An Investigation of Mid-Air Gesture Interaction for Older Adults

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This thesis is submitted for the degree of Doctor of Philosophy

- Cybernetics Programme –

University of Reading

June 2019

Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

Older adults (60+) face natural and gradual decline in cognitive, sensory and motor functions that are often the reason for the difficulties that older users come up against when interacting with computers. For that reason, the investigation and design of age-inclusive input methods for computer interaction is much needed and relevant due to an ageing population. The advances of motion sensing technologies and mid-air gesture interaction reinvented how individuals can interact with computer interfaces and this modality of input method is often deemed as a more “natural” and “intuitive” than using purely traditional input devices such mouse interaction. Although explored in gaming and entertainment, the suitability of mid-air gesture interaction for older users in particular is still little known. The purpose of this research is to investigate the potential of mid-air gesture interaction to facilitate computer use for older users, and to address the challenges that older adults may face when interacting with gestures in mid-air. This doctoral research is presented as a collection of papers that, together, develop the topic of ageing and computer interaction through mid-air gestures. The initial point for this research was to establish how older users differ from younger users and focus on the challenges faced by older adults when interacting with mid-air gesture interaction. Once these challenges were identified, this work aimed to explore a series of usability challenges and opportunities to further develop age-inclusive interfaces based on mid-air gesture interaction. Through a series of empirical studies, this research intends to provide recommendations for designing mid-air gesture interaction that better take into consideration the needs and skills of the older population and aims to contribute to the advance of age-friendly interfaces.

Acknowledgements

I thank all the volunteers for their participation throughout the research, the University of Reading's Hugh Sinclair Unit and Psychology department for their help with recruitment. I would also like to thank my supervisor Dr. Faustina Hwang for her guidance, support and patience during the course of my doctoral research. The research is funded by the Brazilian Science Without Borders Programme, an initiative under the Ministry of Education and CAPES Foundation. Project number BEX 13037-13-7.

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1 *Introduction*

1 Introduction

Before the emergence of personal computing in the late 1970s, computers and information systems were largely inaccessible by the general population and their use would normally require extensive training and technical skills only available to a restricted niche of the society (i.e. programmers and command-line interfaces) [2]. This situation drastically changed with the first efforts of researchers and computer engineers who were responsible for introducing the early concepts of the Human-Computer Interaction field (HCI) in the early 1980s [5], an area of research and practice that embraces a more "humanistic" approach and interdisciplinary knowledge (e.g. cognitive science, human factors engineering, social sciences) with means to investigating the limitations of computing systems and improving computer tools through a better understanding of how people use them [2, 3]. Although it is an area in constant development, the Association for Computing Machinery (ACM) defines Human-Computer Interaction (HCI) as *"a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them"* [8].

Through the first initiatives of HCI practitioners and the appearance of the first Graphical User Interfaces (GUI), computers became more "user friendly" [2] – that is, computer interfaces became easier to learn and operate once users did not need to type commands in order to accomplish computer tasks: instead, users were gradually provided with different combinations of on-screen elements (the disruptive WIMP paradigm – *Windows, Icons, Menus, Pointer*) [5] and input techniques [6] with aims to make interaction easier and more efficient for those who were not proficient in using computers.

Eventually, the popularity of computing systems increased and the evolution of personal computer platforms (i.e. operating systems) established the idea that everyone could be a potential computer user [2, 3].

Computers, nowadays, have become an essential part of our lives and are ubiquitously present not only in our work routine, but also in our personal and social activities. An ever-expanding number of citizen services are now mediated through digital interfaces and the United Nations (UN) has even included “Digital Inclusion” as one of the key goals for Global Sustainable Development [9]. Interactive systems not only evolved in processing power, but also in diversity of devices [5, 6]. The ever-growing number of interactive devices (e.g. desktop computer, laptop, smartphones and tablets) has made it viable to conceive an evolving range of input methods and interaction contexts [6].

