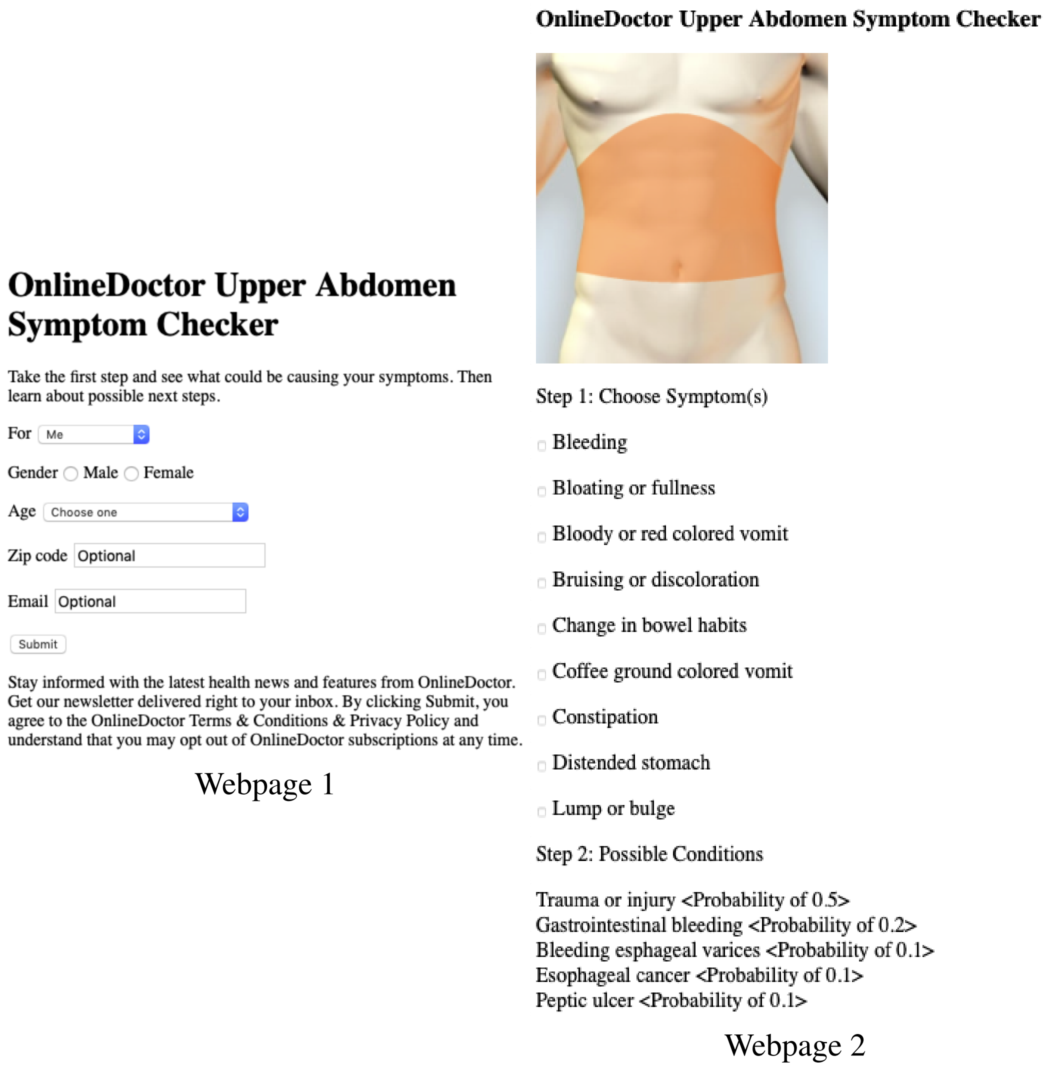

Figure 3.1: Stripped-down webpages for the design task, based off WebMD's symptom checker [61]

3.1.1.1 Tools used

Cataract Impairment Simulation using an Augmented Reality Prototype of Empath-D. The AR prototype of Empath-D was implemented using Unity [64] and Vuforia [67]. Unity provides basic filters such as a Gaussian Blur, which supports functionally simulating the reduced visual acuity of cataracts. The lowest setting on the filter (1; ranging from 0-10) was used for the experiment. It was chosen to represent a mild level of cataract impairment. The filter is overlaid onto the camera video feed and is then seen by users, giving them cataracts-impaired vision. The resulting Android apk was installed into a Samsung Galaxy Note 4 [52], and mounted into a Samsung Gear VR.

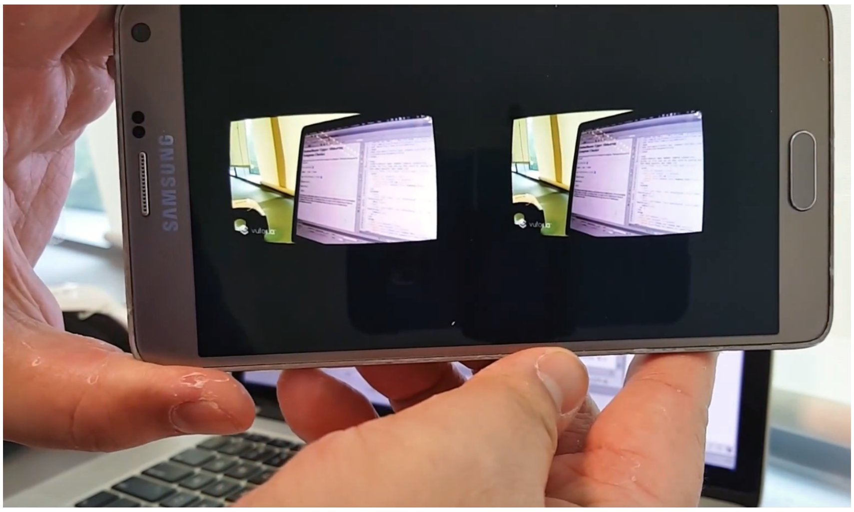

Figure 3.2: Augmented Reality Prototype of Empath-D

WCAG 2.0 Design Guidelines for the Elderly. To help participants focus on the design task, I adopted a portion of the guidelines stemming from [12] as the guidelines for the experiment. The original guidelines are an abstract from the WCAG 2.0 that have been identified by the Web Accessibility Initiative (WAI) as those relevant for designing for the elderly. The guidelines are given in Appendix B.4.2.

3.1.2 Results

3.1.2.1 Workload during Webpage Design

I examined the overall workload and six different dimensions of the NASA-TLX between the two conditions: C1 and C2. Figure 3.3 shows the results. For the overall workload, the two conditions differed significantly (Mann-Whitney U = 4, $n_1 = n_2 = 6$, $p < 0.05$, two-tailed), demonstrating that the use of AR interface reduced the design effort. Almost all participants in C2 (P1 - P5) consistently used the AR interface to evaluate their designs.

Among the six more detailed dimensions, I found that *Mental Demand* was the only dimension that presented a significant difference (Mann-Whitney U = 4, $n_1 = n_2 = 6$, $p < 0.05$, two-tailed). There are two main reasons for the increased

Mental Workload. First, the AR interface allowed users to quickly evaluate their designs, which gave them the confidence that their designs would work (P3, P5, P6). Comparatively, designing with only guidelines required participants to construct a mental model of how an elderly person with cataracts may perceive the design. Second, participants found that the design guidelines are vague, and often had difficulty knowing what they should implement for accessibility for elderly people with cataracts (P1, P3).

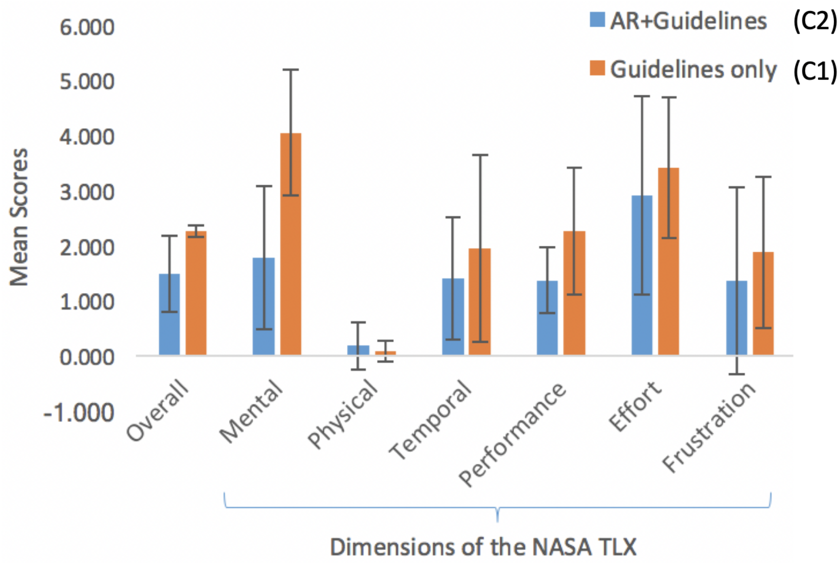

Figure 3.3: Mean scores of the NASA-TLX, showing the overall score and six specific dimensions (lower is better, see [73])

The mean scores for Temporal Demand, Performance, Effort and Frustration are comparatively better in C2, however without statistical significance. This is likely due to the differences in participants' prior experiences with AR and guidelines along with their intuitions. For example, P2 relied heavily on the AR interface to quickly perform evaluations to do his designs, which led to lower temporal demands. P5, on the other hand, paid more attention to the guidelines to come up with paper designs before implementation, resulting in stronger time pressure.

3.1.2.2 Attaining WCAG 2.0 Success Criteria

I examined how well guidelines and guidelines+AR conformed to the accessibility guidelines. I ran *aChecker* [113] (an automated accessibility checker) on the second page of the design tasks for all conditions. A Wilcoxon Signed-Rank test ($W = -2 > -21$, $p > 0.05$, two-tailed) found no significant differences between the two conditions. This suggests that Empath-D is no worse than existing methods (i.e., guidelines) for designing webpages for accessibility. This initial result may be an artefact of the experimental design, where participants who had past experience but not have recent proficiency in HTML-CSS are asked to design webpages in a short fixed period of time, and thus may not be able to fully express their designs. This is evident when we note that 5 participants wanted to–but failed–to increase the size of radio buttons or checkboxes within time. Participants added HTML comments to indicate their intent instead, and as such would not be picked up by *aChecker*.

3.1.2.3 Subjective Feedback

All participants were positive about using the AR interface for design. Participants noted that guidelines given are often unclear, despite being given an extremely focused and shortened version (See Appendix B.4.2), and the AR interface offers a concrete means to situate design (P1, P3, P5). Participants also indicated that they preferred if there were means to allow them to use the AR interface, without having to interrupt the flow of webpage design (P1, P2, P3) – as they needed to wear on and take off the device repeatedly. Accordingly, most participants (P1, P3-P6) used the AR interface for the evaluation, whereas only one used it more frequently even during modifying the webpage. Interestingly, participants noted (P1, P3-P6) despite its usefulness, that prolonged usage would likely cause physical discomfort. Lastly, almost all participants (P1-P4, P6) indicated that they felt empathy for the elderly with cataracts. P1 and P3 in particular remarked that the“vast majority of web pages” or even signage on the streets are not designed for accessibility.

3.1.3 Conclusion

I presented the initial vision toward *Empathetic User Interface Design*, and proposed Empath-D, to achieve this vision. Running over AR/VR devices, Empath-D provides developers or designers with an *Immersive Reality* environment, where they can empathise with the impairments of disabled users and test the usability of their applications. This initial user study with six web designers showed that Empath-D makes it easier for them to design web pages to meet accessibility guidelines for elderly with cataracts, reducing *mental demands* during the design process as compared with simply using design guidelines. It demonstrates the potential to develop a full-fledged system to enable immersive evaluations for application designs.

3.2 Study 2A. Micro-benchmark Performance of Empath-D

A full prototype based on the feasibility study described in Section 3.1 was built and examined [131]. This prototype utilises the multi-device interaction system that is described in Section 2.6.

In this section, I describe the micro-benchmarks that we performed in order to examine the systems latencies that affect the usability of the system: *touch interaction* and *virtual hand*. Specifically, these are the system delays in reflecting physical to virtual world touch interaction and hand tracking. Ideally, these delays are minimised so as to ensure consistency between the user's tactile, visual and proprioceptive perceptions–all of which support the sense of presence [136] in the augmented virtuality–and consequently support naturalistic behaviour and interactions with the environment.

The measure of interaction latency was challenging given the multi-device nature of Empath-D. With a multiple device application such as Empath-D, the software exists on multiple devices. Simple device clock-based methods fail since each device may present with varying clock drifts. To address this, I observed that all the devices involved had screens. This allowed for an elegant solution utilising a high speed camera. I detail this methodology in Section 3.2.2 and Section 3.2.3.

I designed the study methods for this work, and a fellow student implemented the applications to support the study.

3.2.1 Hardware

The Empath-D prototype was implemented using the hardware described in Table 3.1.

Table 3.1: Hardware used for micro-benchmarking

Component	Device Used
VR display	Samsung Gear VR [54] + Samsung Galaxy S7 [51]
RGBD camera	Intel RealSense SR300 [29]
Computer	CPU: Intel Core i7-6700 (4 cores, 3.4 GHz) RAM:s 16 GB DDR4 GPU: NVIDIA GeForce GTX 1080 [16]
Physical IO smartphone	Samsung Galaxy S5 [50]

The Samsung Gear VR was fitted with the Samsung Galaxy S7 as the VR headset. The Intel RealSense SR300 RGBD camera was used for finger tracking, selecting this among alternatives as: 1) its small size and low weight allowed us to easily attach it to the VR headset, and 2) its minimum sensing range is low enough to permit hand tracking at a distance of 30cm. We employed the Samsung Galaxy S5 as the physical IO device, and a powerful laptop (4 core 3.4 GHz CPU, 16GB RAM) as the intermediary device. The choice of the VR headset itself was deliberate. We chose a Samsung Gear VR headset (an untethered smartphone-powered VR device) over more powerful PC-tethered VR devices such as the HTC Vive or Oculus Rift. This was mainly because PC-tethered devices such as HTC Vive use IR lasers to localise the headset, which interferes with the IR laser emitted by the RGB-D camera used for depth sensing in hand tracking.

3.2.2 Result 1: End-to-End Latency of Touch Interaction

Method. As a measure of the overall responsiveness of Empath-D, we computed the latency between a touch input, on the physical smartphone, and the resulting change in the content of the virtual smartphone, rendered in the VR display (See Figure 3.7).

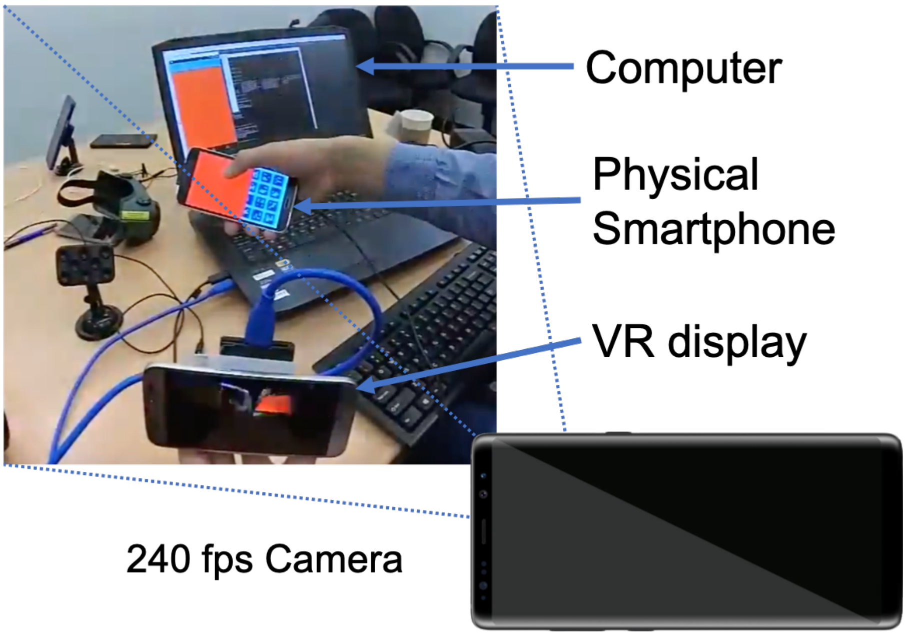

Figure 3.4: Touch Interaction Experiment Setup. The 240 fps camera is used to record the change in colour–red to green–within the same camera view as the event triggers in each device.

To measure this, we utilised a high frame rate camera (Samsung Galaxy Note 8 [53] operating at $240\ fps$) to concurrently record both the screen of the physical smartphone and the virtual phone (displayed in the VR). The phone screen is coloured red initially, and was programmed to turn green as soon as it received a touch input. We repeated the measurement 23 times, capturing (via the video frames) the time gap between (i) the physical smartphone screen turning green and (ii) the virtual smartphone turning green in the VR display.

Results. The average end-to-end latency was $237.70\ msec$ ($SD = 20.43$). By monitoring the intermediary computer, we obtained the breakdown of this delay: (i) smartphone responsiveness (the time from the user touching the screen till the time

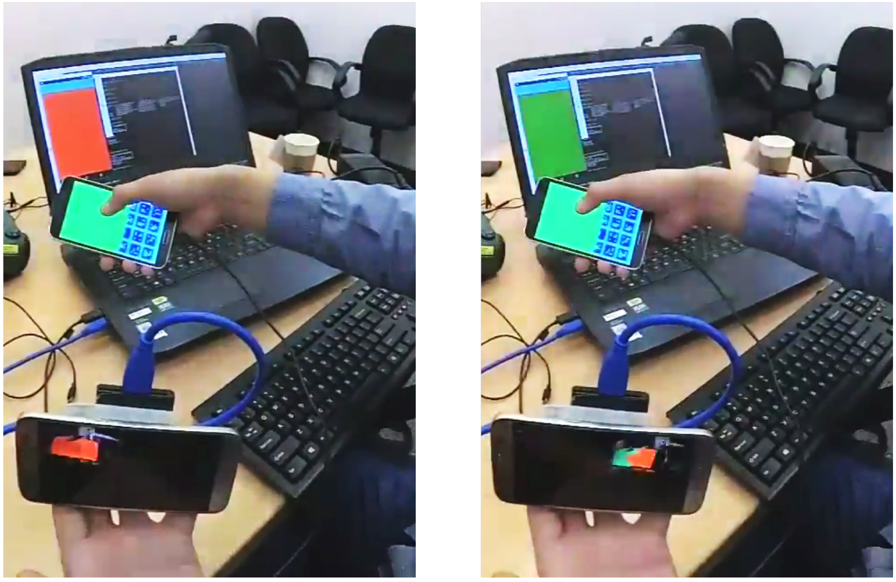

Figure 3.5: Colour change as recorded by the high frame rate camera. L: Touch event has been registered on the physical smartphone, with the screen showing as green. R: Touch event has been received on the computer (fully green) and VR display (partially changed to green).

the phone transmits the touch event to the computer) $= 0.3\ msec$ ($SD = 0.16$); (ii) computer emulation responsiveness (the time from receiving the touch event till the time the screenshot of the modified display is sent to the VR device) $= 141.37\ msec$ ($SD = 6.6$), and (iii) the VR responsiveness (the time from receiving the screenshot till it is rendered on the VR display) $= 10.46\ msec$ ($SD = 8.36$). The remaining latency ($\approx 87\ msec$) can be attributed as the WiFi network latency. These micro-measurements suggest that the default Android emulator used in our studies was the dominant component of the latency (See Figure 3.8). The default Android emulator is known to be fairly slow, and multiple third party emulators (e.g., Genymotion [17]) are reported to provide significantly lower latency. Accordingly, we anticipate that this overall latency can be reduced to $\leq 150\ msec$, without any significant architectural modification of Empath-D.

3.2.3 Result 2: End-to-End Latency of Virtual Hand

Method. The approach in the previous section targeted touch interactions–any point of touch on the screen was sufficient to trigger the colour changes. The latency

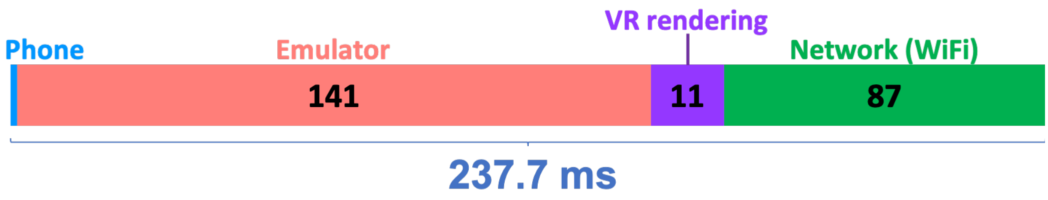

Figure 3.6: Breakdown of End-To-End Latency of Touch Interaction

of the virtual hand (as compared with the actual physical hand) however, ties to no particular smartphone event, and is entirely physical in nature. I designed an occlusion-based method to measure this. A user swipes his finger from the bottom middle of the screen to the top middle of the screen to obscure the red dot that can be observed on both the physical and virtual smartphones. We measured over 20 trials, the time (number of frames, utilising the same high speed camera from before) between the occlusion of the circle on the physical smartphone and the resulting occlusion of the circle on the virtual phone.

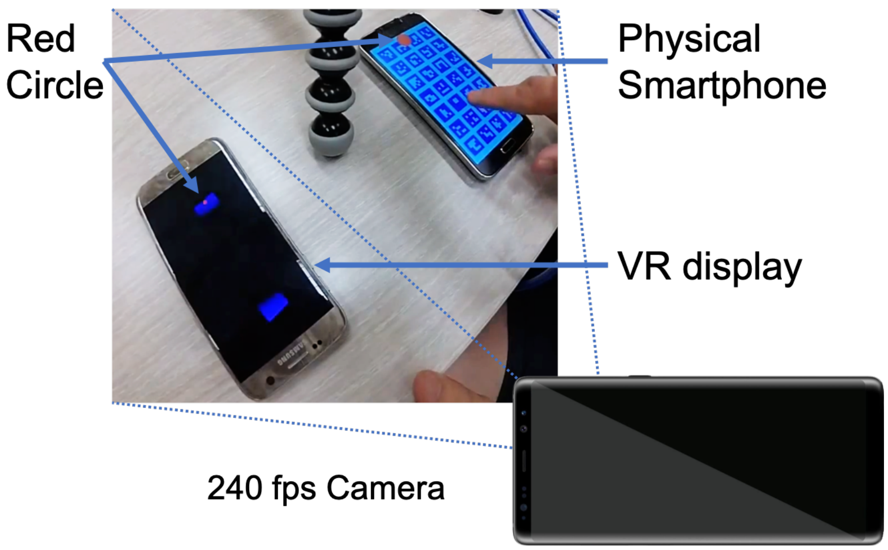

Figure 3.7: Virtual Hand Experiment Setup. The 240 fps camera is used to record the occlusion of the red circle in both the physical smartphone and the virtual smartphone (partially visible in the VR display) within the same camera view as the event triggers in each device.

Results. The average end-to-end latency was $117.46\ msec$ ($SD = 20.44$). Additionally, we measured the component delays of this rendering process as: (i) reading an RGBD frame: $4.90\ msec$ ($SD = 0.58$); (ii) phone tracking: $4.56\ msec$

($SD = 0.25$); (iii) hand tracking: 8.0 $msec$ ($SD = 1.58$), and (iv) the VR responsiveness (the time from receiving the hand mesh till it is rendered on the VR display): 26.99 $msec$ ($SD = 5.22$). The remaining latency, attributable to the WiFi network, is $\approx$ 73 msec, consistent with the measurements reported above in Section 3.2.2. In this benchmark however, WiFi has the highest latency, accounting for 62% of the end-to-end latency (See Figure 3.8).

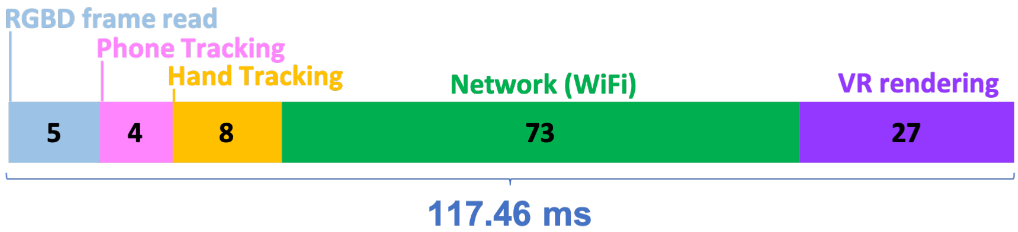

Figure 3.8: Breakdown of End-To-End Latency of Touch Interaction

3.2.4 Conclusion

The latency of the virtual hand of 117.46 msec falls within the 50-200 msec range (as modelled in the Model Human Processor [93, 128]) of uncertainty before the perception of causality breaks down. This demonstrates that the virtual hand is likely to maintain this illusion, supporting the mapping in the mind of users of their physical to virtual hands.

The end-to-end latency of touch interaction of 237.7 msec however, was less than ideal [93, 128], we note that much of this latency is due to high latency (141.37 msec) from the emulator, and may subsequently be addressed by faster emulators or efficiencies in the other components of latency. With use, this latency while high can be mitigated by adaptation by users. I examine the effects of use in the next section.