We are currently watching the rapid development of novel interaction methods that are less dependent on traditional input devices (e.g. mouse-based methods) and are becoming more embodied with the user. According to Norman (2010), *“we will look back on 2010 as the year we expanded beyond the mouse and keyboard and started incorporating more natural forms of interaction such as gestures, speech, and vision – what we computer scientists call the NUI or natural user interface”* [4]. Novel embodied input methods such as mid-air gesture interaction are deemed to be easier, more natural and engaging since it explores the physicality of gestural communication that people already apply when interacting in the real world [6]. Dourish (2001) argues that computer users have been interacting “through” physical objects (e.g. mouse, keyboard, touchscreen surfaces) over the last decades and interactions have been mediated through devices that are not natural to the user [6]. Instead, the author suggests that *“we can better exploit our natural skills if we focus on interacting with computers through our own bodies”* especially when traditional methods are inappropriate or inconvenient to some users [4, 6]. Even though gestures are indeed an essential part of non-verbal human communication, interacting with computers solely through gesture-based interaction may involve challenges that can hinder its implementation. Since our population is aging fast, and older adults are becoming an ever-growing demographic group of active technology users [11], it is pertinent to question, for instance, if mid-air gesture interaction is aligned with the needs and skills of the older population.

According to the World Health Organization (WHO) [11], the definition of older adults and older population is defined conforming to a range of characteristics including chronological age, change in social role and change in functional abilities.

Novel forms of embodied input, such as finger and freehand gestures are now easily available in an expanding range of interaction contexts and more applications that use mid-air gesture interaction are continuing to emerge. Therefore, it is fundamental to evaluate if mid-air gesture interaction is a suitable method for older adults that face natural age-related decline in motor, cognitive and sensory processing and whether this novel input method can facilitate and enhance computer use for the older population.

1.1 Motivation

This doctoral research was first motivated by Donald Norman's (2010) *"Natural User Interfaces Are Not Natural"* piece of work [4]. Back in 2010, Norman explained that, although mid-air gesture interaction may offer useful contributions to the advance of human-computer interaction, fundamental principles of implementation, feedback and conceptual models still apply and it may take a while for us to understand the best manner of implementing this novel input method. Nowadays, however, due to the advances of commercially available gesture-based interfaces and motion sensing technologies (e.g.

Microsoft Kinect, Leap Motion, Myo Armband, and Microsoft HoloLens for instance), interaction through mid-air gestures is a reality that a greater number of users are being gradually exposed to (e.g. gaming, intelligent cars, virtual reality, smart-homes) [1, 7].

Norman (2010) [4] claims that most gestures are neither “natural” nor easy to learn or remember. The author also indicates that some gestures as simple as a hand-waving “hello” or “goodbye” are performed differently by different people. Additionally, other fundamental issues with gestural interaction may include the initial difficulty to discover the set of possible gestures and the precise dynamics of gesture execution. Another usability concern is regarding the range of feedback available to the users once they make a gesture command: How do users know if they made a correct gesture command? Do they get a response if they make it incorrectly? [4]. Furthermore, the lack of standard practices and interface conventions may place further impediments for novice users when interacting with mid-air gestures.

Older adults are one of the user groups that might be more negatively affected by the described challenges of mid-air gesture interaction due to the physical, cognitive and sensory aspects involved in this input technique [4, 7]. Precise gesture execution and fatigue as well as learnability and memorability of new gestures, are some of the challenging aspects that older users may face when interacting in mid-air. However, little research on the usability of mid-air gesture interaction has given attention to the particularities of the older population. Therefore, little is known about the applicability and suitability of mid-air gestures for older users in the context of computer interaction.

Since mid-air gesture interaction is increasing in presence and applicability [1, 4, 7], and we are currently facing a rapid demographic shift with older adults (aged 60 and older) making up a growing proportion of the population worldwide [11], it is fundamental for us in the field of Human-Computer Interaction to seek a better understanding of the challenges and opportunities of this novel input technique for individuals that are historically overlooked by HCI research.

1.2 Research Questions

This thesis presents research concerning the design, evaluation and use of mid-air gestures by older users (60+) in the context of computer interaction. This work places an emphasis on user-centred computing [3], the challenges that older adults may face when interacting through mid-air gestures, and the exploration of opportunities for improvement of gesture-based interfaces with a focus on accessibility and ageing.

Some of the questions that this thesis is intending to answer are related to:

Questions regarding the cognitive aspects of mid-air gesture interaction and ageing:

- Are mid-air gestures easy to learn and to remember for novice older users with little familiarity with this novel input method?
- What are the design principles that may help older users in learning and remembering mid-air gestures more easily?

Questions regarding the motor aspects of mid-air gesture interaction and ageing:

- Taking into account the physical and embodied characteristics of gestural input, in conjunction with the natural age-related declines in dexterity and muscle strength observed in older adults, are mid-air gesture interactions aligned with the motor skills of older users?

- In what aspects does ageing affect the performance of mid-air gestures by older adults in comparison with younger users? And how can we design mid-air gestures that are physically appropriate for the older population?

Questions regarding the sensory aspects of mid-air gesture interaction as well as empowering and supporting older users in using mid-air gestures correctly:

- What are the most efficient ways for providing older users with feedback on where and how to gesture correctly in relation to what is expected by the system?
- Does mid-air gesture interaction facilitate computer use for older users in comparison with traditional input methods?
- In what context older users find mid-air gestures to be useful?
- How to better design age-friendly interfaces for mid-air gesture interaction?

1.3 Methods and Materials

This section briefly summarises the methods and materials used for each of the experimental chapters described below:

Investigating Age-Related Differences in How Novice Users Perform and Perceive Mid-Air Gestures as an Input Method for Computer Interaction **(Chapter 3)** uses a mixed-method approach, including a guessability study and a task-based study. Gesture data was collected using the Leap Motion sensor and analysis included video analysis, SUS and TAM-3 questionnaire responses using Thematic Analysis. Gesture data was analysed using a Linear-Mixed Model.

Text or Image? Investigating the Effects of Instruction Type on Mid-Air Gesture Making with Novice Older Adults **(Chapter 4)** uses a mixed-method approach. Gesture data was collected using the Leap Motion sensor and subjective responses were collected using Likert Scale items. Data was analysed using an Analysis of Variance.

Movement Characteristics and Effects of GUI Design on How Older Adults Swipe in Mid-Air **(Chapter 5)** uses a quantitative and data-driven approach. Movement data was collected using the Leap Motion sensor, Python and Javascript. Data was analysed using a Multivariate Analysis of Variance.

Evaluating the Effects of Feedback Type on Older Adults' Performance in Mid-Air Pointing and Target Selection **(Chapter 6)** uses a mixed-method approach. Feedback modalities were incorporated using Javascript and the Leap Motion gesture recogniser. Subjective data was collected using a NASA TLX questionnaire. Data analysis included an Analysis of Variance.

Investigating the Suitability and Effectiveness of Mid-Air Gestures Co-Designed By and For Older Adults **(Chapter 7)** includes a participatory design session (qualitative approach) and a task-based study (mixed-methods). Participatory design data was collected through co-design methods (think out loud, flowcharts) and video recorded. Gestures data was collected with the Leap Motion sensor in the task-based study and subjective responses were collected through SUS and NASA TLX questionnaires.

1.3.1 Participant Sampling

Despite looking at different aspects of mid-air gesture interaction and different gesture sets, the user studies presented in chapters 4, 5, and 6 were conducted using the same participant sample. The studies were conducted on the same day and place, and the study order was counterbalanced to minimise the eventual presence of learning effects.

In Chapter 7, participants in the co-design study did not participate in the usability testing study in order to avoid the eventual presence of learning effects and legacy bias.

1.4 Thesis Structure

This thesis is written as a collection of papers [10]. Together in the thesis, the papers follow a combination of systematic user studies with a holistic and explorative approach in order to investigate the main areas of ageing and the age-friendly design of mid-air gesture interaction. Figure 1 shows a simplification of thesis structure and list of studies.