3.3 Study 2B. Performance in Physical vs Virtual Interaction in Impaired and Non-Impaired Settings

In the previous section, the system latency was examined. While the latencies determined are known to be noticeable by users, user adaptation can often bridge this gap. In this section we examine how Empath-D impacts usability and real-world fidelity. Specifically, we examine the usability of Empath-D in both an experiment designed with real-world app use, as well as a controlled pointing task. The goal of this study was to compare the performance of Empath-D under three conditions: the baseline being no impairments, physical impairment simulation, and Empath-D's virtual impairment simulation. This study validates that despite the latencies introduced by employing augmented virtuality, it has minimal impact on usability. Secondly, this study also demonstrates that Empath-D can appropriately emulate physical impairment simulators to produce comparable touch accuracies.

3.3.1 Experiment Design

Participants. The user study (approved by SMU's IRB) consisted of 12 participants (9 males) with no pre-existing uncorrected vision impairments (e.g., short-sightedness corrected by spectacles was acceptable, but colour-blindness was not). Users were aged 24-39, with a mean age of 30.3 years (SD = 5).

Tasks. Participants were asked to perform four different tasks split into two task types; *everyday phone use*, and *controlled pointing* (see Table 3.2).

Table 3.2: Smartphone Interaction Tasks

Task Type	Task Code	Task Description
Everyday Phone Use	T1	Perform a Calculation
	T2	Add an Alarm
	T3	Search, Save Image on Browser
Controlled Pointing	T4	Number Search and Point

T1-T3 are everyday tasks users perform on a smartphone. These consist of *performing a calculation* using Google Calculator [21], *adding an alarm* on Google Clock [22], and using Google Chrome [20] to *search and save an image* (See Figure 3.9). They cover smartphone touch interaction of taps, swipes, and long press, on UI widgets such as keyboards, buttons and scrolling content.

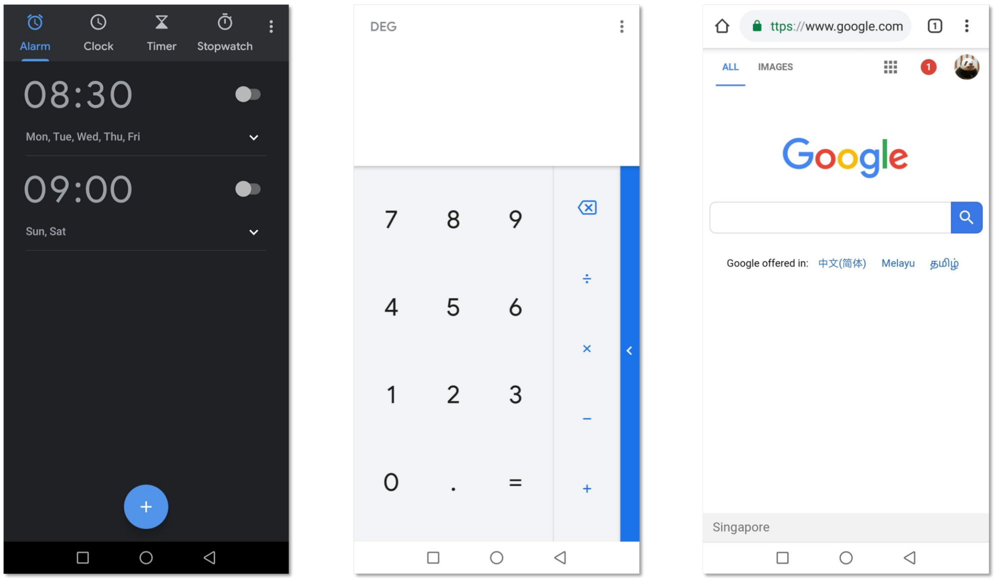

Figure 3.9: Everyday applications used in the study. *Left*: Google Clock, *Middle*: Google Calculator, *Right*: Google Chrome.

Users were asked to perform all tasks using two-handed interaction, holding the phone at a distance that they normally would during daily use ($\approx 25 - 30\ cm$). We chose two-handed interaction to eliminate for phone balancing that is typical in one-handed interaction given the typical size of today's smartphones. At the end of all three tasks (T1-T3), users completed the NASA-TLX [73, 118] to indicate their perceived workload during task performance.

T4, on the other hand, is a controlled pointing task experiment (See Figure 3.10). Participants were given a stimulus number and then asked to click on the button with the corresponding number, as *quickly* and as *precisely* as they could (See Figure 3.10 for a screenshot of the application used in this task).

Only double digit numbers were employed in this task to reduce the variations that may occur from using a mix of single and double digit numbers. The numbers

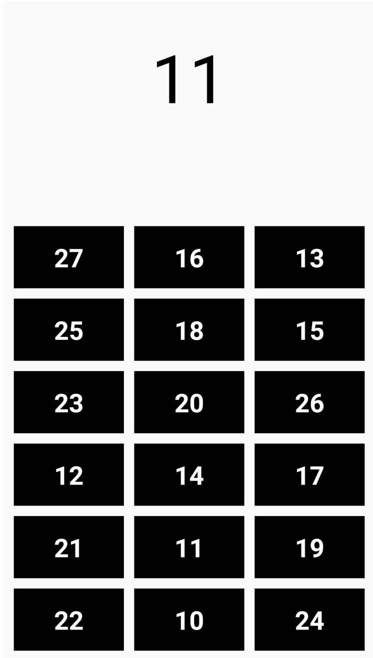

Figure 3.10: Screenshot of the pointing task application. A stimulus number 11 is shown, and the user is required to locate the button (white text on black background) that has that number and click on it.

on the buttons also randomly change with each trial to reduce the effects of learning. Users repeated this task 80 times in succession, for each of the six conditions (A-F; see Table 3.3). We recorded the touch times and positions with the task app.

We conducted a short semi-structured interview (See Appendix B.3.3) at the end of the study to understand users' experiences with, and perceptions of, the physical and virtual impairment simulations.

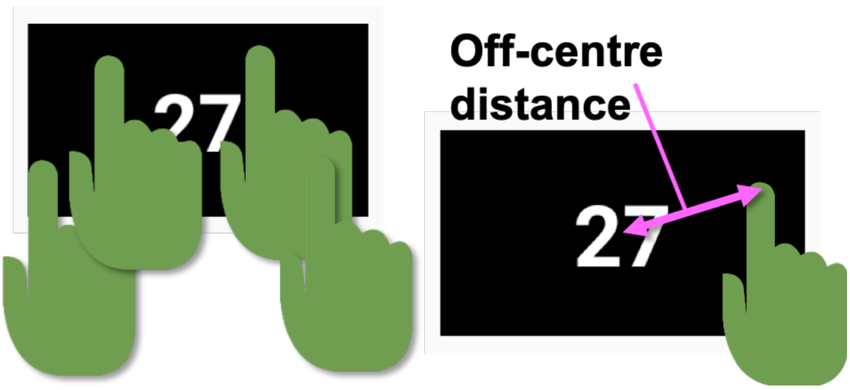

Figure 3.11: Hit and Distance measures in the Pointing task. *Left*: A hit is registered when the user taps anywhere on the button, *Right*: Distance is measured with reference to the centre of the button

Conditions. I adopted a repeated measures design, with participants counterbalanced for condition order (see Table 3.3 for the conditions). Condition A, is the baseline condition, with no impairments and neither physical nor virtual simulators. Condition C is the use of Empath-D with no impairments applied. Conditions B and D are under cataract impairment simulation, utilising both the physical impairment simulator, and Empath-D (virtual) respectively. Conditions E and F are under glaucoma impairment simulation, utilising the physical impairment simulator, and Empath-D (virtual) respectively. Users were asked to experience performing Tasks 1-4 under these six conditions.

Table 3.3: Study Tasks and Conditions

Task	Condition	Impairment	Simulator Type	Environment
T1 -T4	A	none	none	Real
	B	Cataracts	Physical	Real
	C	none	none	Virtual
	D	Cataracts	Virtual	Virtual
	E	Glaucoma	Real	Physical
	F	Glaucoma	Virtual	Virtual

We compared Empath-D with commercial physical impairment simulators [110] (See Figure 3.12). We used a cataract impairment simulator rated at $6/24$, and a glaucoma simulator rated at $20°$ of vision.

Figure 3.12: Physical Impairment Simulators [110]. *Left*: Cataracts Impairment Simulator, *Right*: Glaucoma Impairment Simulator

To calibrate for *visual acuity*, we adapted a test similar to a Snellen eye test chart [160]–showing rows of letters with each lower row having a smaller font size.

We first used the physical impairment simulator to obtain the minimum acceptable font size. Using the same test page in the VR, we applied the impairment and gradually adjusted the severity until we hit the minimum acceptable font size. To calibrate the inner circle of clarity for glaucoma, we implemented an app that allows us to adjust the diameter of a coloured circle. We then used the physical impairment simulator for glaucoma, and adjusted the coloured circle to the point in which the circle reaches the fringe for clarity. We then calibrated the virtual glaucoma simulation in a similar manner. Three independent measurements for visual acuity and circle of clarity were taken from the research team and averaged to determine the final calibration parameters of font size $= 12\ sp$ and diameter $= 60\ mm$.

3.3.2 Result 1: Empath-D vs Physical Smartphone

We first investigate whether the VR-based interaction is a sufficiently faithful replica of the real-world interaction that a user would have with a regular smartphone, *in the absence of any impairments*.

Touch Accuracy. In all six conditions, users were able to achieve high levels of button touch accuracy (see Table 3.4), with the accuracy being 98.8% ($SD = 1.67$) when the users interacted unimpaired with the VR device. Comparing the accuracies between the physical smartphone and the VR device, we noted that the VR condition had an accuracy of 99.12% ($SD = 1.32$) (across all 6 conditions), whereas the use of the physical smartphone provided 100% accuracy. In terms of the location accuracy, we noted a difference of $2.28\ mm$ ($SD = 2.98$) between the use of Empath-D vs a physical smartphone. This difference is well within the uncertainty associated with finger touch interactions [167], and thus demonstrates that user performance was equivalent across both Empath-D and a physical smartphone.

Perceived Workload. NASA-TLX scores indicated that the users did perceive significant differences in their workload using Empath-D, compared to use of the physical smartphone ($Z = 2.824$, $p = 0.005 < 0.05$). This does suggest that the navigating an app within the VR device does require greater cognitive effort than simply interacting with a regular smartphone. However, it is difficult to decipher whether this difference is due to Empath-D-specific issues, or a general lack of familiarity with VR devices.

We additionally investigated the subjective feedback captured by the semi-structured interview. 83% (10) of the users reported perceiving increased latency while using Empath-D, while 2 users indicated that they felt no noticeable latency difference. However, all 12 users indicated that the performance of Empath-D was "acceptable", and they would be able to use the Empath-D system for testing the usability of apps, as long as the apps do not require extremely low-latency interactions (3 users indicated that the system might not be usable for testing real-time games).

3.3.3 Result 2: Empath-D vs Hardware Impairment Simulators

We now study the performance of Empath-D vis-a-vis impairments generated using commercially available hardware. Figure 3.13 shows the overhead of Empath-D under impairment conditions, demonstrating that Empath-D is able to operate without significant performance loss even in the presence of impairments.

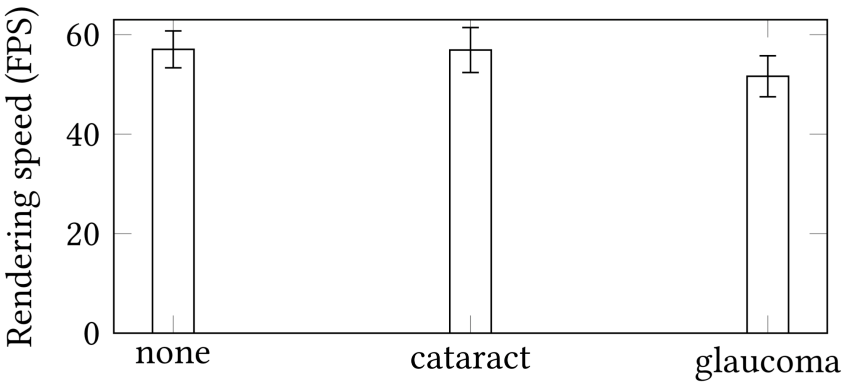

Figure 3.13: Overhead of impairment simulation

Touch Accuracy. Table 3.4 enumerates the accuracy for the pointing task (T4) for two distinct impairments (*Cataract* & *Glaucoma*), for both the VR-based Empath-D system and the hardware impairment simulator. We see that, in the *Cataract* condi-

Table 3.4: Accuracy of Button Touch Across All Users

Impairment	Environment	Accuracy (SD) %
None	Physical	100
	Virtual	98.79 (1.67)
Cataracts	Physical	100
	Virtual	99.09 (1.36)
Glaucoma	Physical	100
	Virtual	99.49 (0.82)

tion, Empath-D had a mean accuracy of 99.09%, which is virtually indistinguishable from that of the hardware device (100%). A similar pattern was observed for the *Glaucoma* impairment (99.49% for Empath-D vs. 100% for Hardware). In terms of the location accuracy, we noted a difference of $1.7\ mm$ ($SD = 1.9$) (for *Cataract*) and $1.2\ mm$ ($SD = 1.6$) (for *Glaucoma*) between the use of Empath-D vs. the impairment hardware. Once again, this difference is well within the uncertainty associated with finger touch interactions [167]. These results provide strong evidence that Empath-D is able to emulate impairment conditions that are equivalent to that of dedicated, commercial hardware.

Perceived Workload. The numerical TLX scores indicated that there was no significant difference for *Cataracts*; however, the difference for *Glaucoma* was significant ($Z = 3.061$, $p = 0.002 < 0.05$), with users indicating a higher perceived workload for the VR device.

3.3.4 Conclusion

The studies show that Empath-D is effective in (a) providing usability that is equivalent to using a real app (on a real smartphone), for applications that do not require ultra-low latency and (b) emulating impairments in a similar fashion to custom hardware devices such as to provide accurate performance that is needed in naturalistic interaction.

3.4 Study 3. Usability for Design

I designed and conducted two studies to examine if Empath-D is a useful tool to design mobile applications for impairment-specific accessibility. In the studies, I focused on 1) cataract-impaired users, one of the most common eye problems that the considerable elderly population experience and 2) an Instagram application–an archetype that encapsulates many common interactions in mobile apps.

In the first study (S1), I recruited cataract-impaired users to examine the usability challenges that they faced under a few everyday use cases of Instagram. In the second study (S2), I recruited experienced designer-developers and got them to redesign a mock-up of Instagram using Empath-D and other accessibility checking tools.

3.4.1 Hardware

Empath-D was run using the hardware described in Table 3.1.

Component	Device Used
VR display	Samsung Gear VR [54] + Samsung Galaxy S7 [51]
RGBD camera	Intel RealSense SR300 [29]
Computer	CPU: Macbook Pro running Windows 10 on Bootcamp
	CPU: Intel Core i7-3720QM (4 cores, 2.6 GHz)
	RAM: 16 GB DDR3
	GPU: NVIDIA GeForce GT 640M [15]
Physical IO smartphone	Samsung Galaxy S7 [51]

Table 3.5: Hardware used to run Empath-D

3.4.2 Design Study 3.1: Usability Challenges of Cataract Impaired Users

Participants. I recruited 4 (all female), ages 65-71 cataract-impaired users (self-reported to be verified by doctors) to identify the usability challenges that they experience in using Instagram. I used a strict participant selection criteria to reduce the effects of other visual impairments on the study condition (cataracts). In particular, all participants were selected for mild-moderate cataracts in *both* eyes, with minimal or no other visual impairments (e.g., low-degree myopia, no glaucoma, no age-related macular degeneration).

With cataracts being a predominantly age-related disease [111], all participants unavoidably also had presbyopia–the loss of elasticity in the lens of the eye which causes issues with near focus. To confirm that the selection criteria was effective and that the usability challenges identified by participants were based on a similar level of cataract impairment, I asked participants to complete the CatQuest-9SF questionnaire [137] (See Appendix B.2.2). The CatQuest-9SF is a questionnaire originally developed to measure pre- and post-cataract surgery outcomes. It was constructed in Swedish (with an English translated version) but has been translated and examined (under Rausch analysis) for Malay, Chinese, and Italian populations, and has consistently shown good psychometric properties [80, 158].

Method. Participants came in for a 1 hour session, where I adopted a master-apprentice frame [124] to explore their use of Instagram on a Samsung Galaxy S7 [51]. The master-apprentice frame positions the user as the master (subject matter expert), and the interviewer as the apprentice. The approach attempts to let the user shape the understanding of the problem, and suppress the biases that the interviewer may impart in the study. To identify the usability issues they faced with Instagram [28], I used an unmodified version with default settings and no accessibility options enabled. They were asked to 1) use the phone *with or without* corrective glasses as they would normally (in line with the notion of everyday living from the CatQuest-9SF [137]), and 2) hold their phones at a normal distance 25-30 cm from their eyes, and not compensate for visual problems (e.g., holding phone very close to see). I focused the participants on three particular use scenarios (T1-T3, See Table 3.6) that are common to Instagram, and cover a wide range of use common to many mobile applications (e.g., reading text, viewing pictures, swipes, touch, text

Table 3.6: Common use scenarios in Instagram framed as design tasks for Study 2

Task	Description
1	Like and bookmark a post
2	Read a post and post a comment
3	Send a message to a friend about where you are

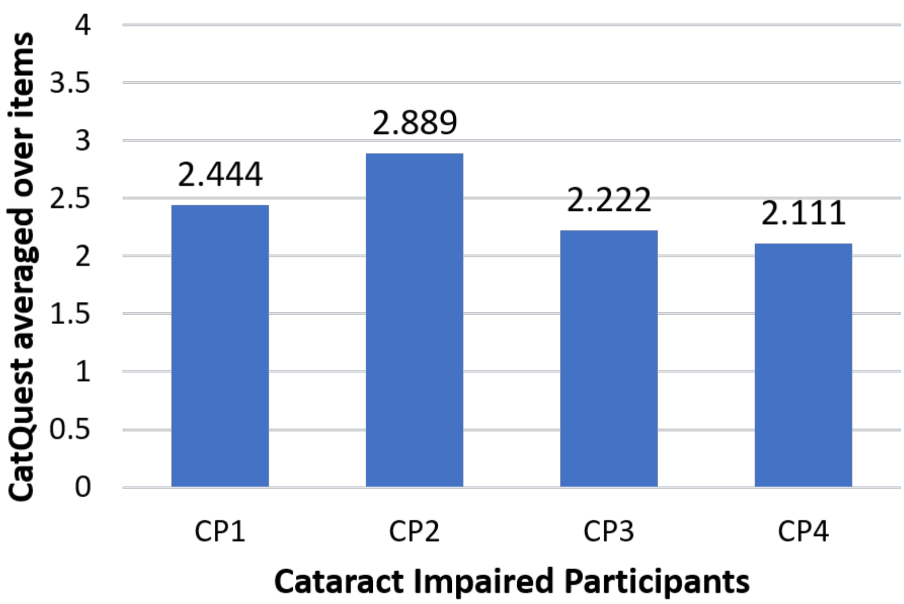

Figure 3.14: All participants had similar mild-moderate (between 2: "some difficulty" to 3: "great difficulty") levels of cataract impairments.

input). Video recordings were made of the session, and coded for the analysis.

3.4.3 Design Study 3.1 Results

From the CatQuest-9SF, all participants were found to match the targeted mild to moderate level of impairments, with cataract impairment scores ranging from 2.111-2.889 (2 being "some difficulty" and 3 being "great difficulty") (See Figure 3.14).

I analysed the observations in S1 to establish a base set of usability challenges that cataract impaired users face (See Cataract Impaired Users, Table 3.7), with respect to the core use tasks detailed in Table 3.6.

The challenges that they faced matched the relevant guidelines provided in the WCAG 2.0-Elderly [12], in all challenges except *letter spacing*. One participant

Table 3.7: Usability Challenges identified in C1 and C2, mapped to WCAG 2.0-Elderly and what Impaired Users identified.

Usability Challenges	WCAG 2.0 -Elderly	Cataract Impaired Users	C1 (Empath-D)	C2 (GAS)
Font size	✓	✓	✓	✓
Letter spacing		✓	✓	
Contrast	✓	✓	✓	✓
Image visibility	✓	✓	✓	✓
Icon visibility	✓	✓	✓	✓
Hit Target			✓	✓

noted that bold text (e.g., *post-text-usr-name*) was harder to see than non-bold text (e.g., *post-text*), as the lower ratios of letter to stroke spacing caused letters to clump together (See Figure 3.17 for italicised examples). The converse problem also occurred; with low font weights, two users found text hard to read. All users noted that with larger font sizes, text became more readable. This demonstrates the need to *appropriately balance font size, font weight and letter spacing*. All participants had problems reading low contrast grey text such as those of *post-viewcomm* and *post-time* (See Figure 3.17). For all participants, *contrast* was the biggest problem, often resulting in the inability to perceive the content at all.

3.4.4 Design Study 3.2: Identifying and Fixing Usability Challenges for Cataract Impaired Users

Participants. I recruited 10 (5 female) experienced HTML-CSS-JS designer-developers, ages 21-31 (mean 24.4) years. The participants were selected to not have any pre-existing uncorrected visual impairments–for example, myopia corrected by spectacles was allowed, but colour blindness was not. To ensure participants had the ability to perform the study task, I administered a coding test for HTML-CSS-JS [6, 26, 27], finding that all participants had the requisite skills (9 of 10 scored similarly, with only one participant demonstrating greater coding ability). I additionally administered the Need For Cognition [91] questionnaire (See

Appendix B.2.1), and did not find significant differences between the two groups of users (each group being assigned to a study condition, with C1:Empath-D or with C2:Google Accessibility Scanner–this is detailed in the next section under Method; NFC scores – C1: 10.6 (5.9) and C2: 13.8(7.8)).

Method. Participants came in for a full day study and were asked to perform the role of a mobile app designer, and redesign a mockup of Instagram for cataract impaired users to support the same three use scenarios described in S1 and for the same reasons (see Table 3.6). This allows me to match the usability challenges identified by cataract impaired users to the usability challenges addressed by designer-developers. The study schedule is given in Figure 3.15. The study tasks were ordered such that it increases in the order of difficulty. This was designed to allow designers to better accommodate to the experimental settings, and get used to designing at the right pace. For each task, participants were given 100 mins to redesign and develop the mockup, rolling over from each session to finally end with a working prototype. Participants were free to choose their process of working with the tools provided. They could modify the designs as they pleased (e.g., reposition, resize, recolor, remove), with only one limiting condition: they should not take away functions from the user interface. For instance, if the bookmark button was the sole means by which to bookmark a post, users cannot remove the bookmark button without implementing bookmarking in a different manner.

The participants were divided into two groups, corresponding to two conditions. In the first condition, C1, participants were given Empath-D, and in the second, C2, they were given *Google Accessibility Scanner* (GAS) [19], a diagnostic tool for Android mobile app accessibility (See Figure 3.16).

I developed the mockup of Instagram using HTML-CSS-JS (See Appendix B.4.3.1 for the mocked up pages and code), and set it up to be compiled using Cordova [5] into an Android apk file. Only two popular Javascript-based APIs were utilised to minimise the learning that was required of participants. jQuery Mobile

Idx	Item	Time Allotted (mins)
1	Start of Study	-
2	Admin (Informed Consent, Briefing)	20
3	Pre-test HTML-CSS-JS skill	30
4	Break	10
5	Task 1	100
6	Lunch Break	60
7	Task 2	100
8	Break	10
9	Task 3	100
10	Break	10
11	Interview	20
12	Admin (Closing, Compensation)	20

Figure 3.15: Study schedule used for Design Study 3.2. Tasks in blue highlight the design segments of the study.

was used to provide a mobile-like experience, yet having all the code in a single HTML file to simplify the organisation of the code. jQuery (a Javascript library) was provided to support simpler coding of the UI logic. This serves as the baseline application mockup (see Figure 3.17) that all participants start with.

I deliberately chose HTML-CSS-JS as the underlying means to develop this app as it provides three distinct advantages: 1) users can focus on aspects of design, as compared to native-app coding, 2) they may easily inspect and simulate changes using browser-based mobile emulation (e.g., in Google Chrome), and 3) the HTML-CSS-JS can be run through existing accessibility checkers [113] for WCAG 2.0 compliance.

Participants were briefed on the WCAG 2.0 [92], and given a link to an abstract version of WCAG 2.0 geared towards older users (WCAG 2.0-Elderly) [12]. The WCAG 2.0-Elderly was provided as a guiding document since it provides the closest match to our desired elderly demographic of which 78.6% suffer from cataracts [123]. Participants were also given a description of cataracts, and its underlying symptoms (See Appendix B.4.3.3). Participants also had unfettered access to the Internet to support seeking information on any aspect of the task. Lastly, to help participants to lower the challenges of implementation and focus them on de-

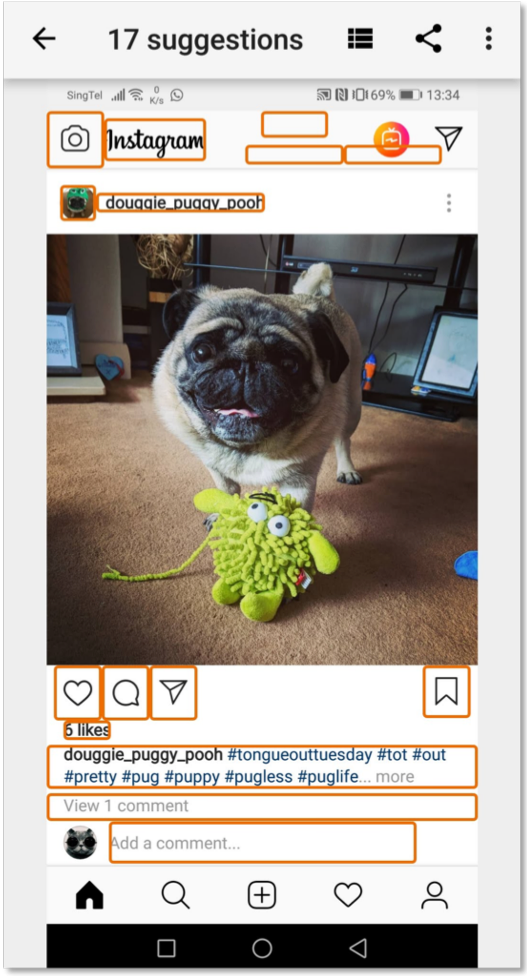

Figure 3.16: Google Accessibility Scanner. The scanner allows you to take screenshots of the app to be assessed. Potential accessibility problems are highlighted by the orange boxes–users can click on them to learn more about the problem.

sign, I provided them with: 1) cheatsheets for HTML-CSS-JS [10, 25, 33], and 2) assistance on implementation (e.g., how to adjust HTML elements, code a JS function, or image editing) but not design issues, and 3) other non-design related support (e.g., compiling the apk and installing it in a smartphone). The support provided was meant to reduce the impact of individual differences in coding ability and Android app development familiarity, which may affect less-experienced participants from design.

All participants performed the study using a 13-inch MacBook Pro, installed with tools common to web development (e.g., Sublime Text [59] / Atom [7], with code completion / syntax highlighting features). They were also free to install any

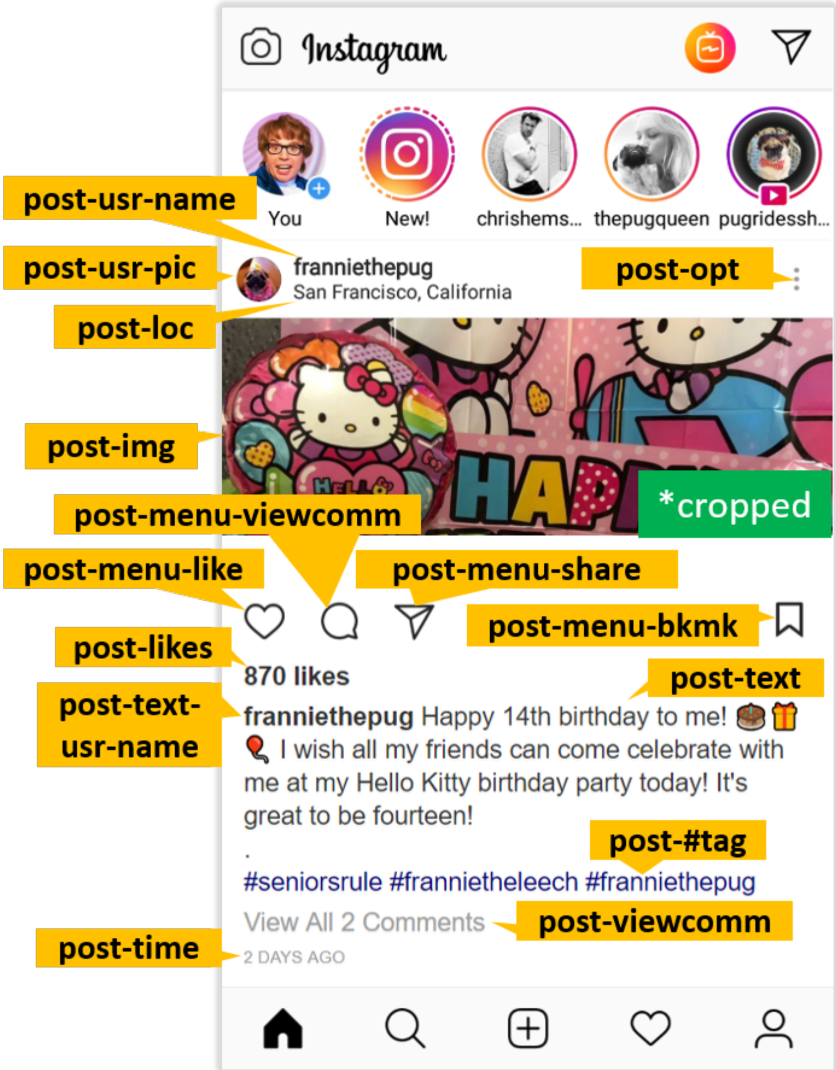

Figure 3.17: First page of the mockup baseline design used for S2 with example labels of UI elements used in the analysis.

tools that they preferred to use, though no participants felt the need to and were comfortable with the tools given. An external monitor was connected to the computer and was recorded using a video camera to capture holistic data of all that the user was doing in the design task (e.g., searching for information, focusing on an element for redesign). A separate video camera in parallel was also used to capture the interactions that a user had with Empath-D or GAS. I adopted a think-aloud protocol, getting participants to verbalise their thoughts as they performed the design task. At the end of each task, participants were asked to fill in the NASA Task Load Index (NASA-TLX) [73] with reference to the whole design task and System Usability Scale (SUS) [90] with reference to the system they used (C1: Empath-D or C2: GAS).

3.4.5 Design Study 3.2 Results

I made a detailed breakdown of the changes made to the base mock-up at the element level, and separated them made into positive and negative categories (see Figure 3.18) for each condition. I determined positive/negative changes by being in line with the WCAG 2.0 and data from cataract impaired users (S1), but ignore for the magnitude of changes and how they affect overall usability. For example, if a design guideline indicates that font sizes should be enlargeable/enlarged to support vision, and the user made a change to enlarge the font size, this counts as a positive change. However, if the user instead reduces the font size, this registers as a negative change. I further separated each positive and negative category into the key usability challenges (e.g., font size, letter spacing).

Accuracy and Coverage. In C1 (Empath-D), participants were able to more accurately (94.2%, 180 positive changes) identify usability challenges than without (C2) (85.6%, 160 positive changes). From Figure 3.18, we see that Empath-D supports positively identifying 19.4% more usability challenges across the different UI elements. Notably, Empath-D allowed participants to identify *letter spacing* problems, a usability challenge not picked up at all in C2. This was because GAS did not report issues of letter spacing. Users in C1 however, could *directly observe* through Empath-D impairment simulation that words “clumped together” (P4), and made appropriate changes. Participants in C2 picked up 40% more contrast usability challenges than in C1, however, this is at the detriment of wrongly identifying 100% more contrast usability challenges across the different UI elements. This indicates that GAS (C2) is unreliable in identifying contrast usability challenges.

Examining for all UI elements where positive changes were identified, participants in C1 were able to uniquely identify usability challenges in 7 (15.2% of all elements) UI elements: *post-usr-pic*, *post-opt*, *post-img*, *msg1-back*, *msg1-newmsg*, *msg1-pic*, and *msg2-back*. This is pertinent particularly since images (*post-img*) (see Figure 3.17), are a central mechanic to deciding to further interact in Instagram, and that cataract impaired users (S1) reported not being able to perceive the details in images, particularly those that are complex (e.g., colourful images with fine details that may obscure the focal subject of the image).

Magnitude of Changes. To better understand the effects of the changes made, I collated the UI elements into their functional categories and analysed the differences between C1 and C2 (see Table 3.8). Only letter spacing is definitively significant as users in C2 did not make letter-spacing changes at all. While no significant differences were found for the rest of the conditions, this is largely due to the nature of a design task. Take for instance the size of text. The only change that may be specified is that an element should meet a minimum size in order to be perceivable. However, users may increase the size of text much more than that, as they feel that it does not impact scrolling significantly.

Given that text is central to performing T1-T3, we see that in both C1 and C2, participants increased the font sizes, with C1 being larger across all UI functions. Letter spacing was modified only in C1, with spacing ranging from 1.5-1.83 across the different UI functions.

a C1 only
b C2 only
c C1 and C2

UI element	Positive						Negative					
	Font size	Letter spacing	Contrast	Visibility	Icon Visibility	Hit Target	Font size	Letter spacing	Contrast	Visibility	Icon Visibility	Hit Target
post-usr-pic				a								
post-usr-name	c	a	a									
post-loc	c	a	b				b		b			
post-opt					a							
post-img				a								
post-menu-like			c		c	c						
post-menu-viewcomm			b		c	c						
post-menu-share			b		c	c						
post-menu-bkmk			b		c	c			b			
post-likes	c	a	a						b			
post-text-usr-name	c	a							b			
post-text	c	a										
post-#tag	c	a							c			
post-viewcomm	c	a	c									
post-time	c		c						b			
comm-pic				c								
comm-name	c	a							c			
comm-text	c	a							c			
comm-#tags	c	a							c			
comm-time	c		c						b			
comm-usr-pic			c									
comm-input-placeholder	c								b			
comm-input-text	c								b			
comm-post	c		c									c
msg1-title	a					c						
msg1-back						a						
msg1-newmsg						a						
msg1-search	c											
msg1-suggestions	c											
msg1-pic				a								
msg1-name	c											
msg1-lastseen	c											
msg2-back					a							
msg2-pic				c								
msg2-name	c								b			
msg2-msg	c								b			
msg2-takepic			b		c				b			
msg2-input-placeholder	c											
msg2-input-text	c					c						a
msg2-input-box			b			c						c
msg2-post	c		c			c						b

Figure 3.18: Coverage matrix of the usability challenges positively/negatively addressed by designer-developers. a indicates challenges identified only by Empath-D (C1). b indicates challenges identified only by Google Accessibility Scanner (C2). c indicates challenges identified by *both* Empath-D and Google Accessibility Scanner. Blank cells indicate that no users identified challenges in either condition for that UI element.

This was corroborated by the observational data captured during the experiments. In C2, users found it hard to understand and use the relevant WCAG 2.0 success criteria (1.4.4 - Resize text). While 1.4.4 suggests that "text can be resized without assistive technology up to 200 percent without loss of content or functionality", participants also considered the resulting penalty to interaction (having to scroll a lot more due to larger text/buttons). Conversely, participants in C1 had the ability to directly simulate the cataract impairment using Empath-D, verifying that the font sizes that they chose were sufficiently large such that they could be perceived, and yet minimise the penalty to interaction.

Figure 3.19 shows an example design by a P8 in C2 (left), and P10 from C1 (right). In the former design, P8 focused on supporting the design task T1, enlarging the buttons for the two to 11 times larger a hit and visible area than the baseline. This resulted in less content being able to be seen in one page view (pushing down *post-likes*). While the much larger buttons help users to accurately press the buttons, we find from S1 that the cataract impaired users reported not having problems with pressing the buttons due to their familiarity with using mobile apps such as WhatsApp or Facebook. A more comprehensive set of screenshots that show this balance is given in Figure 3.20.

Usability of Tools. Participants using Empath-D reported higher SUS scores of 76.3 (*Acceptable*) as compared to using GAS, having a score of 65.2 (*Marginal*) [83]. One contributing reason is that all users found that GAS can be unreliable. It reported suggestions in app designs despite its obvious irrelevance or was unable to flag issues with some UI elements despite similar UI elements being flagged elsewhere in the UI, e.g., *post-menu-share*) (See Figure 3.21). However, 2 users (40%) indicated that overall GAS was useful for the in situ examination of the accessibility of mobile apps, providing a more concrete means (compared to WCAG guidelines) to identify potential problems that users may then map to cataract impairment.

Comparing Empath-D to GAS, more users reported observing the importance

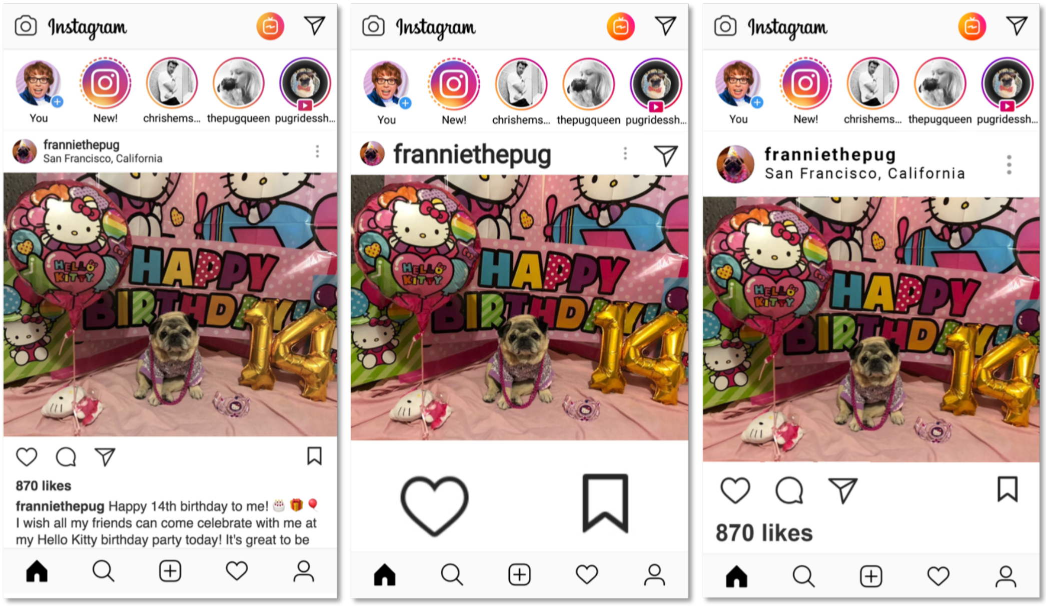

Figure 3.19: Balancing interaction design–one-page screenshot views of scrolling content. Left: Unmodified base app. Centre: Design from C2 (Google Accessibility Scanner) with very large like and bookmark buttons sacrificing content and interaction. Right: Design from C1 (Empath-D) showing balance in design despite changes made to increase elements.

Table 3.8: UI elements, grouped by key functions showing mean changes made by designer-developers.

UI Function	Cond -tion	Font Size (%)	Letter Spacing (px)	Cont -rast (%)	Visi -bility (%)	Hit Target (%)
button	1	58	1.83	18	98	118
	2	44	0	60	185	107
image-content	1	-	-	-	5	-
	2	-	-	-	0	-
image-profile	1	-	-	-	63	-
	2	-	-	-	16	-
text-content	1	52	1.5	-6	-	-
	2	31	0	-5	-	-
text-input	1	59	-	0	-	23
	2	34	-	0	-	20
text-navigation	1	28	-	0	-	-
	2	25	-	-1	-	-
text-status	1	43	1.63	31	-	-
	2	28	0	12	-	-
text-username	1	68	1.69	18	-	-
	2	40	0	8	-	-

of design elements that may otherwise have been overlooked when using Empath-D (3 vs 1 users). 3 (60%) users commented that Empath-D was easy to use, realistic and concrete. However, users (2, 40%) also indicated the need for *real-time editing* tools and annotation tools. With real-time editing tools, one may make changes and instantly observe the effects of the changes. Annotation tools on the other hand allow a run-through of the simulation, noting issues, and deferring the changes to post-simulation. While most users (4, 80%) of Empath-D noticed the latency in the system, all of them found that the latency did not affect their ability to use it to design. Users were mixed over the physical visual strain that was experienced when using Empath-D. 2 (40%) users reported not experiencing any strain at all in using Empath-D, while 2 (40%) users reported that it was straining on the eyes. Of the two users who reported visual strain, one had been working late nights, which may have contributed to this visual strain.

All users in C1 on the other hand found that Empath-D provided a concrete means to immediately identify usability problems. One user noted that Empath-D enabled her to identify problems with letter-spacing, which she stated was not in the WCAG 2.0. However, this is inaccurate–the WCAG 2.0 does contain recommendations about adjusting letter spacing–buried deep in Success Criterion 1.3.2 (Meaningful Sequence). We believe this reflects three issues in the WCAG 2.0: 1) that the WCAG 2.0 while extremely comprehensive, is onerous for use, and 2) the difficulty in mapping the pathophysiology of impairments to specific guidelines, and 3) it can be hard to interpret. The interviews with users alluded to this. Users found the WCAG 2.0 to be extremely lengthy (4, 40%), and often found it hard to map guidelines relevant to cataract impairment (5, 50%). User also found that the guidelines can be hard to interpret (8, 80%). One user suggested that *interactive examples* rather than textual explanations may present a clearer picture. However, they noted that the WCAG 2.0-Elderly (and WCAG 2.0 itself) is a rich source of information to provide conceptual guidance on possible issues to focus on (8, 80%).

No significant differences were found in the scores of the NASA-TLX.

Table 3.9: System Usability Score and NASA-TLX scores

Condition	SUS	NASA-TLX
1	$76.33^{\ddagger}$	11.64
2	$65.17^{\dagger}$	10.71

not Acceptable / $Marginal^{\dagger}$ / $Acceptable^{\ddagger}$ [83]

3.4.6 Conclusion

I studied the effects of using Empath-D, an augmented virtuality impairment simulation system, to support experienced designer-developers to design a mobile application for cataract-impaired users. The studies with 4 cataract-impaired elderly and 10 experienced mobile developers show that with the aid of augmented virtuality and WCAG 2.0 guidelines, the developers were able to better identify usability challenges of the cataract-impaired users and made more positive changes to the app design compared using the Google Accessibility Scanner with WCAG 2.0 guidelines. The developers also noted that Empath-D is more usable than the best in-situ tool for accessibility inspection–Google Accessibility Scanner–as Empath-D helps them to immediately and uniquely identify usability problems (i.e., letter spacing) and see the effect of changes made, while the accessibility scanner often points out irrelevant problems to the target users and can be unreliable for many design components of the target application.

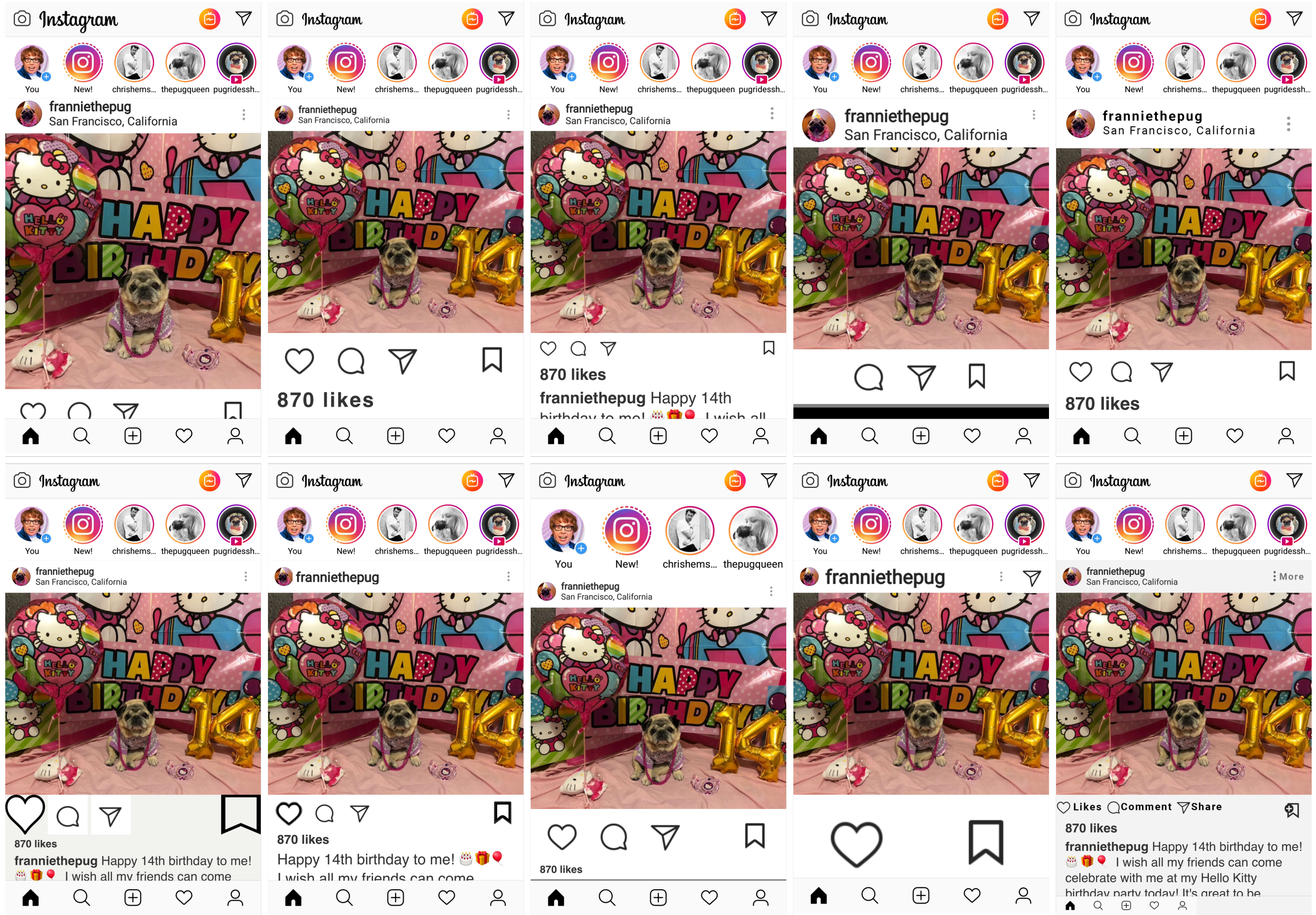

Figure 3.20: Final design screenshots of the landing page from all 10 participants. Images show what can be seen from one phone screen. Top row: Empath-D; Bottom row: Google Accessibility Scanner.

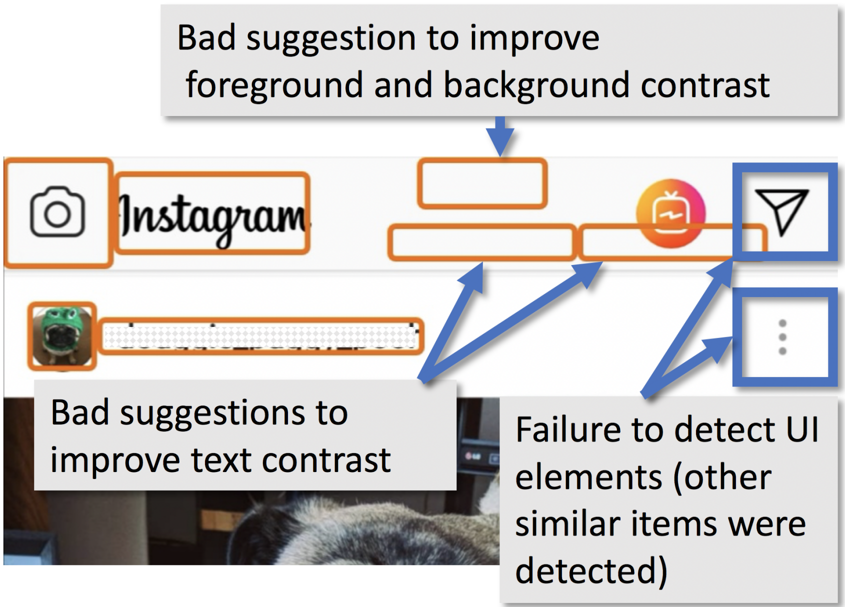

Figure 3.21: Scan from Google Accessibility Scanner showing bad suggestions.

Chapter 4

Related Work

This chapter surveys previous work related to this dissertation. My work spans across accessibility, human-computer interaction (HCI), mobile computing, and virtual/mixed reality. The intersection of these domains has allowed us to develop a first of its kind augmented virtuality impairment and environment simulation system to support mobile app designers to target and support impaired users in their designs. To the best of my knowledge, this is the first work to recognise the importance of this problem and to produce a viable and extensible solution. Empath-D and its validation build on the work in several areas, namely the design of applications for accessibility, the support that applications currently have towards accessibility, and in modelling and simulation for design. The following sections discuss these prior work.

4.1 Designing Applications for Accessibility

Newell et al. [144] point out that traditional user-centred design techniques provides little guidance for designing interfaces for elderly and disabled users due to the large variation amongst the type and degree of impairments. Many accessibility design guidelines [55,79,92] and tools [88,109,113,114,117,140,162] have been proposed and refined. However, the problems pointed out by Newell remain largely unsolved, which hinders elaborate design for a target user group with a specific impairment.