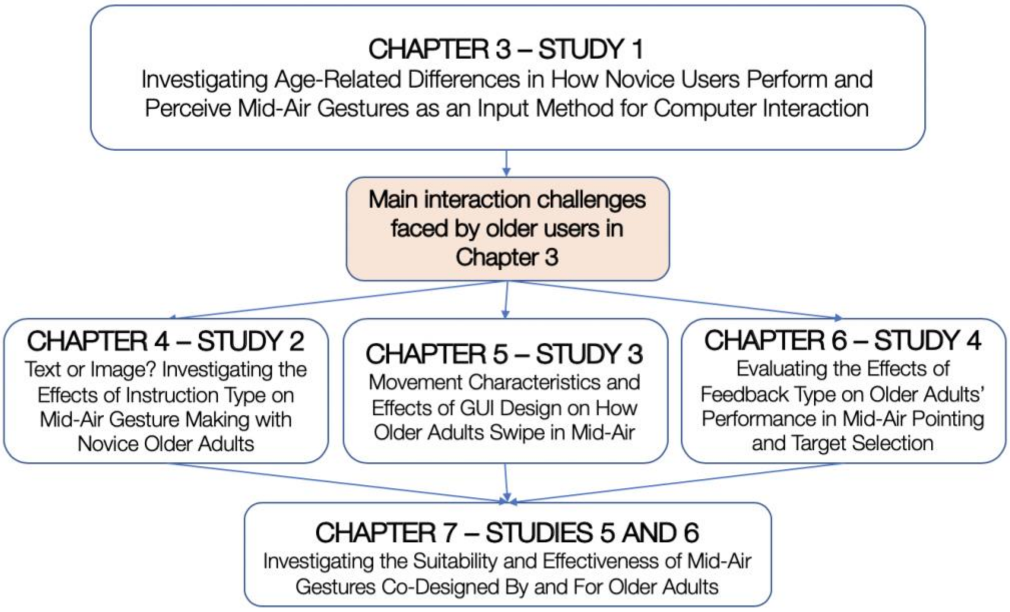


Figure 1 Thesis structure and list of studies

Chapter 2 presents a general review of key literature on ageing and computers, as well as challenges and opportunities for gesture-based interaction. The chapter also serves as a starting point for the discussions that will be further elaborated in the following chapters. A more detailed review will appear within the papers that make up the thesis.

Chapter 3 reports the first user study of this thesis. This paper investigates age-related differences in how novice users perform and perceive mid-air gestures as an input method for computer interaction. Chapter 3 presents the findings of a gesture guessability study and a task-based study using mid-air gestures for computer tasks with participants of two age groups. Recommendations are also provided for the design of gesture-based interfaces that take into consideration the particularities of older users. The findings of this chapter also serve as the guiding point for the questions explored within the following chapters of this thesis.

Chapter 4 addresses the challenges of providing on-screen instructions on gesture making for older adults with no experience in gesturing in mid-air. The learnability of new mid-air gestures was a fundamental issue identified in Chapter 3 that can affect how older adults interact with gesture-based interfaces. Therefore, methods for supporting older adults in learning and making correct gesture commands are explored in Chapter 4. Three methods for providing on-screen instructions on gesture making are compared in Chapter 4: static pictorials, text-based instructions and animated pictorials. This paper aimed to identify age-friendly interface design choices that support the learning of new mid-air gestures by older users.

Chapter 5 explores the applicability of the swipe gesture for the older population. The swipe gesture is a highly recurrent gesture for menu navigation that older users are likely to encounter when interacting with gesture-based interfaces in the real world [1]. As one of the findings of Chapter 3, older adults presented great difficulties when trying to navigate through a carousel menu by swiping left and right in mid-air. This issue consequently lead to a high number of failed gesture attempts. In order to deconstruct this problem, Chapter 5 aimed to investigate how older adults intuitively swipe in mid-air when interacting with three different on-screen carousel-styled menus with means to better understand how to adapt gesture-based interfaces for the gesturing skills of older users.