We begin with definitions. Many terms have been used to describe the common goal of making technology accessible to all types of users. A non-exhaustive set of nomenclature are *universal design* [139, 164], *inclusive design* [99, 125, 130], and more recently, *ability-based design* [170]. These terms overlap greatly in what they try to do in supporting the common goal of technology accessibility, differing usually on conceptual focus and coverage.

For example, one definition of *universal design* states "The design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialised design." [102]. Comparing, one definition for *inclusive design* states: "The design of mainstream products and/or services that are accessible to, and usable by, as many people as reasonably possible on a global basis, in a wide variety of situations and to the greatest extent possible without the need for special adaptation or specialised design." [11]. These terms have also evolved with its use, and as of an EU Ministers' meeting of 2009, many of these terms have been regarded as converging towards the term *universal design* [148].

This dissertation adopts a definition that is most closely aligned to the ideas of ability-based design [170]. While accessibility design often asks the question of designing by considering the impairments of a user, *ability-based design*, throws the focus rather, on a user's abilities, and what he can do. The user's ability, is also considered in the **context** in which it is exercised. These are important distinctions. Empath-D not only supports the multi-modal capability to simulate impairments, but also supports the simulation of the environment of use. As such, designers can consider the abilities of users, and innovate applications that *empower* users, rather than only redesigning existing applications to *accommodate* their use.

4.2 Supporting Application Accessibility

In the following subsections, we examine the different types of support for application accessibility. This section deals with techniques that are widely adopted. The subsequent section tackles modelling and simulation techniques, which while there are numerous works on, mostly reside in the research domain and have not seen widespread use.

4.2.1 Operating System Accessibility Support

Modern operating systems (OSes) desktop and mobile provide accessibility support that covers visual, auditory, and motor disabilities. For instance, Windows 10 [72], macOS Mojave [35], Android [3] and iOS [32] all provide talk back options to support vision-impaired users. This feature describes user interfaces and their objects, allowing users with impaired vision to navigate the user interface. Other common features are the ability to configure text size, colours, cursor-based magnification, text-to-speech, and dictation (speech-to-text).

While some of these features may work on their own without additional intervention by application developers (e.g., text-to-speech on text content), more often than not, developers need to understand accessibility problems and utilise the underlying accessibility APIs to enable these features. For instance, without item descriptors for UI elements such as buttons, screen readers will not be able to describe the intent of the button.

As with design guidelines (e.g., WCAG 2.0 [92]), they provide general accessibility support, and are not targeted to specific impairments. They–as with the WCAG 2.0–focus on high-level abstractions of impairments that are broadly the modality of the impairment such as vision, auditory, speech, motor impairments. Impaired users have to configure the accessibility features such as to best support their use of the device and its applications, which more often than not requires user accommodation.

4.2.2 Design Guidelines

Newell et al [144] highlighted that the standard guidelines for designing disabled-friendly UIs are too general and lacked empathy for users. Design guidelines [4, 31,55,79,92] as with OS-level accessibility both focus on high-level abstractions of accessibility (e.g., vision, auditory, speech). For instance the WCAG 2.0 [92] lists that the use of colour "is not used as the only visual means of conveying information, indicating an action, prompting a response or distinguishing a visual element". This requires *interpretation*–the designer needs to understand what that guideline means, and formulate multiple solutions before choosing an implementation design in his application. This can prove to be challenging given the ambiguity in specification language and the requisite level of accessibility knowledge being barriers [101,105].

Design guidelines are often misused. Petrie et al. [149] reported 30% of the websites in their sample overstating claims about their accessibility. They suggest that site owners may not fully understand the differences between automated (such as with aChecker [113]) and manual testing with users, and may without questioning rely on the results of automated testing. This is corroborated by Lazar et al. [134], who found that the site owners they surveyed were unclear about the role of accessibility tools and the related guidelines. In an empirical study of blind users on the Web, Power et al. [150] found that the WCAG 2.0 was able to cover only 50.4% of the problems they encountered. This study provided direct evidence that demonstrated the ineffectiveness of a guidelines-only (and problem-solving) approach to designing for disability.

While much work has been done in the area of accessibility for the web [92, 100, 150], considerably less work has been done on mobile app accessibility. With web content increasingly being accessed from mobile devices, the W3C released a note to help map the WCAG for mobile devices [40]. To support developers to consider accessibility in their designs, Apple [31] and Google [4] both released mobile accessibility guidelines, which are considerably simpler than the WCAG. The mapping of web guidelines to mobile applications are important in today's ecosystem, especially given the blurring of the lines between web and mobile applications as provided by frameworks such as Cordova [5] and React Native [48], or Progressive Web Apps [47].

4.2.3 Accessibility Checking Tools

With web content being a key means by which information is disseminated, accessed, and doing so on the go, web accessibility is increasingly prioritised by different jurisdictions [1, 55, 69] and web content owners [149]. A check as of Nov 2018 on a listing of such available tools provided by the Worldwide Web Consortium Web Accessibility Initiative [70] shows 119 different *automated* accessibility checkers spanning across 12 reference guidelines (e.g., WCAG 1.0, 2.0, 2.1, US Section 508 [55], JIS-Japanese Industrial Standard). Ivory et al. [127] also provide a comprehensive set of accessibility checking tools categorised across different user abilities (e.g., vision, hearing, mouse use, keyboard use). Many well known examples of these tools exist: DynoMapper [13], WAVE [68], and aChecker [113]. These tools flag out the compliance of web content with the accessibility guidelines. For instance, aChecker [113] reports the compliance with the WCAG, classifying problems into "Known", "Likely" and "Potential" problems, identifying the specific snippets of HTML that raise these issues.

Google in 2016 introduced accessibility unit testing on Android [77]. Integrated via Espresso [14] (an Android UI testing framework) and Robolectric [49] (an Android unit test framework), accessibility checks piggyback on existing unit tests that have been written in application development to report possible accessibility problems. Simultaneously, Google also introduced Google Accessibility Scanner [19], an accessibility inspection tool that allows developers to take snapshots of application UIs, and produce an annotated report over this snapshot on the accessibility issues. This supports a direct means of examining accessibility problems on Android applications *without needing to code*. Apple provides similar functionality to Google through *Accessibility Inspector* [8]. It allows a developer to run audits to identify accessibility issues, and also supports interactive mouseover accessibility inspection.

Since these tools rely on guidelines, they too suffer from the same problems identified previously in Section 4.2.2.

4.3 Modelling and Simulation for Design

4.3.1 Virtual Environment Simulation

The conception of virtual reality (or environments) began early in the 1950s with Morton Heilig's vision of an "Experience Theatre" that could encompass the senses and draw the viewer into the activity [89]. Predating digital technologies, he filed a patent [120] in 1957 for a stereoscope that today could be mistaken for an early prototype of a Samsung Gear VR [54]. This led to the development of Sensorama [121], in which sight, sound, smell and touch could be simultaneously engaged. In the patent, Heilig recognised its utility to "teach and train individuals, without subjecting the individuals to possible hazards of particular situations".

Digital VR as we know it today began with Ivan Sutherland and his student Bob Sproull's work on a head-mounted display (nicknamed The Sword of Damocles) that showed 3D wireframes as processed by a computer [161]. Simulation for the purposes of entertainment, military training (e.g., flight simulations) and healthcare predate VR. However, the introduction of VR presented immersion that could not be achieved before–generating a greater sense of *presence* [136], that supports users presenting natural physiological and psychological responses (e.g., fear, as elicited from a walk the plank over a deep pit VR simulation [155]).

While VR is most commonly found as a head-mounted display today (e.g., Samsung Gear VR [23, 54], a fundamental problem persists–the user is unable to see their own bodies, and is thus limited in natural physical interaction. Instead representations of body parts (typically arms) are given to support the *context specific interactions* (e.g., motion tracking to support waving, on-device buttons used for selection), and are tracked via instrumentation such as with the Oculus Touch [44], wands from the HTC Vive [24] or gloves [56,66]. An alternative that helps with this are Cave Automatic Virtual Environments (CAVE) [103]. Cruz-Neira et al [103] developed the CAVE, which uses multiple stereo projectors synchronised with stereo-shutter glasses to present VR in a cube-like room. Users can see their own bodies, and interact with the virtual world using specially designed instruments. While CAVEs offer such advantages, they are costly to setup, requiring high-end projectors, tracking systems and computing equipment on top of the large space to set it up in. Since Empath-D requires physical interactions with a mobile phone to support naturalistic actions and responses, a *pure VR solution is insufficient*.

Rosenberg [151] working for Armstrong Labs in the United States Air Force developed *Virtual Fixtures* the first fully immersive *mixed reality* system that enabled human users to control robots in real-world environments. This included physical objects and virtual overlays termed *fixtures* that were implemented haptically and auditorily. The use of such fixtures improved the remote operation performance of users, despite users not being able to see their own hands.

There is a tremendous body of work that deals with the many ways in which mixed reality may be employed–through visual, auditory, or haptic means–to support user interaction. Some example applications are the use of mixed reality for training [45, 108], games [97, 172]. This dissertation focuses on *augmented virtuality*, a subconcept of mixed reality (as described in Section 2.1).

The latest wave of interest in virtual and mixed reality stems primarily from the virtual [23,43,46,54] and mixed reality [36,38,39] headsets finally being within the reach of the consumer. This has resulted in new interest from the research community to explore the means by which to interact or use such systems. While earlier work adopted hand-based instrumentation in the form of gloves and other such devices (wands), more recent work has targeted less obtrusive techniques for hand interaction [86]. In particular for augmented virtuality techniques, there has been recent work to explore how input may be performed on physical objects. McGill et al. [141] and Knierim et al. [133] both explored keyboard input techniques using real hands brought into the virtual world, as well as avatar representation hands. In the mobile interaction space, [132] used a hovering to highlight keys on a mobile phone's virtual keyboard in order to support typing (without being able to see a hand). While Empath-D is not the first to develop hand-based augmented virtuality approaches nor to support input on mobile devices, it is the first of its kind approach to combine both approaches–augmented virtuality interaction with mobile devices–to provide a greater sense of presence (as compared to [132]) to support naturalistic interaction.

4.3.2 Impairment Simulation

4.3.2.1 Physical Impairment Simulation

Numerous works in different forms or compositions have been developed and studied [2, 63, 110, 116, 146, 171, 174]. The earliest known work in physical impairment simulation for design was carried out in the 1950s. Industrial designers wore artificial limbs to empathise with war veterans who had limbs amputated [106]. In later work, Pastalan et al. [146, 147], used physical impairment simulations of visual, auditory and tactile sensitivities modelling the elderly between 70-80 years of age to empathise environmental considerations for architecture.

Later work by Wood & Troutbeck [171] studied the impact of visual impairment on driving. They simulated three forms of visual impairments; cataracts, ocular visual field restrictions and monocular vision in their studies. These impairments were implemented by modifying swimming goggles to suspend the impairment filters (e.g., frosted lenses to reduce contrast and increase glare sensitivity), and *calibrated using standardised tests*. Physical impairment simulation has also been used to examine the implications on wayfinding for visually impaired users. Rousek et al. [153], used five different visual impairment simulation goggles produced by Flax [110] in their study. Notably, these physical impairment simulation goggles are also calibrated to correspond to specific visual pathologies of the impairments. For instance, cataract simulators are rated correspondingly with visual acuities such as 20/80 etc., which correspond to standardised measures using charts such as the Snellen chart [160]. Empath-D uses the same impairment simulation goggles to demonstrate its ability to provide similar functionality.

Cardoso et al. [96] provide a good overview of the different physical impairment simulation techniques that have been used in prior work. These range from the simplest of simulations such as foam earplugs to simulate hearing loss, to braces that restrict motion.

4.3.2.2 Virtual Impairment Simulation

Many different pieces of work address virtual impairment simulation [82, 88, 109, 114, 115, 122, 129, 140, 145, 162, 165, 166, 169], however, this review will highlight the key papers that presented more groundbreaking work in this area. In the virtual space, the earliest known work that uses computerised approaches to impairment simulation for design was by Higuchi et al. [122]. They developed a computational model of human vision over light adaptation, spatial and spectral sensitivity. This approach allowed them to simulate elderly vision such as to evaluate the design of shower control panels.

Takagi et al. [162] built aDesigner, a disability simulator that helps designers ensure that their web content and applications are accessible and usable by the visually impaired. It parses a web page's HTML to perform various analyses such as reaching-time analysis (how long it takes to get to content) and annotating inaccessible content. It then visualises these analyses to aid the designer to identify accessibility problems. Mankoff et al. [140] similarly developed a system EASE (Evaluating Accessibility through Simulation of User Experience) to simulate the experiences of users with vision or motor impairments on the desktop. The advantage provided by EASE is that it is independent of any particular application or operating system, and allows evaluations to be made *across different applications* and *simulations over IO* such as keyboards and mice (as a motor impairment). This is important especially in light of realistic usability studies which may span across multiple application and input device use. Goodman-Deane et al. [115] describe an early prototype of their own software that targets both visual and auditory impairments. Similar to [122], it overlays visual impairments on snapshots of images. Auditory impairments are generated as using frequency-based techniques to emulate hearing loss such as frequency selectivity and loudness recruitment.

Visual impairments are often a function of where a user is looking. To these ends, Vinnikov et al. [165] and Kamikubo et al. [129] both adopt gaze-tracking techniques such as to present impairments that track to where a user is looking. Head mounted displays (HMDs) such as the Samsung Gear VR [54] have become cheaply available to mainstream consumers. They support head-tracking, and allow for a rough estimate of line of sight such as to perturb visual impairments accordingly. More recent work has adopted these HMDs to develop virtual impairment simulations [82, 169], including Empath-D [98, 131]. However, both [82] and [169] utilise these HMDs as augmented reality displays. Empath-D on the other hand leverages the full power of virtual environment simulation that is necessary for design context, and brings the key components of reality (i.e., hand and phone tracking) into the environment.

Biswas et al. [84, 85] propose a more orthogonal approach to impairment simulation. Their work is closely related to the work on user modelling and simulation such as GOMS modelling [94,95]. By creating impaired user models for perception, cognition and motor behaviour, it is able to predict their cursor traces and task completion times, which allow designers to make decisions on an interface's usability for impaired users.

Chapter 5

Conclusion

The growth of adoption of personal and ambient computing devices and the advent of high-speed connectivity has enabled extremely powerful and diverse mobile computing applications that are used everywhere. Unfortunately, without appropriate means by which to evaluate designs for users with disabilities, the potential of these mobile computing applications cannot be sufficiently considered such to empower users with disabilities–a demographic that arguably could benefit more from these mobile computing capabilities.

This dissertation provided a solution to this problem. It presents Empath-D an augmented virtuality impairment simulation system that allows designers evaluate their mobile application designs through experiencing the impairments of users with disabilities.

In this chapter, I first summarise in Section 5.1, the research contributions made by this dissertation. Next, I describe the possible future work in Section 5.2. Finally, Section 5.3 places this dissertation in perspective with the current state of inclusive mobile application research.

5.1 Contributions

The overall contribution of this dissertation is the support of mobile app evaluation in the process of designing apps for visually impaired users. This encompasses two major contribution areas in Human Computer Interaction. The first area is an artefact contribution–Empath-D–its concept, design, and validation of its ability to support naturalistic interactions using augmented virtuality, emulate impairments and its impact on usability. The second area is in empirical contributions: this dissertation examines the effects of impairments on cataract impaired users, and shows that the use of impairment simulation in Empath-D results in superior design outcomes in identifying usability problems.

5.1.1 Artefact Contribution

This dissertation has contributed to the design and validation of our system, Empath-D, the first of its kind augmented virtuality system that allows the emulation of impairments and supports naturalistic interactions with a virtual smartphone. The key design concept of Empath-D is the ability to perform naturalistic interactions with a physical/virtual smartphone in a way that supports a user's tactile, proprioceptive, and visual perceptions to maintain and support presence in the virtual environment. To support tactile and proprioceptive perceptions, we let users hold on to a physical smartphone. To maintain visual perception, we brought the user's actual hands into the virtual reality, and mirrored physical-virtual interaction with the smartphone. This required a tight integration and calibration within the system to produce low latencies sufficient for use. We showed through our experiments, that the system is able to emulate visual impairments on par with existing physical simulators. Lastly, we showed that despite the latencies introduced by utilising augmented virtuality, Empath-D can be intuitively used such that the accuracy of touch is minimally compromised.

5.1.2 Empirical Contribution

This dissertation has also produced important empirical contributions. Through the two-part study methodology, I identified usability problems that impaired users faced, and the usability problems that could be identified using the most current design methods vs Empath-D. This formed a basis to compare and understand the usability issues that an augmented virtuality solution like Empath-D can offer over existing methods. This is an important empirical contribution, since future studies can be performed for other impairments using a similar basis. My experiments showed that current tools such as design guidelines and Google Accessibility Scanner are severely lacking, but alternately have some advantages (*completeness in coverage*) which may be employed in concert with Empath-D which provides a *concrete experience*. I also identified some of the issues of using such an augmented virtuality solution for design–by being immersed in the system, users lack the ability to make notes over the usability issues the identified, and therefore demonstrating the need for more work in the area of tool support. Most importantly, the demonstration of the superiority of in-situ naturalistic impairment simulation over current methods is a strong indicator to the accessibility research community that 1) there is a severe gap in the tools that enable designers to design for accessibility, 2) such methods or alternatives are worthwhile researching and improving on, and 3) the work has only begun in this new area, and much more work needs and can be done to support the creation of an empirically validated database of impairments.

5.2 Future Research Directions

The previous sections discussed the more immediate considerations for augmented virtuality-based simulations for design. In this section, I discuss the longer term research directions for this area.

Matching usability problems with design outcomes. My thesis research has focused on supporting the identification of usability problems in application designs. While identification is an important step towards addressing the problems, it is not necessarily clear that the identification of these usability problems translates into designs that always better supports impaired users.

First, is there a mismatch between impairment simulation outcomes and the adapted abilities of users? Intuitively, if one experiences the issues that are involved, then one may be able to identify and address it. Impairment simulation works to bring up the issues pertinent to a particular setting of that impairment, however, users with disabilities often through necessity develop mitigating strategies (e.g., raising the phone closer to the eyes to see) in coping with their impairments. That is, impairment simulations are often a representation of the *initial challenges* of becoming disabled. Silverman et al. [157] notably find that experience simulation can reduce the perceived adaptability of being physically disabled. This may lead to overcompensation for the abilities of users with impairments in the designs, and may not sit well with users. More work needs to be done in this area to understand the impact of user adaptation towards application usability.

Simulation fidelity and range of testing Empath-D needs to be further developed to support greater sensing capabilities that match or even *supersede* those provided by the smartphone. The sensing capabilities of the physical smartphone should be appropriately represented in the virtual environment in a seamless fashion. For instance, location in the virtual environment can be mapped to the virtual coordinates in the environment and reflected in the virtual phone, and virtual cameras that show frames of the virtual environment on the virtual smartphone are but two examples of enhancements that support existing geolocation and camera applications respectively. However, by providing capabilities that are not available on existing hardware, and by providing realistic environmental simulations such as the home or the streets, Empath-D becomes a more powerful prototyping tool for interaction design. For instance, a smartphone may have a virtual rangefinder widget enabled. This may have different scenarios of use, and different implications when used on the streets or at home. For instance a blind user at home may use his virtual rangefinder enabled smartphone to locate objects. The same virtual phone on the streets may be used through a sweeping motion to generate a three-dimensional audio field that cues the blind user of obstacles in his periphery. This application of Empath-D goes beyond impairment scenarios, and opens many opportunities for research that deals with interaction design with mobile and wearable devices.

Advanced tool support Empath-D is a prototype augmented virtuality tool to support the evaluation of mobile applications designs for users with disabilities. The use of augmented virtuality poses several problems for evaluation. First, the attention of users is required for them to examine the usability problems. If they do not pay attention to an issue, or fixate on another, they miss some important usability problems. Second, users often want to identify several usability problems at once when using Empath-D. Since they are immersed in the VR, they cannot make a note of the identified issues. One potential solution is to develop a cursor overlay. It would allow users to use digital styluses to circle and note down the problematic aspects of the UI. The same annotations may also be used as a means to develop a heat map over areas that have been considered and remind users to examine other aspects of the UI.

Even when a user focuses on a suspected problem in the UI, they may not be able to conceptualise all the problems related to that element. While the Empath-D offers a concrete experience, guidelines offer *completeness*. An intelligent inspection mode within Empath-D that marries the benefits of both could potentially provide the support needed by designers (especially novices) to better understand the problems.

Developing an open-source library of impairments and impairment profiles. Empath-D is meant to be an open-source tool, that any designer may adopt to aid in their design for accessibility and positively impact the lives of users with disabilities.

It is the long-term goal of Empath-D to develop a library of *empirically validated impairments* and *impairment profiles* to support this. The work in this dissertation has mainly developed and tested vision impairments; and while we also developed auditory impairments and haptic impairment prototypes, these have not been evaluated with users. With great diversity in impairments and the difficulties of access to users with disabilities, I believe the work to develop these impairments and profiles, can only be accomplished by exciting and leveraging the research community. This dissertation is the first step in this direction.

5.3 Closing Remarks

This dissertation demonstrates that the use of augmented virtuality impairment simulation is an effective means of supporting designers to evaluate the designs of mobile apps for users with impairments. This work breaks ground in an area of accessibility, that has far too long focused firstly on the web [134, 150], and secondly on creating design guidelines and frameworks [4, 31, 92] that have limited efficacy in supporting users with impairments.

Empath-D is nascent system, but has tremendous potential to do more. Through the studies in this dissertation that examines designers using Empath-D, this dissertation guides the way for future researchers to begin a new area of research–to develop new impairment simulations and modalities for augmented virtuality, and to study and validate them. This requires significant effort and interest from the accessibility research community. This will develop a body of work that has direct impact on today's applications towards better designs, and also supports the creation of new classes of applications that directly support users with impairments. While researchers may provide the tools and theoretical underpinnings, the development of mature tools and more critically–its adoption–still relies on the economic interests of designer-developers. I believe that this dissertation and Empath-D has taken a step in the right direction. By providing a truly authentic experiences through the eyes of users with disabilities, I am confident that we can encourage and empower designers to do more for mobile accessibility.

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Appendix A

Implementing Empath-D

The following describes the implementation work that was primarily performed by a fellow student, with design directions and inputs from the professors and I.

A.1 Tracking the physical smartphone

Empath-D uses fiducial markers, displayed on the physical smartphone's screen, to localise the smartphone efficiently (See Figure A.1). It takes a colour image as an input, and returns the transformation relative to the camera's coordinate system: translation and rotation, i.e., x, y, z, roll, pitch, yaw from the RGB-D camera's coordinate system. We employ a technique proposed and detailed in [112].

The Empath-D Hand Tracker component tracks the physical phone using markers captured by the camera. Each marker, displayed on the phone screen, has a distinct pattern. The tracker knows the position of each marker (e.g., top-left, top-right, bottom-left and bottom-right) in the physical smartphone screen's coordinate system. The system first detects these markers in a given colour image, identifying them based on their unique patterns (See Figure A.1).

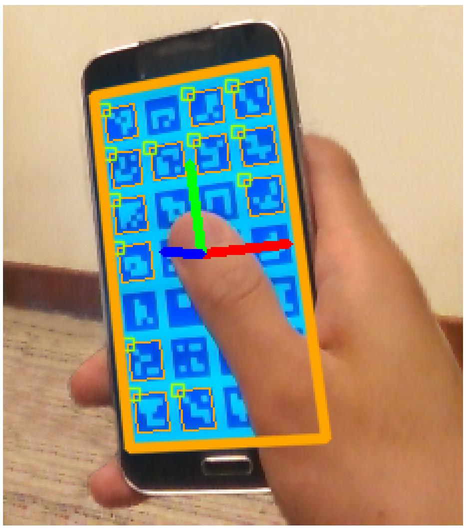


Figure A.1: Tracking the physical phone with fiducial markers.

In particular, the system recognises the coordinates of each of the four corners of each marker. Moreover, the system knows the true size of, and separation between, each marker.

It then uses an object pose estimation algorithm (provided by openCV's *solvePnP* function [58]), along with the array of fiducial marker points, to compute the 3-D position and orientation of the smartphone. The stream of images from the Android emulator are then mapped onto the virtual world coordinates of the virtual phone (See Figure A.2). Past results [112] show that this technique can compute an object's position and orientation with sub-cm level accuracy.

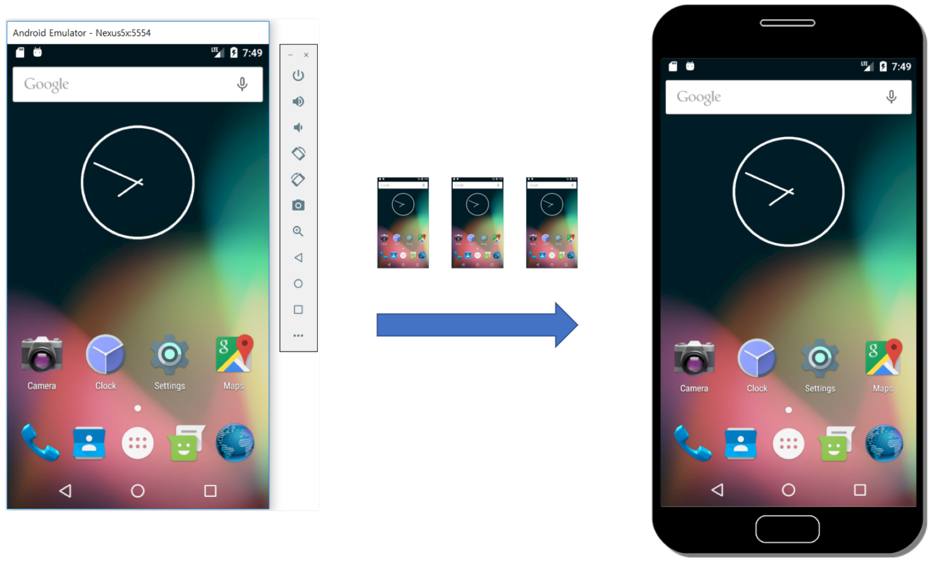


Figure A.2: Android Emulator screen frames streaming and mapped onto position and orientation of the phone from fiducial marker tracking.

This fiducial marker-based algorithm would fail under two conditions: (a) when all the markers are occluded by the user's hand, and (b) if the ambient illumination levels are too low or too high, reducing the contrast level of the markers. To tackle (a), the smartphone screen uses an entire array of markers displayed across the scene, thereby ensuring correct smartphone tracking as long as some part of the phone is visible. Contrast concerns are not particularly relevant in our scenario, as we assume that the user is testing the app in a regularly lit work/office environment.

A.2 Hand Segmentation

Empath-D uses the frames captured by the RGBD camera to track and segment the user's hand. For each frame, we extract the segment (polygon of pixels) that represents the user's hand, and render that segment in the virtual world. As the goal of hand-tracking is to provide the user with a natural view of her smartphone interactions, we restrict the tracking technique to a 3D region of interest (ROI) that is centred at the phone, with a depth of $2cm$ and a planar boundary of $6cm$ (See Figure A.3). In other words, we only track the hand while it is $\leq 2cms$ away from the smartphone screen, and within $\leq 6cms$ of the smartphone edges.

A straightforward approach is to apply a depth-based segmentation strategy, where we first isolate only the foreground points which lie within a depth=$2cm$ of the smartphone surface. However, we empirically observed that the glossy surface of the smartphone resulted in inaccurate depth estimation for points located on the smartphone's screen. This

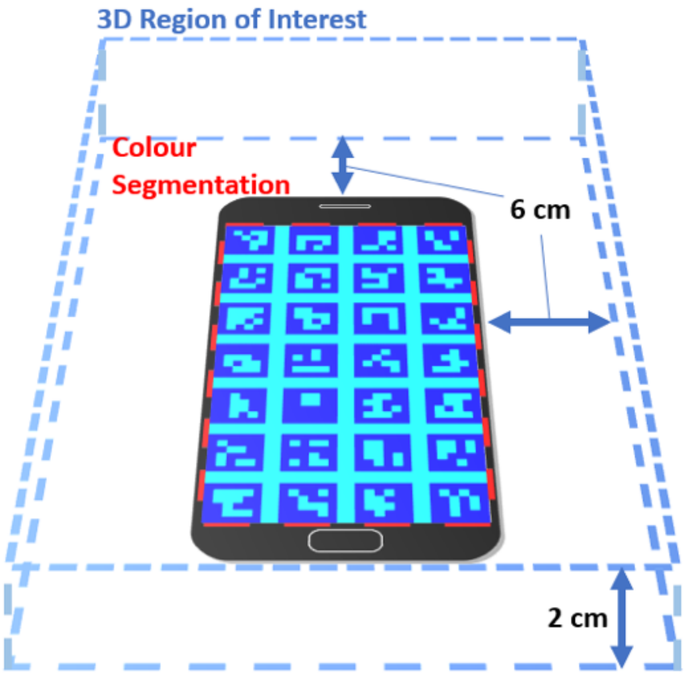


Figure A.3: 3D Region of Interest for Phone-Hand Segmentation

is because the Intel SR300 uses infrared coded light patterns to perform depth sensing. Glossy surfaces have high reflectivity, which perturb these coded light patterns. Accordingly, we implemented two separate segmentation methods (detailed in Algorithm 1): (case A) a colour-based segmentation approach to identify points which are directly over the smartphone, and (case B) a depth-based approach to identify points which are near, but not over, the smartphone's screen. We apply the colour-based segmentation to the points inside the screen's border (thick orange contour in Figure A.1) and the depth-based approach to the points outside.

Colour-based segmentation: We adopt the colour-based technique proposed in [159]. The approach tests RGB values to segment foreground (hand) from background, coloured in blue. In our scenario, we target human skin as the foreground. Human skin has a property common in all races: its R value has about twice the value of G and B ($R \approx 2G \approx 2B$). Given the property of human skin, we obtain a formula that discriminates the foreground from the background whose B value is 1 (line 11 in Algorithm 1). τ is a user-tunable threshold which allows it adapt to different lighting conditions.

However, note that, to enable tracking of the phone, the phone's screen cannot be completely blue, but will need to contain the array of fiducial markers. We tackle both problems simultaneously by using blue (R=0, G=0, B=1) to colour the markers, over a cyan (R=0, G=1, B=1) background. Here we modified only G value, which is unused in the colour-based segmentation.

Points outside the smartphone's screen are segmented using the depth-based approach. After identifying the points corresponding to the user's hand, the system translates these points to 3D coordinates in the camera's coordinate system, using the associated depth values.

Algorithm 1 Hand Segmentation

Input: $T \leftarrow$ *Phone's translation* (3-D vector)
Input: $R \leftarrow$ *Phone's orientation* (3×3 rotation matrix),
Input: $F \leftarrow$ *RGBD Frame*, 2-D array that each entry $F_{i,j}$ holds a color value and 3-D position relative to the camera.
Input: $V \leftarrow$ *3-D region of interest* (relative to the phone)
Output: $fgMask$, 2D bool array whose dimension equals to F

$fgMask[i, j] \leftarrow$ **false** for all (i, j)
for point (i, j) **in** F **do**
  if (i, j) in *screen_border* **then**
    /* Case A: Blue background segmentation */
    $fgMask[i, j] \leftarrow 1 - Blue(F_{i,j}) + 0.5 \cdot Red(F_{i,j}) > \tau$
  else
    /* Case B: Depth-based segmentation */
    $pos_{phone} \leftarrow R^{-1} \cdot (Position(F_{i,j}) - T)$
    $fgMask[i, j] \leftarrow (pos_{phone} \in V)$
  end if
end for
return $fgMask$

A.3 Rendering the hand in the virtual world

After detecting the hand segment, the system renders it in the virtual world. The system passes the tracked hands to the *Virtual World Renderer*, sharing the (i) 3D structure of the hands (surface mesh), (ii) colour image of the RGB-D frame (texture), and (iii) mapping between the surface mesh and the colour image (UV map). In common rendering engines (e.g. Unity), the 3D structure of the hand is represented by a *triangle mesh*–i.e., a set of vertices, constituting individual small triangles. The mesh is rendered at the same location as the user's hand in the real world. As the user's hand is localised in the coordinates of the RGB-D depth camera, the location is offset by an additional depth value (7 cm in our implementation), to reflect the additional distance between the centre of the user's eyes and the depth camera. An important characteristic of our algorithm is that we render the *actual image* of the user's hands over this triangle mesh. Figure A.4 illustrates the Delaunay triangulation of a set of points. The mesh is combined with the hand's image (Figure A.5), and rendered in the VR display. Extracting and rendering the actual image of the user's finger enhances the immersive feeling of real-life smartphone navigation in the virtual world.

The complexity of the mesh–i.e., the number of vertices (or triangles) in the rendered hand–is an important parameter in the rendering process. A larger number of vertices captures the contours of the hand more precisely, resulting in a more life-like image. However, this also results in added rendering latency in the rendering engine. To support the twin objectives of low-latency and life-like rendering, we utilise a sub-sampling technique to construct the mesh. Specifically, Empath-D preserves all the points on the edges of the segment, to preserve the precise contours of the hand. However, it performs a 32-fold down-sampling of the interior points (prior to constructing the Delaunay triangulation), along both the row and column axes, to reduce the computational time significantly, without materially affecting the reconstructed hand image. We shall show, in Section A.5, how our prototype Empath-D implementation uses this technique to achieve our twin objectives.

Figure A.4: Delaunay Triangulated Mesh of Hand

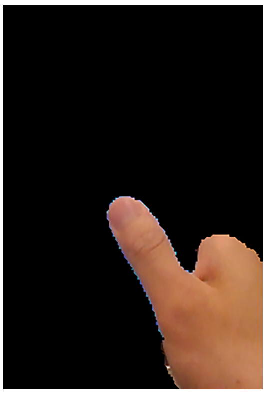


Figure A.5: Segmented Hand

A.4 Impairment Simulation

Empath-D aims to enable evaluation of the usability of app designs under visual, auditory, and haptic impairment simulation (See Figure A.6). Realistic simulation of various impairments in the VR world is the essential requirement to achieve this goal.

There has been a thread of research to simulate impairments through physical simulator devices [2,63,110,153,174]. For instance, Zimmerman et al., use goggles and enclosing materials to simulate low vision impairments [174]. These hardware simulators generalise the impairment pathology rather than emulate exactly how an impairment is. However, impairments can vary greatly between individuals. For instance, glaucoma generally progresses in deterioration from the periphery towards the centre of vision, but in reality, it comes in different shapes and severity, affecting the usability of applications in different ways. Existing physical impairment simulators simply approximate this as a central circle of clarity, with blur through to the periphery. Empath-D is advantageous over existing physical simulators in the following ways, it allows: 1) impairments to be customised, 2) simultaneous manifestation of multiple impairments, 3) the addition of new impairments easily.

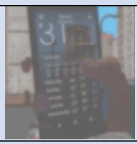
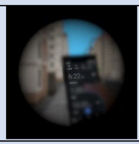
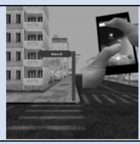
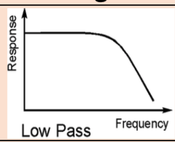
	Visual			Auditory	Haptic
Impairment	**Cataract**	**Glaucoma**	**Colour Blindness**	**High-frequency Hearing Loss**	**Hand Tremors**
Presentation					
Functional Presentation	Loss of visual acuity	Loss of peripheral vision	Degradation in colour presentation	Loss of high frequency audio	Hand movement resulting in inability to interact

Figure A.6: Visual, auditory, and haptic impairments implemented in Empath-D

A.4.1 Web Configuration Dashboard

Figure A.7 shows the prototype of the web interface for designers to customise impairments for the target user group. The web interface can be configured with the necessary hooks to enable or disable impairments. Each impairment can be set up with parameters that reflect the functional representations of impairments. We represent cataracts using a combination of a Gaussian blur filter, and a contrast reduction filter–each with its own intensity adjustments to reflect the different levels of impairment.

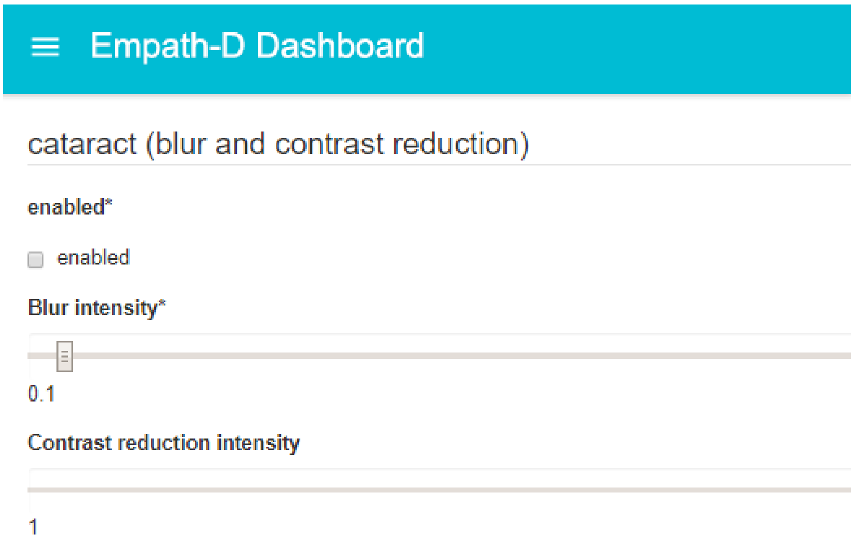


Figure A.7: Screenshot of the Empath-D impairment configuration dashboard

A.4.2 Simulating Visual Impairments

Vision is the dominant sensory system by which humans perceive the world, and is a key focus for Empath-D. Vision impairment is one of the most common causes of accessibility problems that comes with age. Common vision impairments include cataracts, glaucoma, and age-related macular degeneration. Such vision impairments present as reduced visual acuity, loss of central/peripheral vision, or decreased contrast sensitivity. It is widely studied that these symptoms can affect the interaction with various desktop and mobile applications; for example, humans use peripheral vision to pre-scan text ahead of his/her point of focus. As the peripheral vision narrows, the scanning becomes less effective, which slows reading [135]. In this work, we examine and simulate two commonly found visual impairments - cataracts and glaucoma.

Our approach is to apply an image effect at the "eyes" (i.e., a camera pair of view renderers) of the VR scene. From this camera pair, the image effect will apply to all other objects in the scene (e.g., smartphone, fingers, scene), just as how impaired users would experience it. We employed various image filters for different impairments, which 1) provide realism of impairments to help designers to find out usability issues and take corrective actions, and 2) have small computational overhead not to add noticeable delays to our entire emulation.

This approach is flexible and lightweight. The impairment simulator's intensity is configurable at runtime, with the image effects only being applied at the last stage of the rendering pipeline.

Glaucoma presents functionally as a *loss in peripheral vision*. To simulate glaucoma, we use a vignette with a clear inner circle, blurred inner-outer circle, and black extending

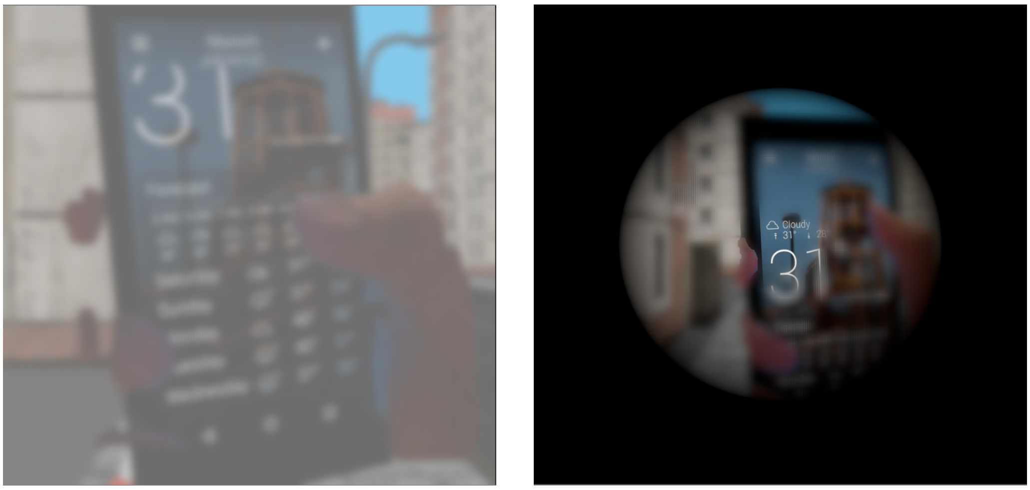


Figure A.8: Simulated cataract (left) and simulated glaucoma (right)

outwards from the outer circle (see Figure A.8). ***Cataracts*** presents functionally as *reduced visual acuity* and *reduced contrast sensitivity*. We use a blur filter to simulate reduced visual acuity, and a contrast reduction filter to simulate reduced contrast sensitivity (see Figure A.8).

The functional aspects of vision impairments are straightforward to create in VR, which give Empath-D high extendability to implement other types of visual impairments. While we just described two impairments pertaining to our studies, it is easy to create other impairments such as colour filters to simulate colour blindness. However, we leave the effect of eye movements on impairments as the future work. Since eye-tracking is currently not supported in Empath-D, a user will need to move his head to achieve the same effect.

A.4.3 Simulating Other Modalities

We discuss how other modalities may be simulated in Empath-D.

Hand Tremors. Hand tremors are a common symptom of Parkinson's disease or Essential tremor and make it hard for one to precisely point on a touchscreen. A hand tremor may be characterised by the frequency and amplitude of oscillatory movement. Since we present virtual representations of the user's hand (i.e., as a 3D mesh) to enable his interaction with the virtual mobile phone, Empath-D similarly perturbs this 3D mesh in VR to create hand tremors. While a user may physically not experience hand movement, the visual perturbation would be sufficient to hinder accurate touch to simulate hand tremors.

Hearing Loss. High-frequency hearing loss is a common impairment for the elderly population. People diagnosed with high-frequency hearing loss are unable to hear sounds between 2,000 Hz and 8,000 Hz. These people often struggle to understand or keep up with daily conversations (missing consonants in higher registers, such as the letters F and S or female voices). Empath-D applies a bandpass filter over the output sound of the target application to diminish the sound signals between 2kHz and 8kHz and plays the filtered audio feed through the VR device.

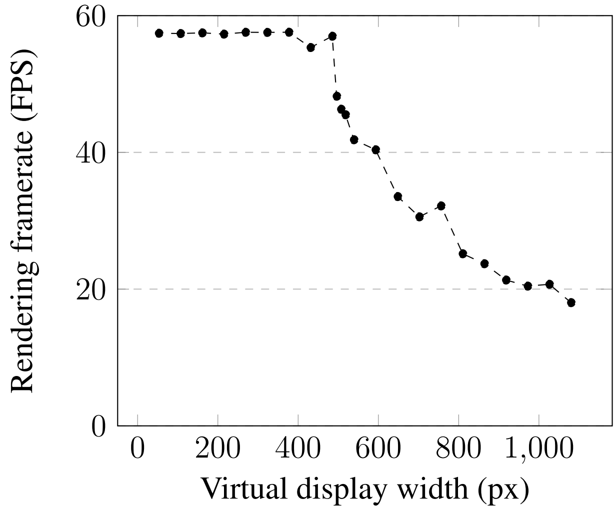


Figure A.9: Rendering frame rate under varying virtual display resolution (width : height = 9 : 16, default resolution of Android emulator is 1080x1920)

A.5 Implementation

A.5.1 Rendering an Emulated App

We used empirical studies to determine an appropriate screen resolution and frame rate to render the emulated app (and the smartphone) in the VR headset. Empath-D obtains screenshots of its mobile emulator using the Android virtual display [60] and transmits these screenshots over WiFi to the Gear VR device. The overhead of transmitting and rendering these emulated screenshots is proportional to their resolution. The default 1080p resolution could sustain a frame rate of only 18 fps, which causes visible jerkiness. To reduce this overhead, we reduced the resolution (using *setDisplayProjection()* method), and applied *differential transmissions*, sending a screenshot only when the emulated app's display changes.

Figure A.9 shows the experimental results on the tradeoff between the resolution and the rendering frame rate, obtained while playing a video to ensure continuous change of the screen content. The frame rate saturates at 57 fps, at a screen resolution of 485$\times$863. Moreover, through another user study (described next) to understand the minimum resolution to read an app's contents, we empirically verified that the participants had no issues in reading the app's content at the resolution of 485$\times$863. Hence, we choose this resolution as our default, although this setting can be modified (e.g., we can pick a higher resolution, and a lower frame rate, for an app with mostly static content).

A.5.2 Rendering the Virtual Hand

As discussed in Section A.3, the rendering latency of the virtual hand is proportional to the number of vertices in the Delaunay triangulation-based mesh. To reduce the latency, we apply a non-uniform sampling approach. Specifically, Empath-D preserves all the points on the edges of the segment, to preserve the precise contours of the hand. However, it performs a downsampling of the interior points (prior to constructing the Delaunay triangulation), along both the x and y axes, to reduce the computational time significantly, without materially affecting the reconstructed hand image. We empirically determined the sampling rate

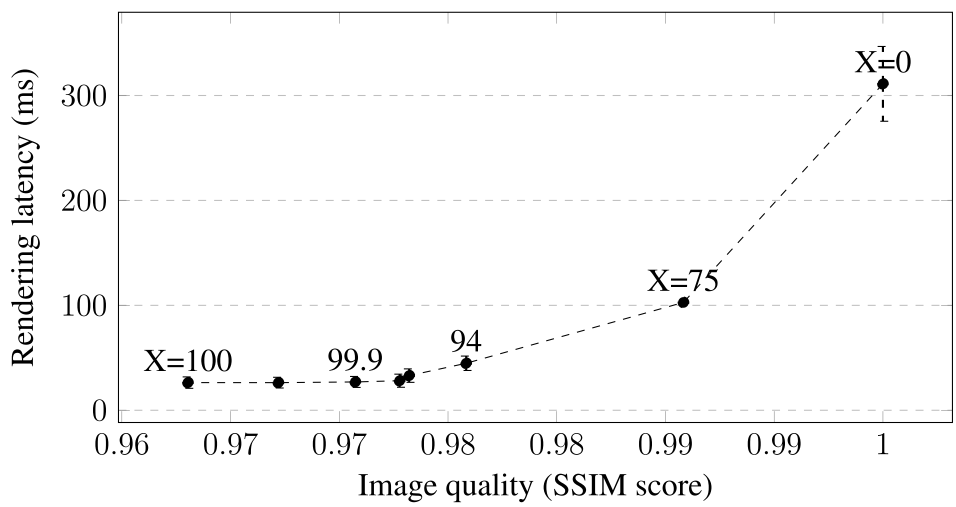


Figure A.10: Rendering latency vs. image quality of the virtual hand

X, by varying X and measuring both (i) the processing latency and (ii) the SSIM [104, 168] (*Structural SIMilarity*; a metric of perceived image quality) of the hand images, using 200 RGB-D frames. Figure A.10 shows the results. Without any subsampling ($X = 0\%$), the rendering latency is 311.1 $msec$, which is too high for our responsiveness goal. We empirically downsample the internal pixels by a factor of 32 ($X = 99.9\%$), i.e., choosing every 32^{nd} pixel on the grid. This results in a latency of 26.9 $msec$, while keeping the $SSIM = 0.976$, a level indistinguishable with the original as perceived by a human.

A.5.3 Environment Emulation

To enable holistic evaluation of app interactions, Empath-D emulates not just the virtual phone, but the entire virtual world as well. In our current implementation, we emulated a crowded *Urban Street* environment, which includes crosswalks, traffic lights, pedestrians and commonplace roadside obstacles. To further mimic real-world movement, our implementation allows the user to navigate the virtual world by (i) rotating her head (this uses the head tracking ability of the VR device), and (ii) by 'walking in place', using the technique proposed in [163] as this does not require any additional hardware on the VR device.

A.5.4 VR Manager

This component currently executes on the VR smartphone, and is responsible for combining the output of the various components (*Hand Tracker*, *Phone Tracker* and *Virtual Phone*) in the virtual world. This component, implemented as a Unity application, renders these various components. This component is also responsible for applying the impairments on the output of the virtual world. The image effects simulating low vision impairments are defined as a script, *Shaders* in Unity.

Appendix B

User Study Materials and Design Screenshots

B.1 Informed Consent

B.1.1 Feasibility Study [98]

SMU-IRB: Participant Information Sheet and Informed Consent Form (Hardcopy)

Title of Research Study: Empathetic Design for the Elderly using Augmented Reality.
Principal Investigator, Title, and Affiliation: Kenny Choo, PhD candidate, SMU

Purpose of Research Study. This study aims to understand how an augmented reality (AR) simulation of vision impairment can affect the design of user interfaces for the elderly.

Study Procedures and Duration. Participation involves attending a laboratory session in which you will customise a basic web page for the elderly using the controls provided. You will be required to do this task twice, each on a different day. This corresponds to 2 different conditions, (A) where you will be given design guidelines for the elderly, or (B) where you will be given design guidelines for the elderly, and the augmented reality interface that simulates vision impairment to help you with design. We will let you know the order of conditions that you will be doing. At the end of condition B, we will conduct a short semi-structured interview to understand your experience with the AR interface. It is expected that the entire study will last no more than 2 hours spread over 2 days (1 hour per day). Participation in this study is entirely voluntary. You can withdraw from the study, or choose not to answer any specific questions or participate in any specific procedures without penalty.

Benefits of Study. You will contribute towards new knowledge in accessibility design for the elderly using AR interfaces.

Possible Risks of Study. Some people experience discomfort in prolonged use of AR interfaces. If you do experience discomfort, you may stop to rest or discontinue participation at any time.

Confidentiality and Privacy of Research Data. The information you provide will be kept strictly confidential. We will not capture any personally identifiable information other than your name and signature on the hardcopy informed consent form. You will be given a participant ID (PID) to preserve your anonymity that will be used on all your responses. Only a master list will link your name to this PID. Only the Principal Investigator and the research team will have access to the information you provide us. Your responses will be reported in an anonymised/aggregated form in which no individual will be identified.

Contact Details.