Chapter 6 analyses the effects of different uni-and-bimodal feedback modalities on how older adults perform point-and-select tasks in mid-air. The findings of Chapter 3 included the observation that pointing gestures were poorly performed by older adults in comparison with younger adults. Older users also indicated that sometimes they were not sure if their gestures were being made correctly or in the right place. Therefore, this paper evaluates different methods for providing age-friendly feedback on gesture making in order to support older users in their course of mid-air interaction through a target acquisition experiment.

Chapter 7 assimilates the findings of the preceding chapters and explores the concept of co-designing mid-air gestures with and for older users with the means of facilitating computer use. First, a co-design study with older adults is presented. Then, a usability study is conducted in order to evaluate the suitability and effectiveness of this approach as well as to compare the mid-air gestures co-designed by older adults with traditional input methods (e.g. mouse interaction) and off-the-shelf gestures that may not necessarily take into consideration the needs and skills of older users.

Chapter 8 summarises and highlights main findings of each experimental chapter (Chapters 3 to 7) and presents a general discussion about designing age-friendly mid-air gesture interaction. In addition to listing the contributions of this thesis, Chapter 8 also provides suggestions for future work.

References are listed at the end of each chapter and also together at the very end of the thesis.

References

1. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258. http://dx.doi.org/10.1145/2783446.2783599

2. Ben Shneiderman. 1980. Software Psychology: Human Factors in Computer and Information Systems. Winthrop, USA.

3. Donald A. Norman and Stephen W. Draper. 1986. User-Centered System Design: New Perspectives on Human-Computer Interaction. L. Erlbaum Assoc. Inc., USA.

4. Donald A. Norman. 2010. Natural User Interfaces Are Not Natural. *interactions*. 17, 3, 6-10. https://doi.org/10.1145/1744161.1744163

5. Jakob Nielsen. 1994. Usability Engineering. Kaufmann Publishers, USA.

6. Paul Dourish. 2001. Where the Action is: The Foundations of Embodied Interaction. MIT Press, Cambridge, MA, USA.

7. Sukeshini A. Grandhi, Gina Joue, and Irene Mittelberg. 2011. Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 821-824. https://doi.org/10.1145/1978942.1979061

8. Thomas T. Hewett, Ronald Baecker, Stuart Card, Tom Carey, Jean Gasen, Marilyn Mantei, Gary Perlman, Gary Strong, and William Verplank. 1992. ACM SIGCHI Curricula for Human-Computer Interaction. *Technical Report*. ACM, New York, NY, USA.

9. United Nations. 2015. Sustainable Development Goals. In *Department of Economic and Social Affairs' knowledge platform*. Retrieved September 2018 from: https://sustainabledevelopment.un.org/

10. University of Reading's Graduate School. 2016. Writing a Thesis as a Collection of Papers. In *Guide for Examiners of Research Degrees*. Retrieved September 2018 from: http://www.reading.ac.uk/web/files/graduateschool/gradschwritingthesisascollectionofpapers.pdf

11. World Health Organization (WHO). Ageing and Life Course. In *Global Health and Ageing*. Retrieved September 2018 from: http://www.who.int/ageing/en/

2 *General Literature Review*

2 General Literature Review

This chapter is intended to present a general introduction to the subjects of ageing, computer use and gestures. More detailed literature is reviewed within the studies integrating the following chapters.

2.1 Population Ageing

In the United Kingdom, around 25% of the population is currently over 60 years old and this number is projected to increase to 35% by the year of 2050. Furthermore, people born in the 2010s are expected to reach a life expectancy of over 85 years, according to the European Union statistics department [4]. Not limited to Europe, the population is also ageing in developing countries and the world's share of people aged 80 years or more is expected to double by 2080, according to the United Nations [15]. This drastic shift in demographics makes ageing a highly relevant topic in the field of Human-Computer Interaction and greater efforts for making computers more accessible to the general older population is much needed.

2.1.1 Definition of Older Adults

Older adults are commonly defined according to a range of characteristics including chronological age as well as changes in functional abilities and social role. According to the United Nations [15], the older age is usually related to retirement from work force at age of 60 or 65 years. However, due to an increasing life expectancy globally, some countries also define a separate group of oldest adults – those over the age of 85. Despite older adults are usually defined as users aged 60 and over, research has indicated that adults over the age of 50 may sometimes also identify themselves as "older users" and may appreciate age-inclusive strategies for computer-based interfaces [1].