- For questions/ clarifications on this study, please contact the Principal Investigator, Kenny Choo at email address kenny.choo.2012@smu.edu.sg, or the Supervisor, Professor Lee Youngki at youngkilee@smu.edu.sg.
- If you have any questions or concerns regarding your rights as a participant in this research study and wish to contact someone unaffiliated with the research team, please contact the SMU Institutional Review Board Secretariat at irb@smu.edu.sg or + 65 68281925. When contacting SMU IRB, please provide the title of the Research Study and the name of the Principal Investigator, or quote the IRB approval number (IRB-16-094-A100(1016)).
- You will receive a copy of this participant information sheet and informed consent form for your records.

Principal Investigator's Declaration:

I have explained and defined in detail the research procedures in which the participant (or legal representative) has consented to participate.

I also declare that the data collected for this research study will be handled as stated above.

______________________________ ____________________

Principal Investigator's Name and Signature: Date:

Participant's Declaration:

I understand that participation is voluntary. Refusal to participate will involve no penalty.

I declare that I am at least 18 years of age.

If I am affiliated with Singapore Management University, my decision to participate, decline, or withdraw from participation will have no adverse effect on my status at or future relations with Singapore Management University.

I have read and fully understood the contents of this form, and hereby give consent to the Singapore Management University research team and its affiliates for this project to collect and/or use my data for the purpose(s) described in this form.

_______________________________________ ________________________

Principal Investigator’s Name and Signature: Date:

B.1.2 System Performance Studies [131]

SMU-IRB: Participant Information Sheet and Informed Consent Form (Hardcopy)

Title of Research Study: Empathetic Design for the Elderly using Augmented Reality / Virtual Reality - Examining the fidelity of virtual reality impairment emulation.
Principal Investigator, Title, and Affiliation: Kenny Choo, PhD candidate, SMU

Purpose of Research Study. This study aims to understand how a virtual reality (VR) impairment simulator can realistically simulate impairments. To participate, you should be at least 18 years of age, and have no pre-existing uncorrected vision impairments (e.g., colour blindness is not acceptable, but short-sightedness corrected by spectacles is ok).

Study Procedures and Duration.
Study Part 1. We will ask you to perform tasks common in smartphone use (e.g., adding an alarm). You will perform these tasks in different conditions such as without impairment simulation, with a physical impairment simulation or with a virtual impairment simulation. These impairment simulations simulate the effects of having mild-moderate impairments of cataracts or glaucoma. At the end of each round of a task, we will ask you to compare the conditions by filling in a short survey.

Study Part 2. You will be presented with a grid of buttons with numbers on the smartphone screen. The required input number is displayed at the top of the screen. You will be asked to repeatedly select the corresponding target button as quickly and accurately as possible. This will be repeated under the impairment conditions as with Part 1.

On completion, we will conduct a short semi-structured interview to understand your experience with the VR impairment simulator. Only typed/written notes will be made.

The study will last no more than 2 hours. Participation in this study is entirely voluntary. You may withdraw your data (for as long as it remains identifiable) or from the study, or choose not to answer any specific questions or participate in any specific procedures without penalty at any time. Please email the PI (contact details below) if you wish to do so.

Benefits of Study. We will give you $20 SGD cash (or equivalent voucher) compensation upon completing the both parts of the study.

Possible Risks of Study. Some people experience discomfort in prolonged use of a VR headset. If you do experience discomfort, you may stop to rest or discontinue participation at any time.

Confidentiality and Privacy of Research Data. The information you provide will be kept strictly confidential. We will not capture any personally identifiable information other than your name and signature on the hardcopy informed consent form, and compensation received acknowledgment chit. You will be given a participant ID (PID) to preserve your anonymity that will be used on all your responses. Only a master list will link your name to this PID. Only the Principal Investigator and the research team will have access to the information you provide us. Your responses will be reported in an anonymised/aggregated form in which no individual will be identified.

Contact Details.

- For questions/ clarifications on this study, please contact the Principal Investigator, Kenny Choo at email address kenny.choo.2012@smu.edu.sg, or the Supervisor, Professor Lee Youngki at youngkilee@smu.edu.sg.
- If you have any questions or concerns regarding your rights as a participant in this research study and wish to contact someone unaffiliated with the research team, please contact the SMU Institutional Review Board Secretariat at irb@smu.edu.sg or + 65 68281925. When contacting SMU IRB, please provide the title of the Research Study and the name of the Principal Investigator, or quote the IRB approval number (IRB-16-094-A100-M1(1217)).
- You will receive a copy of this participant information sheet and informed consent form for your records.

Principal Investigator's Declaration:

I have explained and defined in detail the research procedures in which the participant (or legal representative) has consented to participate.

I also declare that the data collected for this research study will be handled as stated above.

______________________________ __________________

Principal Investigator's Name and Signature: Date:

Participant's Declaration:

I understand that participation is voluntary. Refusal to participate will involve no penalty.

I declare that I am at least 18 years of age. I declare that I do not have any pre-existing uncorrected visual impairments.

If I am affiliated with Singapore Management University, my decision to participate, decline, or withdraw from participation will have no adverse effect on my status at or future relations with Singapore Management University.

I have read and fully understood the contents of this form, and hereby give consent to the Singapore Management University research team and its affiliates for this project to collect and/or use my data for the purpose(s) described in this form.

______________________________ __________________

Principal Investigator's Name and Signature: Date:

B.1.3 Cataracts Impaired User Study

SMU-IRB: Participant Information Sheet and Informed Consent Form (Hardcopy)

Title of Research Study: Empathetic Design for the Elderly using Augmented / Virtual Reality - Examining the fidelity of virtual reality impairment emulation.
Principal Investigator, Title, and Affiliation: Kenny Choo, PhD candidate, SMU

Purpose of Research Study. This study aims to understand the potential benefits of virtual environment and impairment simulation towards app innovation and design for accessibility.

Study Procedures and Duration.
As a person who has cataracts, you will help us evaluate a mobile application. We will screen record your interaction (videos of your phone screens, with touch interactions) while you perform the task. Finally, we will conduct an interview to understand your experiences with the app design. The study will last up to 2 hours. You may take short breaks if you feel the need to.

Participation in this study is entirely voluntary. You may withdraw your data (for as long as it remains identifiable), withdraw your participation from the study, choose not to answer any specific questions or participate in any specific procedures without penalty at any time. Please email the PI (contact details below) if you wish to do so.

Benefits of Study. You will be compensated with $20 SGD (cash) for your time and efforts upon completing the study.

Possible Risks of Study. There are no foreseeable risks in performing the study. You may stop to rest or discontinue participation at any time. No compensation will be given if you do not complete the study.

Confidentiality and Privacy of Research Data. The information you provide will be kept strictly confidential. We will not capture any personally identifiable information other than 1) your name and signature on the hardcopy informed consent form, 2) name, signature, identification number, and a copy of your identification on the compensation acknowledgement form (for financial reimbursement). You will be given a participant ID (PID) to preserve your anonymity that will be used on all your responses. Only a master list, which will be kept separate from the study data, will link your name to this PID. Only the Principal Investigator and the research team will have access to the information you provide us. Your responses will be reported in an anonymised/aggregated form in which no individual will be identified.

Contact Details.

- For questions/ clarifications on this study, please contact the Principal Investigator, Kenny Choo at email address kenny.choo.2012@smu.edu.sg, or the Supervisor, Professor Lee Youngki at youngkilee@smu.edu.sg.
- If you have any questions or concerns regarding your rights as a participant in this research study and wish to contact someone unaffiliated with the research team, please contact the SMU Institutional Review Board Secretariat at irb@smu.edu.sg or + 65

68281925. When contacting SMU IRB, please provide the title of the Research Study and the name of the Principal Investigator, or quote the IRB approval number (IRB-16-094-A100-M3(718)).

- You will receive a copy of this participant information sheet and informed consent form for your records.

Principal Investigator's Declaration:

I have explained and defined in detail the research procedures in which the participant (or legal representative) has consented to participate.

I also declare that the data collected for this research study will be handled as stated above.

Principal Investigator's Name and Signature: ____________________ Date: ____________

Participant's Declaration:

I understand that participation is voluntary. Refusal to participate will involve no penalty.

I declare that I am at least 18 years of age.

If I am affiliated with Singapore Management University, my decision to participate, decline, or withdraw from participation will have no adverse effect on my status at or future relations with Singapore Management University.

I have read and fully understood the contents of this form, and hereby give consent to the Singapore Management University research team and its affiliates for this project to collect and/or use my data for the purpose(s) described in this form.

Principal Investigator's Name and Signature: ____________________ Date: ____________

B.1.4 Designer Study

SMU-IRB: Participant Information Sheet and Informed Consent Form (Hardcopy)

Title of Research Study: Empathetic Design for the Elderly using Augmented / Virtual Reality - Examining the fidelity of virtual reality impairment emulation.
Principal Investigator, Title, and Affiliation: Kenny Choo, PhD candidate, SMU

Purpose of Research Study. This study aims to understand the potential benefits of virtual environment and impairment simulation towards app innovation and design for accessibility.

Study Procedures and Duration. You will play the role of a mobile app designer who is redesigning a commonly used mock-up of a social media applicationInstagramto help users who have cataracts use the app while on a street. Before the study task, you will be given a pre-test for HTML-CSS-JS. This test helps us understand your level of expertise and is not a qualification test.

In the study task, you will try to identify the potential issues that such users face and support 3 common app-use tasks. We will provide a short information sheet that explains what cataracts are. You will also have access to the Internet and referred to existing web guidelines for accessibility. If you decide to take part in this study, you will be randomly assigned to either wear (C1) or not wear (C2) a VR simulator to complete the study tasks. Our VR simulator will allow you to experience the impairment (i.e. cataracts) and environment to help you identify the potential issues.

You will also be asked to think aloud while you are performing the tasks. After each study task, you will complete two short surveys on using the system. We will then conduct a short interview at the end of the study to understand your experiences in redesigning the app. The entire study will be video (including face) and audio recorded, with typed or hand-written notes made throughout the study. You may request to remove parts of the recordings you are not comfortable with. Your application designs will be evaluated for its usability in a following experiment of this study.
The study will last for **8 hours** in an SMU meeting room, including breaks (you may also take breaks as and when you need to) in between. The schedule is given in the table below:

Idx	Item	Time Allotted (mins)
1	Start of Study	-
2	Admin (Informed Consent, Briefing)	20
3	Pre-test HTML-CSS-JS skill	30
4	Break	10
5	Task 1	100
6	Lunch Break	60
7	Task 2	100
8	Break	10
9	Task 3	100
10	Break	10
11	Interview	20
12	Admin (Closing, Compensation)	20

Participation in this study is entirely voluntary. You may withdraw your data (for as long as it remains identifiable), withdraw your participation from the study, choose not to answer any specific questions or participate in any specific procedures without penalty at any time. You will not have to return any compensation already paid if you decide to withdraw your data. Please email the PI (contact details below) if you wish to do so.

Benefits of Study. You will be compensated with $120 SGD (cash) for your time and efforts upon completing the study. However, if you withdraw from the study due to physical discomfort, you will be given per-hour (rounded up) pro-rated compensation (e.g., 3.5 hours completed, rounded to 4 = $60).

Possible Risks of Study.
C1: When you wear the VR set, you will be visually unaware of your surroundings, but your hearing will not be affected. As you may not be aware of what the experimenters may be doing, for your safety, we will keep the door open to create a semi-public environment. You also have the option to close the door if you prefer privacy. Some people experience discomfort (e.g. dizziness) in prolonged use of VR headset. If you do experience discomfort, you may stop to rest or discontinue participation at any time.

C2: There are no foreseeable risks in performing the study. If you do experience discomfort, you may stop to rest or discontinue participation at any time.

Confidentiality and Privacy of Research Data. The information you provide will be kept strictly confidential. The application designs resulting from your participation will be used only for the purposes of this study. We will not capture any personally identifiable information other than 1) your name and signature on the hardcopy informed consent form, 2) name, signature, identification number, and a copy of your identification on the compensation acknowledgement form (for financial reimbursement), and 3) the videos. Videos captured will record faces. These videos will be kept in a password protected folder and are only accessible to the research team. No personally identifiable information from the videos will be released. Any video information captured that is to be released will be processed to remove personally identifiable information. For instance, faces will be blurred and audio (from the video) will be transformed such that participants are not identifiable. You will be given a participant ID (PID) to preserve your anonymity that will be used on all your responses. Only a master list, which will be kept separate from the study data, will link your name to this PID. Only the Principal Investigator and the research team will have access to the information you provide us. Your responses will be reported in an anonymised/aggregated form in which no individual will be identified.

Contact Details.

- For questions/ clarifications on this study, please contact the Principal Investigator, Kenny Choo at email address kenny.choo.2012@smu.edu.sg, or the Supervisor, Professor Lee Youngki at youngkilee@smu.edu.sg.

- If you have any questions or concerns regarding your rights as a participant in this research study and wish to contact someone unaffiliated with the research team, please contact the SMU Institutional Review Board Secretariat at irb@smu.edu.sg or + 65 68281925. When contacting SMU IRB, please provide the title of the Research Study and the name of the Principal Investigator, or quote the IRB approval number (IRB-16-094-A100-M3(718)).

- You will receive a copy of this participant information sheet and informed consent form for your records.

Principal Investigator's Declaration:

I have explained and defined in detail the research procedures in which the participant (or legal representative) has consented to participate.

I also declare that the data collected for this research study will be handled as stated above.

______________________________ ____________________

Principal Investigator's Name and Signature: Date:

Participant's Declaration:

I understand that participation is voluntary. Refusal to participate will involve no penalty.

I declare that I am at least 18 years of age. I declare that I do not have any pre-existing uncorrected visual impairments.

If I am affiliated with Singapore Management University, my decision to participate, decline, or withdraw from participation will have no adverse effect on my status at or future relations with Singapore Management University.

I have read and fully understood the contents of this form, and hereby give consent to the Singapore Management University research team and its affiliates for this project to collect and/or use my data for the purpose(s) described in this form.

______________________________ ____________________

Principal Investigator's Name and Signature: Date:

B.2 Questionnaires

B.2.1 Need for Cognition

The following is the short-form version of the Need for Cognition (NFC) questionnaire developed by Cacioppo and Petty [91], and adapted into an electronic format administered through Google Forms. The NFC is a personality variable reflecting the extent to which individuals engage in effortful cognitive activities.

Participant ID:

For each of the statements below, please indicate whether or not the statement is characteristic of you or of what you believe. For example, if the statement is extremely uncharacteristic of you or of what you believe about yourself (not at all like you) please choose ”1”. If the statement is extremely characteristic of you or of what you believe about yourself (very much like you) please choose ”5”.

1. I prefer complex to simple problems.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me
   - ○ 5: extremely characteristic of me
2. I like to have the responsibility of handling a situation that requires a lot of thinking.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me
   - ○ 5: extremely characteristic of me
3. Thinking is not my idea of fun.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me
   - ○ 5: extremely characteristic of me
4. I would rather do something that requires little thought than something that is sure to challenge my thinking abilities.

- ○ 1: extremely uncharacteristic of me
- ○ 2: somewhat uncharacteristic of me
- ○ 3: uncertain
- ○ 4: somewhat characteristic of me
- ○ 5: extremely characteristic of me

5. I try to anticipate and avoid situations where there is a likely chance I will have to think in depth about something.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me
   - ○ 5: extremely characteristic of me
6. I find satisfaction in deliberating hard for long hours.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me
   - ○ 5: extremely characteristic of me
7. I only think as hard as I have to.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me
   - ○ 5: extremely characteristic of me
8. I prefer to think about small daily projects to long term ones.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me
   - ○ 5: extremely characteristic of me
9. I like tasks that require little thought once I've learned them.
   - ○ 1: extremely uncharacteristic of me
   - ○ 2: somewhat uncharacteristic of me
   - ○ 3: uncertain
   - ○ 4: somewhat characteristic of me

○ 5: extremely characteristic of me

10. The idea of relying on thought to make my way to the top appeals to me.

    ○ 1: extremely uncharacteristic of me
    ○ 2: somewhat uncharacteristic of me
    ○ 3: uncertain
    ○ 4: somewhat characteristic of me
    ○ 5: extremely characteristic of me

11. I really enjoy a task that involves coming up with new solutions to problems.

    ○ 1: extremely uncharacteristic of me
    ○ 2: somewhat uncharacteristic of me
    ○ 3: uncertain
    ○ 4: somewhat characteristic of me
    ○ 5: extremely characteristic of me

12. Learning new ways to think doesn't excite me very much.

    ○ 1: extremely uncharacteristic of me
    ○ 2: somewhat uncharacteristic of me
    ○ 3: uncertain
    ○ 4: somewhat characteristic of me
    ○ 5: extremely characteristic of me

13. I prefer my life to be filled with puzzles I must solve.

    ○ 1: extremely uncharacteristic of me
    ○ 2: somewhat uncharacteristic of me
    ○ 3: uncertain
    ○ 4: somewhat characteristic of me
    ○ 5: extremely characteristic of me

14. The notion of thinking abstractly is appealing to me.

    ○ 1: extremely uncharacteristic of me
    ○ 2: somewhat uncharacteristic of me
    ○ 3: uncertain
    ○ 4: somewhat characteristic of me
    ○ 5: extremely characteristic of me

15. I would prefer a task that is intellectual, difficult, and important to one that is somewhat important but does not require much thought.

    ○ 1: extremely uncharacteristic of me
    ○ 2: somewhat uncharacteristic of me

○ 3: uncertain

○ 4: somewhat characteristic of me

○ 5: extremely characteristic of me

16. I feel relief rather than satisfaction after completing a task that requires a lot of mental effort.

    ○ 1: extremely uncharacteristic of me

    ○ 2: somewhat uncharacteristic of me

    ○ 3: uncertain

    ○ 4: somewhat characteristic of me

    ○ 5: extremely characteristic of me

17. It’s enough for me that something gets the job done; I don’t care how or why it works.

    ○ 1: extremely uncharacteristic of me

    ○ 2: somewhat uncharacteristic of me

    ○ 3: uncertain

    ○ 4: somewhat characteristic of me

    ○ 5: extremely characteristic of me

18. I usually end up deliberating about issues even when they do not affect me personally.

    ○ 1: extremely uncharacteristic of me

    ○ 2: somewhat uncharacteristic of me

    ○ 3: uncertain

    ○ 4: somewhat characteristic of me

    ○ 5: extremely characteristic of me

B.2.2 CatQuest-9SF

The CatQuest-9SF is a short-form questionnaire of the Catquest [138], which was originally developed to measure pre- and post-cataract surgery outcomes. It was constructed in Swedish, with an English translated version given here. The CatQuest-9SF has been also been examined under Rausch analysis for Malay, Chinese, and Italian populations, and has consistently shown good psychometric properties [80, 158].

Participant ID:

Please read the following carefully

The aim of this questionnaire is to establish what difficulties you have in your daily life due to impaired sight.

Please answer the questions in the questionnaire as honestly as you can. The questionnaire contains questions about your difficulties due to impaired sight in connection with certain everyday tasks. If you use glasses for distance and/or close-up purposes, the questions are about what it is like when you use your best glasses.

The questions in this questionnaire apply to your situation during the past 4 weeks.

When you answer the questions, you must try to think ONLY of the difficulties that your sight may be causing you. We appreciate that it may be difficult to decide just what your sight means to you if you also have other problems such as joint pains or dizziness for example. We would still ask you to try to answer how important you think your sight is in your ability to perform the following tasks.

We have given response options in the questions below. Different people may put things differently, however, try to see the response options as equal parts of the scale, ranging from the greatest to least difficulty caused by your sight in performing various activities.

A. Do you find that your sight at present in some way causes you difficulty in your everyday life?

   ○ Yes, very great difficulty
   ○ Yes, great difficulty
   ○ Yes, some difficulty
   ○ No, no difficulty
   ○ Cannot decide

B. Are you satisfied or dissatisfied with your sight at present?

   ○ Very dissatisfied

- ○ Fairly dissatisfied
- ○ Fairly satisfied
- ○ Very satisfied
- ○ Cannot decide

C. Do you have difficulty with the following activities because of your sight?

   If so, to what extent? Choose the option that best corresponds to your situation.

Reading text in newspapers

- ○ Yes, very great difficulty
- ○ Yes, great difficulty
- ○ Yes, some difficulty
- ○ No, no difficulty
- ○ Cannot decide

Recognising the faces of people you meet

- ○ Yes, very great difficulty
- ○ Yes, great difficulty
- ○ Yes, some difficulty
- ○ No, no difficulty
- ○ Cannot decide

Seeing the prices of goods when shopping

- ○ Yes, very great difficulty
- ○ Yes, great difficulty
- ○ Yes, some difficulty
- ○ No, no difficulty
- ○ Cannot decide

Seeing to walk on uneven surfaces, e.g., cobblestones

- ○ Yes, very great difficulty
- ○ Yes, great difficulty
- ○ Yes, some difficulty
- ○ No, no difficulty
- ○ Cannot decide

Seeing to do handicrafts, woodwork, etc.

- ○ Yes, very great difficulty
- ○ Yes, great difficulty

- ○ Yes, some difficulty
- ○ No, no difficulty
- ○ Cannot decide

Reading subtitles on TV

- ○ Yes, very great difficulty
- ○ Yes, great difficulty
- ○ Yes, some difficulty
- ○ No, no difficulty
- ○ Cannot decide

Seeing to engage in an activity/hobby that you are interested in

- ○ Yes, very great difficulty
- ○ Yes, great difficulty
- ○ Yes, some difficulty
- ○ No, no difficulty
- ○ Cannot decide

B.2.3 System Usability Scale [90]

Participant ID:

Task:

- ○ Task 1
- ○ Task 2
- ○ Task 3

Please record your immediate response to each item. Do not think about items for an extended period.

	1: Strongly Disagree	2: Disagree	3: Neither Agree nor Disagree	4: Agree	5: Strongly Agree
I think that I would like to use this system frequently	○	○	○	○	○
I found the system unnecessarily complex	○	○	○	○	○
I thought the system was easy to use	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system	○	○	○	○	○
I found the various functions in this system were well integrated	○	○	○	○	○
I thought there was too much inconsistency in this system	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly	○	○	○	○	○
I found the system very cumbersome to use	○	○	○	○	○
I felt very confident using the system	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system	○	○	○	○	○

B.2.4 NASA-TLX [73]

Participant ID:

Task:

- ○ Task 1
- ○ Task 2
- ○ Task 3

Please choose the values based on a careful read of the descriptions given below.

Mental Demand. How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Physical Demand. How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

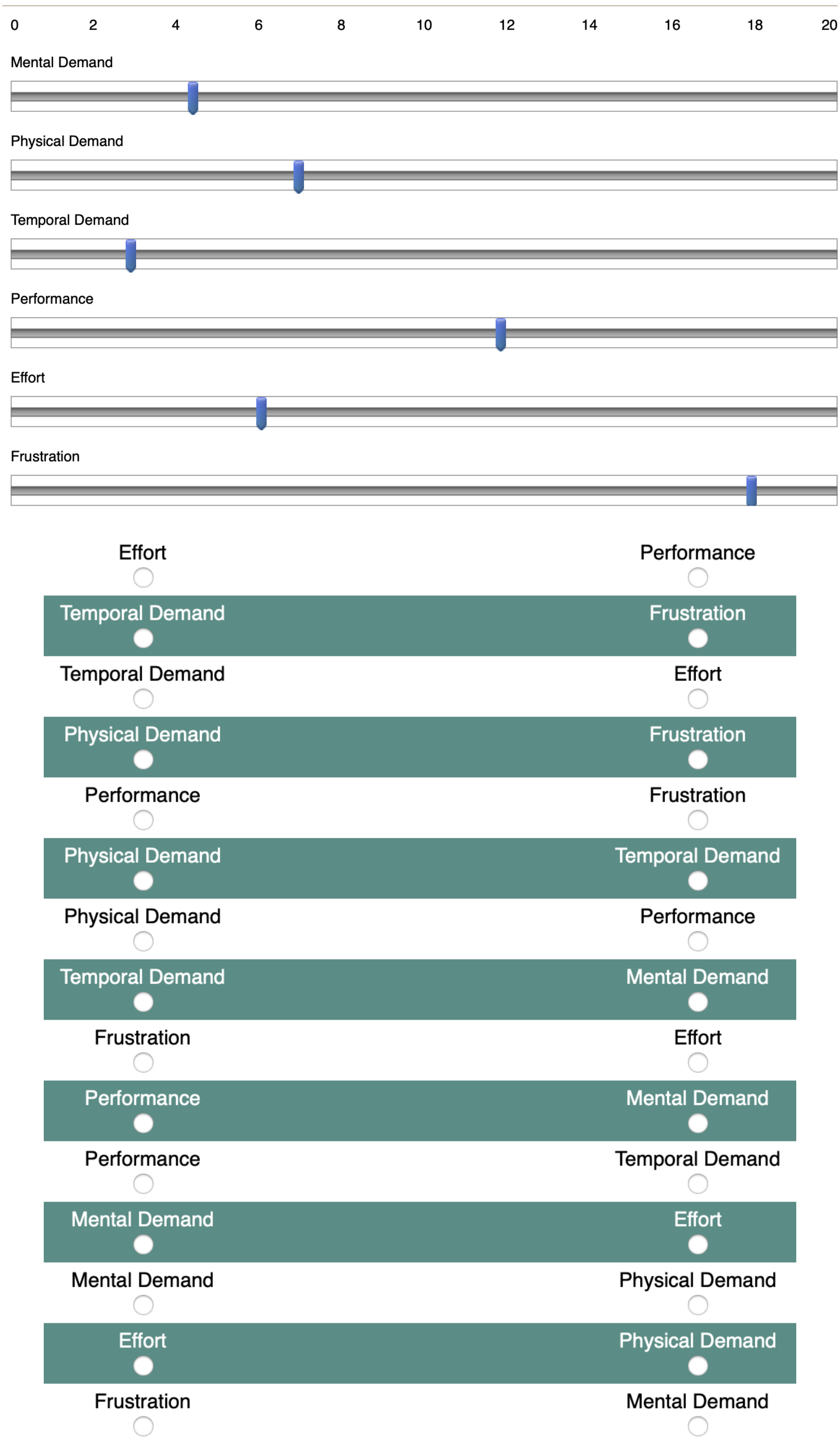
Temporal Demand. How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Performance. How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Effort. How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration. How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Select the Scale Title that represents the more important contributor to workload for the specific task(s) you performed in this experiment.