2.2 Older Adults and Computers

According to Gregor and Newell (2001) [13], older adults can be divided into three groups:

1) "Fit" older adults, who do not present disabilities nor age-related health issues, but whose needs and abilities differ from the younger population and may gradually change as they get older.
2) "Frail" older adults, who are most likely to present accentuated changes in cognitive, sensory and motor functions.
3) "Disabled" older adults, whose ageing process may have affected long-term disabilities and vice-versa, and which a heavy reliance on assistive interventions is present.

It is fundamental to mention that, according to the authors, ageing is usually associated with disabilities and assistive technologies. HCI research often fail to acknowledge a whole spectrum of capability levels related to growing older. Ageing is indeed associated with gradual reduced capabilities but it does not necessarily constitute a disability. Furthermore, the relationship between older people and technology is full of stereotypes that may be detrimental to the efforts of making HCI research more age-inclusive. Common allegations such as “older people are not interested in using computers”, and that they “cannot understand how to use computers”, besides being false and unfair [8], may also lead to further exclusion. For that reason, this thesis aims to focus on the first group of older adults: those who do not present specific disabilities but may be affected by natural and gradual age-related decline in cognitive, sensory and motor skills [1].

Ageing naturally brings changes in cognitive, sensory and motor processes [14]. These changes are most likely to affect how older adults interact and perceive technology in general [1, 6]. Indeed, research has indicated that older users of technology present different views and attitudes towards computers in comparison with younger users [2, 10, 14]. Even though older adults are growing in number and digital presence, interactive systems often fail to adapting to the changing needs and abilities of older users [1, 11]. Whilst research on understanding the differences between how younger and older adults perceive and interact with computers is important, the current state-of-art in HCI and ageing research lacks the exploration of appropriate and improved interaction methods for older users once these age-related differences are known.

It has been known, for instance, that older adults often struggle in using traditional input methods for computer interaction: in particular mouse-based tasks. Due to age-related decline in vision, memory and motor control [2, 6, 12], older users present more difficulty in dealing with rapid movements and submovements, fine cursor reposition, clicking and double-clicking, and drag and scroll tasks [1, 12]. Although these problems have been acknowledged by HCI researchers in the past [14], further investigations toward improved input methods that take the abilities of the ordinary older user are still needed.

2.3 Gestures

Gesture-based interaction has gained popularity with the advances of motion sensing devices such as the Microsoft Kinect, Leap Motion sensor, and more recently the Microsoft HoloLens. Mid-air gesture interaction, specifically, is being employed in an ever-growing number of interaction contexts that includes gaming [11] and home-based entertainment [9].

Findlater et al. (2013) [10] found that touchscreen gestures reduce the performance gap between younger and older users, whilst Stößel (2009) [3] suggested that (the lack of) familiarity is one of the main dictators of gesture-based interaction by older users. The authors also found that, although slower than younger users, older adults do not necessarily make more errors in touchscreen interaction. The applicability of these results for mid-air gestures, however, is still unknown. Besides novelty and familiarity, a distinctive difference between touchscreen gestures and mid-air gestures is the greater presence of upper limb fatigue in the latter. The presence of fatigue when interacting through gestures has been observed through subjective responses [5, 7], and through EMG analysis [2].

Due to its novelty, the applicability and appropriateness of mid-air gesture interaction to the older population is little known. Mid-air gesture interaction can offer challenges and opportunities for older users, but empirical support is lacking. The following chapters will further discuss the literature regarding ageing and mid-air gesture interaction, and contribute with empirical investigations towards a more age-inclusive application of interaction through mid-air gestures.