0 2 4 6 8 10 12 14 16 18 20
Mental Demand
Physical Demand
Temporal Demand
Performance
Effort
Frustration
Effort
Performance
Temporal Demand
Frustration
Temporal Demand
Effort
Physical Demand
Frustration
Performance
Frustration
Physical Demand
Temporal Demand
Physical Demand
Performance
Temporal Demand
Mental Demand
Frustration
Effort
Performance
Mental Demand
Performance
Temporal Demand
Mental Demand
Effort
Mental Demand
Physical Demand
Effort
Physical Demand
Frustration
Mental Demand

B.3 Task Briefs and Interview Probes

B.3.1 Feasibility Study Semi-structured Interview Probes

Semi-structured Interview Probes for Experiences with the AR interface.

1. Affective Experience
   (a) How did it feel to use the AR interface?
   (b) How did it feel to have the vision of an old person?
   (c) Was the simulation realistic (according to your expectations)?
   (d) What was most memorable about your experience?
2. Design Performance
   (a) Does the tool help you in design?
   (b) i. How Yes/No?
   (c) What did you like/dislike about it?
3. Usability
   (a) Was the system easy to use?
   (b) How would you improve it?
   (c) Physical Issues
      i. Did you have issues with coordination?
      ii. Did you feel dizzy or disoriented?

B.3.2 Simulation Fidelity Study Experiment Task Brief

Experiment Task Brief

Study Part 1 Tasks

You will repeat each task 2 times per condition.

1. Adding an Alarm

Add an alarm for X today. (Vary the timing - 1 am - 11 pm)

2. Perform a Calculation on the Calculator

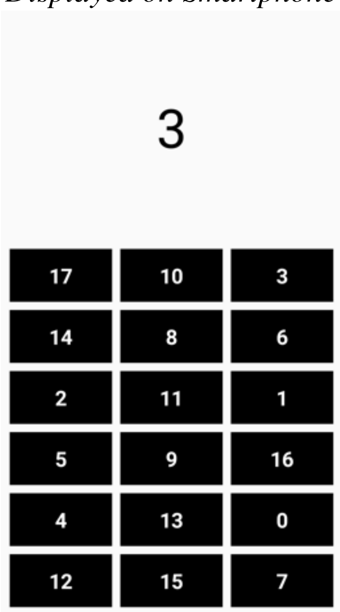
2381×7833	5912×9708	9167×5544	5766×1400
1856×7373	6474×7962	5045×9322	2555×6350
2945×0336	3922×9514	4835×4309	1175×4511

3. Search and Save Image on Browser

Use Google Image Search to look for "cats". Save the second image from the top right.

Study Part 2 Task

Displayed on Smartphone



1. When you begin, you will see a number displayed (in this case, 3).
2. As quickly as possible please click on the black button labelled with this number.
3. With each repetition, the numbers on the button will shuffle.
4. You will repeat this 40 times per condition.

B.3.3 Simulation Fidelity Study Semi-structured Interview Probes

General

1. How did it feel to use the
   (a) Physical Impairment Simulation?
   (b) VR Impairment Simulation?
2. Which is more realistic? Why?
3. Was the simulation realistic (according to your expectations)? How close is this to your actual use of a mobile phone?
4. How did it feel to have impaired vision and use your phone?
5. What was most memorable about your experience?
6. Was the system easy to use (to perform the tasks)?
7. How would you improve it?

Physical Issues

1. Did you have issues with coordination?
2. Did you feel dizzy or disoriented?

B.3.4 Design Experience using Empath-D

Semi-structured Interview Probes - Design Experience in VR Exploration.

<table>
<tr><td>Treatment 1 (no Empath-D)</td><td>Treatment 2 (Empath-D)</td></tr>
<tr><td>General
1. How did it feel to design given these tools?
2. How do you think it feels to have an impairment and use your phone while moving around?
3. What was most memorable about your experience?</td><td>General
1. How did it feel to try and design with this VR Impairment and Environment Simulation?
2. Was it realistic? How?
3. How did it feel to have impaired vision and move about the space?
4. What was most memorable about your experience?
5. Was the system easy to use (to perform the tasks)?
6. How would you improve it?</td></tr>
<tr><td>Design Performance
1. How do the materials help you in thinking about designing?
2. How do the materials help in terms of designing on the streets?
(a) e.g., Did it help you convince one design is better than the others?
(b) How?
3. What did you like/dislike about it?
4. What potential technological solutions may be adopted to tackle the issues you have identified?</td><td>Design Performance
1. How do the materials help you in thinking about designing?
2. How do the materials help in terms of designing on the streets?
(a) e.g., Did it (street simulation) help you convince one design is better than the others?
(b) How?
3. What did you like/dislike about it?
4. What potential technological solutions may be adopted to tackle the issues you have identified?</td></tr>
<tr><td></td><td>Physical Issues
1. Did you have issues with coordination?
2. Did you feel dizzy or disoriented?</td></tr>
</table>

B.4 Design Materials

B.4.1 Baseline Webpages

B.4.1.1 HTML Code for Webpage 1

```
<!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0
   Transitional//EN"
   "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
<html xmlns="http://www.w3.org/1999/xhtml">
<head>
<meta http-equiv="Content-Type" content="text/html;
   charset=UTF-8" />
<title>Untitled Document</title>
</head>

<body>
<h1>OnlineDoctor Upper Abdomen Symptom Checker</h1>
<p>Take the first step and see what could be causing your
   symptoms. Then learn about possible next steps.</p>
<form id="form1" name="form1" method="post" action="">
  <p>For
    <label for="select4"></label>
    <select name="select" id="select4">
      <option value="Me">Me</option>
      <option value="Someone Else">Someone Else</option>
    </select>
  </p>
  <p>Gender
    <label>
      <input type="radio" name="RadioGroup1" value="radio"
         id="RadioGroup1_0" />
      Male</label>
    <label>
      <input type="radio" name="RadioGroup1" value="radio"
         id="RadioGroup1_1" />
      Female</label>
    <br />
  </p>
  <p>Age
    <label for="select5"></label>
    <select name="select2" id="select5">
      <option value="Choose one">Choose one</option>
      <option value="Check for Someone 0-2 years">Check for
         Someone 0-2 years</option>
      <option value="Check for Someone 3-6 years">Check for
         Someone 3-6 years</option>
      <option value="Check for Someone 7-12 years">Check for
         Someone 7-12 years</option>
      <option value="13-17 years">13-17 years</option>
```

```
      <option value="18-24 years">18-24 years</option>
      <option value="25-34 years">25-34 years</option>
      <option value="35-44 years">35-44 years</option>
      <option value="45-54 years">45-54 years</option>
      <option value="55-64 years">55-64 years</option>
      <option value="Over 65">Over 65</option>
    </select>
  </p>
  <p>Zip code
    <label for="textfield"></label>
    <input name="textfield" type="text" id="textfield"
       value="Optional" />
  </p>
  <p>Email
    <input name="textfield2" type="text" id="textfield2"
       value="Optional" />
  </p>
  <p>
    <input type="submit" name="button" id="button"
       value="Submit" />
  </p>
</form>
<p>Stay informed with the latest health news and features
   from OnlineDoctor. Get our newsletter delivered right to
   your inbox. By clicking Submit, you agree to the
   OnlineDoctor Terms &amp; Conditions &amp; Privacy Policy
   and understand that you may opt out of OnlineDoctor
   subscriptions at any time.</p>
</body>
</html>
```

B.4.1.2 HTML Code for Webpage 2

```
<!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0
   Transitional//EN"
   "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
<html xmlns="http://www.w3.org/1999/xhtml">
<head>
<meta http-equiv="Content-Type" content="text/html;
   charset=UTF-8" />
<title>Untitled Document</title>
</head>

<body>
<h1>OnlineDoctor Upper Abdomen Symptom Checker</h1>
<p><img src="./imgs/abdomen.png" width="396" height="421"
   /></p>
<p>Step 1: Choose Symptom(s)</p>
<p>
```

```
  <input type="checkbox" name="checkbox" id="checkbox" />
  <label for="checkbox">Bleeding</label>
</p>
<p>
  <input type="checkbox" name="checkbox2" id="checkbox2" />
  <label for="checkbox2">Bloating or fullness</label>
</p>
<p>
  <input type="checkbox" name="checkbox3" id="checkbox3" />
  Bloody or red colored vomit</p>
<p>
  <input type="checkbox" name="checkbox4" id="checkbox4" />
  Bruising or discoloration </p>
<p>
  <input type="checkbox" name="checkbox6" id="checkbox6" />
  Change in bowel habits</p>
<p>
  <input type="checkbox" name="checkbox7" id="checkbox7" />
  Coffee ground colored vomit</p>
<p>
  <input type="checkbox" name="checkbox8" id="checkbox8" />
  Constipation</p>
<p>
  <input type="checkbox" name="checkbox5" id="checkbox5" />
  Distended stomach</p>
<p>
  <input type="checkbox" name="checkbox9" id="checkbox9" />
  Lump or bulge</p>
<p>Step 2: Possible Conditions</p>
<p>
  <label for="textfield"></label>
Trauma or injury &lt;Probability of 0.5&gt;<br />
Gastrointestinal bleeding &lt;Probability of 0.2&gt;<br />
Bleeding esphageal varices &lt;Probability of 0.1&gt;<br />
Esophageal cancer &lt;Probability of 0.1&gt;<br />
Peptic ulcer &lt;Probability of 0.1&gt;</p>
</body>
</html>
```

B.4.2 Elderly Design Guidelines from the WCAG 2.0

---

1. Text size

Many older people require large text due to declining vision, including text in form fields and other controls.

WCAG 2.0 success criteria:

- **1.4.4 - Resize text** says "text can be resized without assistive technology up to 200 percent without loss of content or functionality"

Example techniques to consider:

- Using relative font-sizes such as percent or ems and ensuring text containers resize
- Providing large fonts by default
- Scaling form elements which contain text
- Avoiding the use of text in raster images
- Providing controls on the Web page that allow users to incrementally change the size of all text on the page up to 200 percent

---

2. Text style and text layout

Text style and its visual presentation impacts how hard or easy it is for people to read, especially older people with declining vision.

WCAG 2.0 success criteria:

- **1.4.8 - Visual Presentation** includes requirements on text style, text justification, line spacing, line length, and horizontal scrolling

Example techniques to consider:

- Avoiding fully-aligned text or center-aligned text
- Using readable fonts
- Using upper and lower case according to the spelling conventions of the text language
- Avoiding chunks of italic text
- Providing a button on the page to increase line spaces and paragraph spaces
- Providing sufficient inter-column spacing
- Avoiding overuse of different styles on individual pages and in sites

3. Colour and contrast

Most older people's colour perception changes, and they lose contrast sensitivity.

WCAG 2.0 success criteria:

- **1.4.1 - Use of Color** requires that color is not used as the only visual means of conveying information, indicating an action, prompting a response, or distinguishing a visual element
- **1.4.3 - Contrast (Minimum)** requires a contrast ratio of at least 4.5:1 for the visual presentation of text and images
- **1.4.6 - Contrast (Enhanced)** requires a higher contrast ratio of at least 7:1 for the visual presentation of text and images

Example techniques to consider:

- Ensuring that a contrast ratio of at least 4.5:1 exists between text (and images of text) and background behind the text
- Ensuring that information conveyed by color differences is also available in text
- Including a text cue whenever color cues are used
- Using a light pastel background rather than a white background behind black text to create sufficient but not extreme contrast
- Using a contrast ratio of 3:1 with surrounding text and providing additional visual cues on focus for links or controls where color alone is used to identify them

B.4.3 Baseline Instagram Mockup

B.4.3.1 Interface Screens

Figure B.1: Main page of mockup showing the full interface

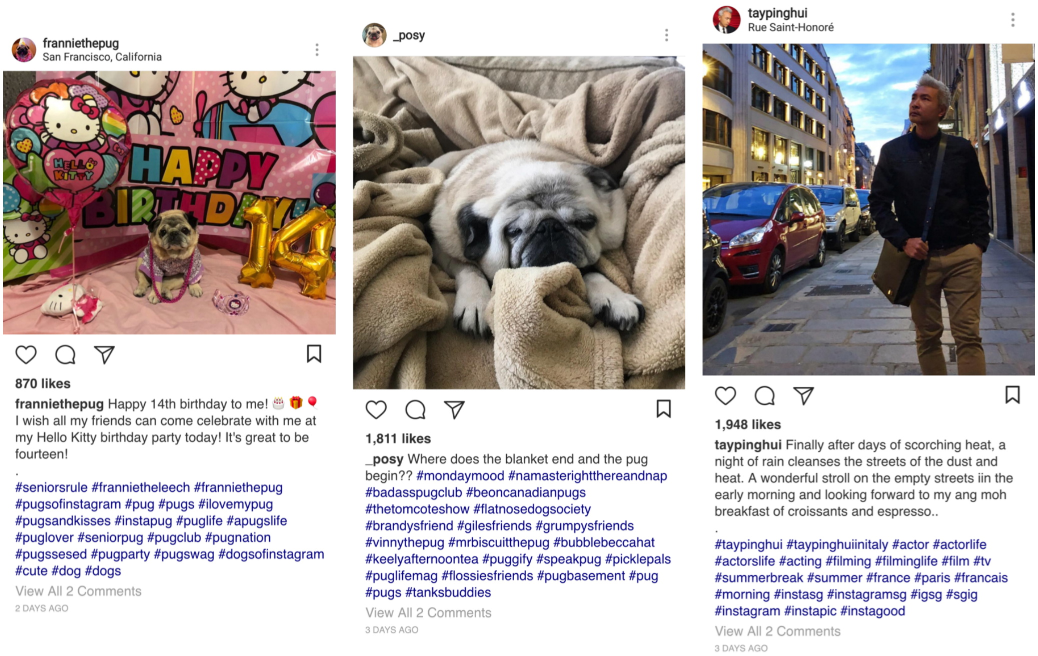


Figure B.2: Three posts included in the main page mockup of Instagram

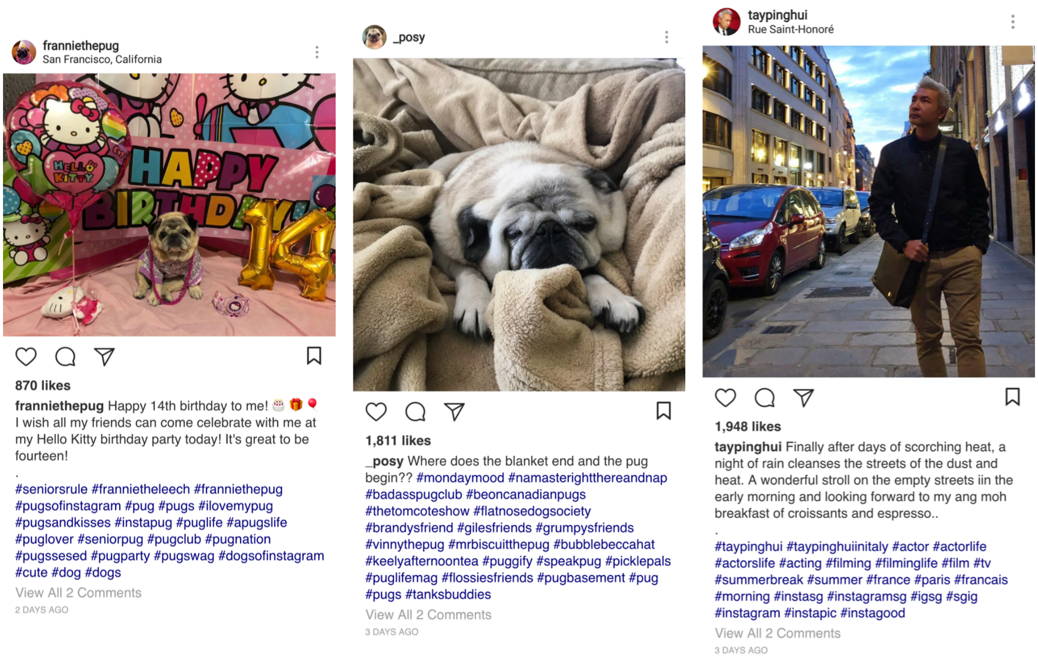


Figure B.3: Three posts included in the main page mockup of Instagram

B.4.3.2 Code

```
 <!DOCTYPE html>
<html lang="en">

<head>
  <meta charset="utf-8">
  <meta name="viewport" content="initial-scale=1,
      maximum-scale=1, user-scalable=no, width=device-width">
  <title>Instagram</title>

  <script type="text/javascript"
      src="js/jquery-2.1.4.min.js"></script>
  <script type="text/javascript"
      src="js/jquery.mobile-1.4.5.min.js"></script>
  <script type="text/javascript" src="cordova.js"></script>
  <!-- <script type="text/javascript"
      src="js/index.js"></script> -->

  <script>
    // Wait for device API libraries to load
    document.addEventListener("deviceready", onDeviceReady,
        false);

    // Device APIs are now available: Put your code here!
    function onDeviceReady() {

      if (cordova.platformId == 'android') {
        StatusBar.backgroundColorByHexString("#EEEEEE");
      }

      $('#cameraBtn').click(cameraTakePicture)

    }

    function goToPage(element) {
      window.location = element.dataset.url;
    }

    function info(el, msg) {
      if (msg) {
        el.innerHTML = msg;
      }
      else {
        el.innerHTML = "This function is not implemented."
      }

      // show the warning
      el.style.display = "inline-block";
```

```
  // hide after some time
  setTimeout(function() {
    el.style.display = "none";
  }, 1000);
}

// Take a picture with the camera
function cameraTakePicture() {
  navigator.camera.getPicture(onSuccess, onFail, {
    quality: 85,
    destinationType: Camera.DestinationType.DATA_URL
  });

  function onSuccess(imageData) {
    $("#myImage").attr("src", "data:image/jpeg;base64," +
        imageData);
  }

  function onFail(message) {

  }
}

function onOptionsClick(element) {
  alert(element);
}

function onLikeClick(element) {
  if (element.dataset.clicked) {
    element.dataset.clicked = "";
    element.src = "res/feed/post-like.png"
  } else {
    element.dataset.clicked = "clicked";
    element.src = "res/feed/post-liked.png"
  }
}

function onCommentClick(element) {
  alert("Clicked Comment");
}

function onForwardClick(element) {
  info(infoMain);
}

function onBookmarkClick(element) {
  if (element.dataset.clicked) {
    element.dataset.clicked = "";
    element.src = "res/feed/post-bookmark.png"
  } else {
```

```
      element.dataset.clicked = "clicked";
      element.src = "res/feed/post-bookmarked.png"
    }
  }

  function onCommentPostClick(content_ref, content_ele) {

    let text = $(content_ele).val();

    if (text) {
      $(content_ref).append(
        "<div class=\"clearfix\"><img
            class=\"comment_profile\" src=\"res/profile.png\"
            alt=\"\"><div class=\"comment_message\"><span
            class=\"user\">itsaustin_powers</span> " + text +
            "</div><div class=\"timestamp\"
            style=\"margin-left:55px;text-transform:none;\">1
            d</div></div>"
      );

      $(content_ele).val("")
    }
  }

  function onMsgPostClick(content_ref, content_ele) {

    let text = $(content_ele).val();

    if (text) {
      $(content_ref).append(
        "<div class=\"msg\" data-role=\"none\">" + text +
            "</div>"
      );

      $(content_ele).val("")
    }
  }

  function onMsgChange(inputele) {
    console.log(inputele.value);
  }

</script>

<link rel="stylesheet" href="css/index.css">
<link rel="stylesheet"
   href="css/jquery.mobile-1.4.5.min.css">

<!-- Put all css here! -->
<style>
```

```
input:focus {
 outline: none;
}

.info {
 background-color: red;
 color: white;
 font-size:0.85em;
 width: 100%;
 height: 1.5em;
 display: none;
 margin-top: -1px;
 padding: 3px 5px;
}

.stories img {
 width:100%;
 display:block;
}

.pagecontent {
 width:100%;
 height:2175px; /* adjust to limit height of scroll*/
 background-color:grey;
 margin:50px 0px 0px 0px;
 border:0px;
 padding:0px;
 overflow-y:scroll;
 z-index:1;
}

.postcontent {
 margin-bottom:-5px;
}

.postcontent .postcontent-click {
 width: 48px;
 height: 48px;
 position: absolute;
 right:0px;
}

.postcontent img {
 width:100%;
}

.postmenu {
 background-color:white;
}
```

```
.postmenu img {
 height: 2.5em;
}

.likes {
 background-color:white;
 margin-top:-6px;
 padding:5px 13px;
 font-size:0.9em;
 font-weight:bold;
}

.user {
 font-weight:bold;
}

.comments {
 background-color:white;
 color: #A0A0A0;
 margin-top:-6px;
 padding:5px 13px;
 font-size:0.9em;
}

.message {
 background-color:white;
 margin-top:-6px;
 padding:5px 13px;
 font-size:0.9em;
}

.timestamp {
 background-color:white;
 color: #A0A0A0;
 margin-top:-6px;
 padding:5px 13px;
 font-size:0.6em;
 text-transform:uppercase;
}

.hashtag {
 color: Navy;
}

.menubar {
 width:100%;
 background-color:white;
 position:fixed;
 bottom:0px;
 margin-bottom:0px;
```

```
  border-bottom:0px;
  padding-bottom:0px;
  box-shadow: rgba(128, 128, 128, 0.15) 0px -1px;
  z-index:2;
}

.menubar div {
  width:20%;
  /* height:43px; */
  background-color:#ffffff;
  /* background-color:#fafafa; */
  display:inline-block;
  float:left;
  z-index:2;
}

img.menuitem {
  width:100%;
  height:100%;
}

img.menuitem_enabled {
  width:100%;
  height:100%;
  filter:brightness(0%);
}

img.menuitem_disabled {
  width:100%;
  height:100%;
  filter:brightness(100%);
}

img.menuitem_profile_border {
  width:20%;
  height:48px;
  position:absolute;
  bottom:0px;
  right:0px;
  z-index:1;
  filter:brightness(100%);
}

img.menuitem_profile_border_enabled {
  width:20%;
  height:48px;
  position:absolute;
  bottom:0px;
  right:0px;
  z-index:1;
```

```
  filter:brightness(0%);
}

img.menuitem_profile {
  width:20%;
  height:48px;
  position:absolute;
  bottom:0px;
  right:0px;
  z-index:2;
  filter:brightness(100%);
}

img.comment_profile {
  width: 12%;
  padding:5px;
  float: left;
}

.comment_message {
  width: 78%;
  padding:5px;
  float: left;
  background-color:white;
  margin-top:5px;
  font-size:0.9em;
}

.clearfix {
  *zoom:1 /* for IE */
}

.clearfix:before,
.clearfix:after {
    content: " ";
    display: table;
}

.clearfix:after {
    clear: both;
}

hr {
  /* border-top: 1px solid #ffffff; */
  border: none;
  color: #333;
  background-color: #efefef;
  height: 1px;
}
```

```
    input {
     background-color:white;
     border:0;
     width:223px;
     float:left;
     padding:10px 5px;
     margin:12px 0;
     padding:5px;
     font-size:0.9em;
    }

    input::placeholder {
     font-size: 0.9em;
    }

    input[type="text"] {
     background: transparent;
    }

    .comment_post {
     background: transparent;
     /* background-color: #ffffff; */
     float: left;
     width: 40px;
     padding:0;
     margin:17px 0;
     font-size:0.9em;
     text-align: center;
     color:#609afd;
     font-weight: lighter;
    }

    .msg {
     background-color: #eee;
     padding: 14px;
     margin: 5px 10px;
     border-radius: 20px;
     font-size: 1em;
     text-align: left;
     display: table;
     float: right;
     clear: both;
    }

  </style>

</head>

<body style="">
```

```
<div id="homePage" data-role="page"
   style="background-color:white;">

  <div data-role="header"
     style="background-color:black;margin:0px 0px 0px
     0px;border:0px;padding:0px;width:100%;;
  position:fixed;top:0px;z-index:3; box-shadow: 0 1px 1px
     0 rgba(0, 0, 0, 0.1);">

   <img id="cameraBtn" src="res/topbar-camera.png" alt=""
      style="width:13.3%;float: left;z-index:4;">
   <img id="topHomeBtn" src="res/topbar-title.png" alt=""
      style="width:60.1%;float:left;z-index:4;"
      data-url="#homePage" onclick="goToPage(this);" >
   <img src="res/topbar-tv.png" alt=""
      style="width:13.3%;float:left;z-index:4;"
      onclick="info(infoMain);">
   <img id="messagePageBtn" src="res/topbar-message.png"
      alt="" style="width:13.3%;float:left;z-index:4;"
      data-url="#messagePage" onclick="goToPage(this);">

   <!-- Info -->
   <div id="infoMain" class="info"
      onclick="info(this);"></div>

  </div>

  <!-- ============== Feed Page ===============-->
  <div data-role="content" class="pagecontent">
   <!-- Stories -->
   <div class="stories" style="margin-top:-2px"><img
      src="res/stories.png" alt=""
      onclick="info(infoMain);"></div>

   <!-- Main Content -->
   <div>
    <!-- ========== Post 1 ========== -->
    <div id="post1" class="post">
     <!-- Content -->
     <div class="postcontent">
      <div class="postcontent-click"
         onclick="info(infoMain);"></div>
      <img src="res/feed/post01.png" alt="">
     </div>

     <!-- Menu -->
     <div class="postmenu">
      <img src="res/feed/post-like.png" alt=""
         onclick="onLikeClick(this);" data-clicked="">
```

```
  <img src="res/feed/post-comment.png" alt=""
     data-url="#commentPage1"
     onclick="goToPage(this);">
  <img src="res/feed/post-forward.png" alt=""
     onclick="onForwardClick(this);">
  <img src="res/feed/post-bookmark.png" alt=""
     style="float:right;"
     onclick="onBookmarkClick(this);"
     data-clicked="">
</div>

<div>
  <!-- Likes -->
  <div class="likes">870 likes</div>

  <!-- Post Initiator -->
  <div class="message">
    <span class="user">franniethepug</span>
    Happy 14th birthday to me!
       &#x1F382;&#x1F381;&#x1F388; I wish all my
       friends can come celebrate with me at my Hello
       Kitty birthday party today! It's great to be
       fourteen!
    <br>.<br>
    <span class="hashtag">#seniorsrule</span>
    <span class="hashtag">#frannietheleech</span>
    <span class="hashtag">#franniethepug</span>
    <span class="hashtag">#pugsofinstagram</span>
    <span class="hashtag">#pug</span>
    <span class="hashtag">#pugs</span>
    <span class="hashtag">#ilovemypug</span>
    <span class="hashtag">#pugsandkisses</span>
    <span class="hashtag">#instapug</span>
    <span class="hashtag">#puglife</span>
    <span class="hashtag">#apugslife</span>
    <span class="hashtag">#puglover</span>
    <span class="hashtag">#seniorpug</span>
    <span class="hashtag">#pugclub</span>
    <span class="hashtag">#pugnation</span>
    <span class="hashtag">#pugssesed</span>
    <span class="hashtag">#pugparty</span>
    <span class="hashtag">#pugswag</span>
    <span class="hashtag">#dogsofinstagram</span>
    <span class="hashtag">#cute</span>
    <span class="hashtag">#dog</span>
    <span class="hashtag">#dogs</span>
  </div>

  <!-- Comments -->
```

```
    <div class="comments" data-url="#commentPage1"
       onclick="goToPage(this);">View All 2
       Comments</div>

    <!-- Time Stamp -->
    <div class="timestamp">2 days ago</div>

  </div>
</div>


<!-- ========== Post 2 ========== -->
<div id="post2" class="post">
  <!-- Content -->
  <div class="postcontent">
    <div class="postcontent-click"
       onclick="info(infoMain);"></div>
    <img src="res/feed/post02.png" alt="">
  </div>

  <!-- Menu -->
  <div class="postmenu">
    <img src="res/feed/post-like.png" alt=""
       onclick="onLikeClick(this);" data-clicked="">
    <img src="res/feed/post-comment.png" alt=""
       data-url="#commentPage2"
       onclick="goToPage(this);">
    <img src="res/feed/post-forward.png" alt=""
       onclick="onForwardClick(this);">
    <img src="res/feed/post-bookmark.png" alt=""
       style="float:right;"
       onclick="onBookmarkClick(this);"
       data-clicked="">
  </div>

  <div>
    <!-- Likes -->
    <div class="likes">1,811 likes</div>

    <!-- Post Initiator -->
    <div class="message">
      <span class="user">_posy</span>
      Where does the blanket end and the pug begin??
      <span class="hashtag">#mondaymood</span>
      <span
         class="hashtag">#namasterightthereandnap</span>
      <span class="hashtag">#badasspugclub</span>
      <span class="hashtag">#beoncanadianpugs</span>
      <span class="hashtag">#thetomcoteshow</span>
      <span class="hashtag">#flatnosedogsociety</span>
```

```
      <span class="hashtag">#brandysfriend</span>
      <span class="hashtag">#gilesfriends</span>
      <span class="hashtag">#grumpysfriends</span>
      <span class="hashtag">#vinnythepug</span>
      <span class="hashtag">#mrbiscuitthepug</span>
      <span class="hashtag">#bubblebeccahat</span>
      <span class="hashtag">#keelyafternoontea</span>
      <span class="hashtag">#puggify</span>
      <span class="hashtag">#speakpug</span>
      <span class="hashtag">#picklepals</span>
      <span class="hashtag">#puglifemag</span>
      <span class="hashtag">#flossiesfriends</span>
      <span class="hashtag">#pugbasement</span>
      <span class="hashtag">#pug</span>
      <span class="hashtag">#pugs</span>
      <span class="hashtag">#tanksbuddies</span>
    </div>

    <!-- Comments -->
    <div class="comments" data-url="#commentPage2"
        onclick="goToPage(this);">View All 2
        Comments</div>

    <!-- Time Stamp -->
    <div class="timestamp">3 days ago</div>

  </div>
</div>

<!-- ========== Post 3 ========== -->
<div id="post3" class="post">
  <!-- Content -->
  <div class="postcontent">
    <div class="postcontent-click"
        onclick="info(infoMain);"></div>
    <img src="res/feed/post03.png" alt="">
  </div>

  <!-- Menu -->
  <div class="postmenu">
    <img src="res/feed/post-like.png" alt=""
        onclick="onLikeClick(this);" data-clicked="">
    <img src="res/feed/post-comment.png" alt=""
        data-url="#commentPage3"
        onclick="goToPage(this);">
    <img src="res/feed/post-forward.png" alt=""
        onclick="onForwardClick(this);">
    <img src="res/feed/post-bookmark.png" alt=""
        style="float:right;"
        onclick="onBookmarkClick(this);"
```

```
    data-clicked="">
</div>

<div>
  <!-- Likes -->
  <div class="likes">1,948 likes</div>

  <!-- Post Initiator -->
  <div class="message">
    <span class="user">taypinghui</span>
    Finally after days of scorching heat, a night of
        rain cleanses the streets of the dust and
        heat. A wonderful stroll on the empty streets
        iin the early morning and looking forward to
        my ang moh breakfast of croissants and
        espresso..
    <br>.<br>
    <span class="hashtag">#taypinghui</span>
    <span class="hashtag">#taypinghuiinitaly</span>
    <span class="hashtag">#actor</span>
    <span class="hashtag">#actorlife</span>
    <span class="hashtag">#actorslife</span>
    <span class="hashtag">#acting</span>
    <span class="hashtag">#filming</span>
    <span class="hashtag">#filminglife</span>
    <span class="hashtag">#film</span>
    <span class="hashtag">#tv</span>
    <span class="hashtag">#summerbreak</span>
    <span class="hashtag">#summer</span>
    <span class="hashtag">#france</span>
    <span class="hashtag">#paris</span>
    <span class="hashtag">#francais</span>
    <span class="hashtag">#morning</span>
    <span class="hashtag">#instasg</span>
    <span class="hashtag">#instagramsg</span>
    <span class="hashtag">#igsg</span>
    <span class="hashtag">#sgig</span>
    <span class="hashtag">#instagram</span>
    <span class="hashtag">#instapic</span>
    <span class="hashtag">#instagood</span>
  </div>

  <!-- Comments -->
  <div class="comments" data-url="#commentPage3"
    onclick="goToPage(this);">View All 2
    Comments</div>

  <!-- Time Stamp -->
  <div class="timestamp">3 days ago</div>
```

```
        </div>
      </div>

    </div>
  </div>

  <div data-role="footer">
    <div class="menubar">
      <div data-url="#homePage" onclick="goToPage(this);">
        <img class="menuitem"
            src="res/bottombar-home-sel.png" alt="">
      </div>
      <div data-url="#searchPage" onclick="info(infoMain);">
        <img class="menuitem" src="res/bottombar-search.png"
            alt="">
      </div>
      <div data-url="#addPage"onclick="info(infoMain);">
        <img class="menuitem" src="res/bottombar-cam.png"
            alt="">
      </div>
      <div data-url="#favPage"onclick="info(infoMain);">
        <img class="menuitem" src="res/bottombar-fav.png"
            alt="">
      </div>
      <div data-url="#profilePage"
          onclick="info(infoMain);">
        <img class="menuitem"
            src="res/bottombar-profile.png" alt="">
      </div>
    </div>
  </div>


</div>

<!-- ============== Message Page ===============-->
<div id="messagePage" data-role="page"
    style="background-color:white;">

  <div data-role="header"
      style="background-color:black;margin:0px 0px 0px
      0px;border:0px;padding:0px;width:100%;;position:fixed;
  top:0px;z-index:3; box-shadow: 0 1px 1px 0 rgba(0, 0, 0,
      0.1);">
    <img id="msgBackButton" src="res/back.png"
        style="width:13.3%; float: left;"
        data-url="#homePage" onclick="goToPage(this);">
    <img id="msgTop" src="res/msg/msg-top.png"
        style="width:86.7%; float: left;"
        onclick="info(msgMessage);">
```

```
    <!-- Info -->
    <div id="msgMessage" class="info"
       onclick="info(this);">This function is not
       implemented.</div>
  </div>

  <div data-role="content" style="width:100%; margin: 44px
     0 0 0; padding: 0;">
    <!-- Search and Suggestions -->
    <div><img id="msgTop"
       src="res/msg/msg-searchandsuggest.png"
       style="width:100%;"
       onclick="info(msgMessage);"></div>

    <div>
      <img id="msgTop" src="res/msg/msg-f1.png"
         style="width:100%;" data-url="#messagePageUser1"
         onclick="goToPage(this);">
      <img id="msgTop" src="res/msg/msg-f2.png"
         style="width:100%;" onclick="info(msgMessage);">
    </div>

  </div>

  <div data-role="footer">
    <div class="menubar">
      <img id="msgTop" src="res/msg/msg-cam.png"
         style="width:100%;float:left;"
         onclick="info(msgMessage);">
    </div>
  </div>

</div>

<!-- ============== Message User 1 ===============-->
<div id="messagePageUser1" data-role="page"
    style="background-color:white;">

  <div data-role="header"
      style="background-color:black;margin:0px 0px 0px
      0px;border:0px;padding:0px;width:100%;;
  position:fixed;top:0px;z-index:3; box-shadow: 0 1px 1px
     0 rgba(0, 0, 0, 0.1);">
    <img id="msgBackButton" src="res/msg/msg-f1-top.png"
       style="width:100%;float:left;"
       data-url="#messagePage" onclick="goToPage(this);">

    <!-- Info -->
```

```
    <div id="msgMessageUser1" class="info"
       onclick="info(this);">This function is not
       implemented.</div>

  </div>

  <div data-role="content" style="width:100%; margin: 44px
     0 0 0; padding: 0;">

    <div id="msgUser1Content" style="position: absolute;
       bottom: 70px; right:0px; text-align: right;">
    </div>

  </div>

  <div data-role="footer">
    <div class="menubar">
      <img id="msgTop" src="res/msg/msg-bottom-inputs.png"
         style="width:100%;position:absolute; bottom:0px;
         z-index:1;" onclick="info(msgMessageUser1);">
      <input id="msg_user1" type="text" placeholder="Write
         a message..." data-role="none"
         style="position:absolute;left:70px;bottom:5px;
         z-index:2;width:210px;"
         onkeyup="onMsgChange(this);">
      <div class="comment_post"
         style="position:absolute;bottom:5px;right:10px;"
         onclick="onMsgPostClick(msgUser1Content,
         msg_user1);">Post</div>
    </div>
  </div>

</div>


<!-- ============== Comment Page 1 ===============-->
<div id="commentPage1" data-role="page"
   style="background-color:white;">

  <div data-role="header"
     style="background-color:black;margin:0px 0px 0px
     0px;border:0px;padding:0px;width:100%;;
  position:fixed;top:0px;z-index:3; box-shadow: 0 1px 1px
     0 rgba(0, 0, 0, 0.1);">
    <img id="msgBackButton" src="res/back.png"
       style="width:13.3%; float: left;"
       data-url="#homePage" onclick="goToPage(this);">
    <img id="msgTop" src="res/comment/comm-top.png"
       style="width:86.7%; float: left;"
       onclick="info(commMessage1);">
```

```
  <!-- Info -->
  <div id="commMessage1" class="info"
     onclick="info(this);">This function is not
     implemented.</div>
</div>

<div data-role="content" style="width:100%; margin: 44px
   0; padding: 0; box-shadow:none;">
  <!-- Original post -->
  <div id="commentP1content">
    <div class="clearfix">
      <img class="comment_profile"
         src="res/comment/comm-1-0.png" alt="">
      <div class="comment_message">
        <span class="user">franniethepug</span>
        Happy 14th birthday to me!
           &#x1F382;&#x1F381;&#x1F388; I wish all my
           friends can come celebrate with me at my Hello
           Kitty birthday party today! It’s great to be
           fourteen!
        <br>.<br>
        <span class="hashtag">#seniorsrule</span>
        <span class="hashtag">#frannietheleech</span>
        <span class="hashtag">#franniethepug</span>
        <span class="hashtag">#pugsofinstagram</span>
        <span class="hashtag">#pug</span>
        <span class="hashtag">#pugs</span>
        <span class="hashtag">#ilovemypug</span>
        <span class="hashtag">#pugsandkisses</span>
        <span class="hashtag">#instapug</span>
        <span class="hashtag">#puglife</span>
        <span class="hashtag">#apugslife</span>
        <span class="hashtag">#puglover</span>
        <span class="hashtag">#seniorpug</span>
        <span class="hashtag">#pugclub</span>
        <span class="hashtag">#pugnation</span>
        <span class="hashtag">#pugssesed</span>
        <span class="hashtag">#pugparty</span>
        <span class="hashtag">#pugswag</span>
        <span class="hashtag">#dogsofinstagram</span>
        <span class="hashtag">#cute</span>
        <span class="hashtag">#dog</span>
        <span class="hashtag">#dogs</span>
      </div>

      <!-- Time Stamp -->
      <div class="timestamp"
         style="margin-left:55px;text-transform:none;">2
         d</div>
```

```
      </div>
      <hr>

      <div class="clearfix">
        <img class="comment_profile"
            src="res/comment/comm-1-1.png" alt="">
        <div class="comment_message">
          <span class="user">rascalpug</span>
          Happy birthday!
        </div>

        <!-- Time Stamp -->
        <div class="timestamp"
            style="margin-left:55px;text-transform:none;">2
            d</div>

      </div>

      <div class="clearfix">
        <img class="comment_profile"
            src="res/comment/comm-1-2.png" alt="">
        <div class="comment_message">
          <span class="user">bigbrotherbenny</span>
          Happy birthday Frannie!!! Love you!
        </div>
        <!-- Time Stamp -->
        <div class="timestamp"
            style="margin-left:55px;text-transform:none;">2
            d</div>
      </div>

    </div>

  </div>

  <div data-role="footer">
    <div class="menubar clearfix">
      <img class="comment_profile" src="res/profile.png"
          alt="">
      <input id="comment_content1" type="text"
          placeholder="Add a comment..." data-role="none">
      <div class="comment_post"
          onclick="onCommentPostClick(commentP1content,
          comment_content1);">Post</div>
    </div>
  </div>

</div>
```

```
<!-- ============== Comment Page 2 ===============-->
<div id="commentPage2" data-role="page"
   style="background-color:white;">

  <div data-role="header"
     style="background-color:black;margin:0px 0px 0px
     0px;border:0px;padding:0px;width:100%;;
  position:fixed;top:0px;z-index:3; box-shadow: 0 1px 1px
     0 rgba(0, 0, 0, 0.1);">
    <img id="msgBackButton" src="res/back.png"
      style="width:13.3%; float: left;"
      data-url="#homePage" onclick="goToPage(this);">
    <img id="msgTop" src="res/comment/comm-top.png"
      style="width:86.7%; float: left;"
      onclick="info(commMessage2);">

    <!-- Info -->
    <div id="commMessage2" class="info"
      onclick="info(this);">This function is not
      implemented.</div>
  </div>

  <div data-role="content" style="width:100%; margin: 44px
     0; padding: 0; box-shadow:none;">
    <!-- Original post -->
    <div id="commentP2content">
      <div class="clearfix">
        <img class="comment_profile"
           src="res/comment/comm-2-0.png" alt="">
        <div class="comment_message">
          <span class="user">_posy</span>
          Where does the blanket end and the pug begin??
          <span class="hashtag">#mondaymood</span>
          <span
             class="hashtag">#namasterightthereandnap</span>
          <span class="hashtag">#badasspugclub</span>
          <span class="hashtag">#beoncanadianpugs</span>
          <span class="hashtag">#thetomcoteshow</span>
          <span class="hashtag">#flatnosedogsociety</span>
          <span class="hashtag">#brandysfriend</span>
          <span class="hashtag">#gilesfriends</span>
          <span class="hashtag">#grumpysfriends</span>
          <span class="hashtag">#vinnythepug</span>
          <span class="hashtag">#mrbiscuitthepug</span>
          <span class="hashtag">#bubblebeccahat</span>
          <span class="hashtag">#keelyafternoontea</span>
          <span class="hashtag">#puggify</span>
          <span class="hashtag">#speakpug</span>
          <span class="hashtag">#picklepals</span>
          <span class="hashtag">#puglifemag</span>
```

```
          <span class="hashtag">#flossiesfriends</span>
          <span class="hashtag">#pugbasement</span>
          <span class="hashtag">#pug</span>
          <span class="hashtag">#pugs</span>
          <span class="hashtag">#tanksbuddies</span>
        </div>

        <!-- Time Stamp -->
        <div class="timestamp"
            style="margin-left:55px;text-transform:none;">2
            d</div>

      </div>
      <hr>

      <div class="clearfix">
        <img class="comment_profile"
            src="res/comment/comm-2-1.png" alt="">
        <div class="comment_message">
          <span class="user">ismaeljalal10</span>
          I don't see posy
        </div>

        <!-- Time Stamp -->
        <div class="timestamp"
            style="margin-left:55px;text-transform:none;">2
            d</div>

      </div>

      <div class="clearfix">
        <img class="comment_profile"
            src="res/comment/comm-2-2.png" alt="">
        <div class="comment_message">
          <span class="user">bella_belles_8</span>
          We love Posy the blankey :)
        </div>
        <!-- Time Stamp -->
        <div class="timestamp"
            style="margin-left:55px;text-transform:none;">2
            d</div>
      </div>

    </div>

  </div>

  <div data-role="footer">
    <div class="menubar clearfix">
```

```
      <img class="comment_profile" src="res/profile.png"
         alt="">
      <input id="comment_content2" type="text"
         placeholder="Add a comment..." data-role="none">
      <div class="comment_post"
         onclick="onCommentPostClick(commentP2content,
         comment_content2);">Post</div>
    </div>
  </div>

</div>

<!-- ============== Comment Page 3 ===============-->
<div id="commentPage3" data-role="page"
   style="background-color:white;">

  <div data-role="header"
     style="background-color:black;margin:0px 0px 0px
     0px;border:0px;padding:0px;width:100%;;
  position:fixed;top:0px;z-index:3; box-shadow: 0 1px 1px
     0 rgba(0, 0, 0, 0.1);">
    <img id="msgBackButton" src="res/back.png"
       style="width:13.3%; float: left;"
       data-url="#homePage" onclick="goToPage(this);">
    <img id="msgTop" src="res/comment/comm-top.png"
       style="width:86.7%; float: left;"
       onclick="info(commMessage3);">

    <!-- Info -->
    <div id="commMessage3" class="info"
       onclick="info(this);">This function is not
       implemented.</div>
  </div>

  <div data-role="content" style="width:100%; margin: 44px
     0; padding: 0; box-shadow:none;">
    <!-- Original post -->
    <div id="commentP3content">
      <div class="clearfix">
        <img class="comment_profile"
           src="res/comment/comm-3-0.png" alt="">
        <div class="comment_message">
          <span class="user">taypinghui</span>
          Finally after days of scorching heat, a night of
             rain cleanses the streets of the dust and heat.
             A wonderful stroll on the empty streets iin the
             early morning and looking forward to my ang moh
             breakfast of croissants and espresso..
          <br>.<br>
          <span class="hashtag">#taypinghui</span>
```

```
      <span class="hashtag">#taypinghuiinitaly</span>
      <span class="hashtag">#actor</span>
      <span class="hashtag">#actorlife</span>
      <span class="hashtag">#actorslife</span>
      <span class="hashtag">#acting</span>
      <span class="hashtag">#filming</span>
      <span class="hashtag">#filminglife</span>
      <span class="hashtag">#film</span>
      <span class="hashtag">#tv</span>
      <span class="hashtag">#summerbreak</span>
      <span class="hashtag">#summer</span>
      <span class="hashtag">#france</span>
      <span class="hashtag">#paris</span>
      <span class="hashtag">#francais</span>
      <span class="hashtag">#morning</span>
      <span class="hashtag">#instasg</span>
      <span class="hashtag">#instagramsg</span>
      <span class="hashtag">#igsg</span>
      <span class="hashtag">#sgig</span>
      <span class="hashtag">#instagram</span>
      <span class="hashtag">#instapic</span>
      <span class="hashtag">#instagood</span>
    </div>

    <!-- Time Stamp -->
    <div class="timestamp"
       style="margin-left:55px;text-transform:none;">2
       d</div>

  </div>
  <hr>

  <div class="clearfix">
    <img class="comment_profile"
       src="res/comment/comm-3-1.png" alt="">
    <div class="comment_message">
      <span class="user">chongdennis</span>
      Bro, heading there next week! Let me know if there
         is a restaurant worth going! Thanks!
    </div>

    <!-- Time Stamp -->
    <div class="timestamp"
       style="margin-left:55px;text-transform:none;">2
       d</div>

  </div>

  <div class="clearfix">
```

```
        <img class="comment_profile"
           src="res/comment/comm-3-2.png" alt="">
        <div class="comment_message">
         <span class="user">dianayung2</span>
         What a beautiful shot!! N OMG!! You are making my
            mouth water!! Enjoy :P:P:P
        </div>
        <!-- Time Stamp -->
        <div class="timestamp"
           style="margin-left:55px;text-transform:none;">2
           d</div>
      </div>

     </div>

    </div>

    <div data-role="footer">
     <div class="menubar clearfix">
      <img class="comment_profile" src="res/profile.png"
         alt="">
      <input id="comment_content3" type="text"
         placeholder="Add a comment..." data-role="none">
      <div class="comment_post"
         onclick="onCommentPostClick(commentP3content,
         comment_content3);">Post</div>
     </div>
    </div>

  </div>

</body>

</html>
```

B.4.3.3 Understanding Cataracts

This extract was taken from the Singapore National Eye Centre webpage [9] to provide a basic understanding on cataracts as it relates to design considerations.

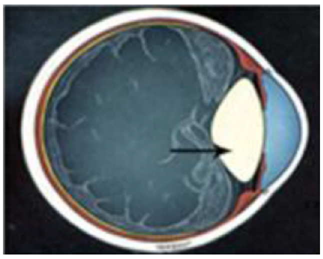
What is a Cataract?

Cataract is a condition in which the clear lens of the eye becomes cloudy, preventing sufficient light rays from entering the eye and impairing vision.

What causes Cataract?

It is common in the elderly due to ageing. Our recent Tanjong Pagar study found that over 80% of people aged 60 and above have some form of cataracts.

Prolonged ultra-violet light exposure, long term use of medications such as steroids and certain illnesses like diabetes are also risk factors for the development of cataracts. In the young, cataract can be present at birth or develop because of injury.



Cataract

Reduced vision, colour and contrast sensitivity

Glare

What are the symptoms?

The first sign is usually blurring of vision. Other complaints may include frequent change of glasses due to increasing short-sightedness in the adults, colours appearing dull, poor vision in bright light, glare, haloes around lights, difficulty reading or watching television or driving at night.