2.4 Gesture Recognition Technologies

2.4.1 Microsoft Kinect

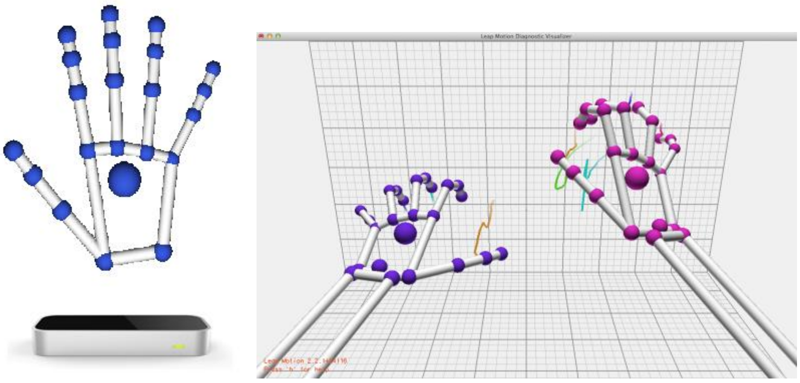
Advances in computer vision and 3D depth cameras have created opportunities for further exploration of motion sensing technologies and gesture-based interactions in HCI. The trend started with the launch of the Microsoft Kinect in 2010, a camera-based sensing device that was first developed to be used in video gaming alongside with Microsoft Xbox console (Figure 1). Due to its low cost and wide availability, Kinect's impact has extended beyond the gaming context. Researchers and practitioners in the areas of HCI, computer science, engineering and robotics have applied Kinect's full-body sensing capabilities to create novel ways to interact with motion-based interfaces and other tasks, such as for motivating physical rehabilitation [17] and for recognising sign language [18]. The Kinect depth sensor consists of an infrared projector combined with an infrared camera, which has also a CMOS sensor. Additionally, its 3D sensing is possible by comparing patterns detected by both the IR camera and the IR projector through normalised cross correlation [19]. Furthermore, Kinect's robust full-body 3D motion tracking, including hand and arm gestures, can be incorporated in interactive systems using programming languages such as C++, C# or Visual Basic [20].

Figure 1 The Microsoft Kinect sensor

2.4.2 Leap Motion

Despite its robustness for full-body tracking, the Kinect was not particularly suitable for detecting finger gestures and fine movements. For that reason, the Leap Motion sensor – launched in 2013 – gained expressive notoriety amongst HCI researchers and practitioners for its hand and multiple joint finger tracking. The Leap Motion sensor (Figure 2) consists of a small camera-based device that can be connected to a computer or virtual reality head-mounted display and allows real time hand tracking and gesture recognition. The sensor is a combination of two monochromatic infrared cameras and three infrared LEDs that can then observe hemispherical area to a distance of about 1 meter. By generating almost 200 frames per second of movement data, the Leap Motion sensor is able to translate three-dimensional data by comparing 2D frames captured by its infrared cameras with an average accuracy of 0.7 millimetres. The Leap Motion sensor can be used to perform tasks such as navigating computer-based applications or websites using difference hand and finger gestures, high-precision spatial drawing, and for manipulating 3D objects and spaces in virtual reality for instance [16].

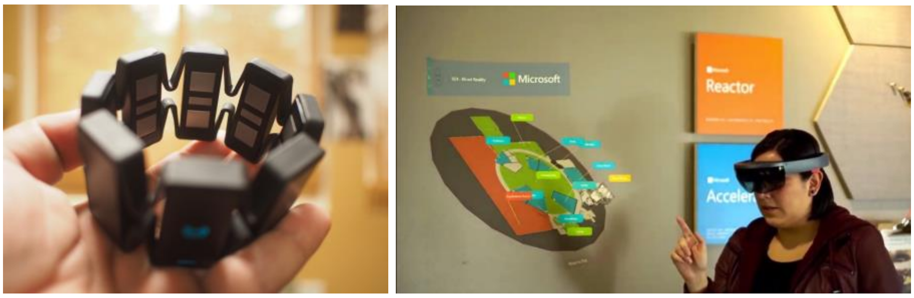
Figure 2 The Leap Motion sensor



2.4.3 Other Gesture Recognition Technologies

Besides purely camera-based sensors for motion detection and gesture recognition, additional commercially available devices such as the Myo Armband and the Microsoft HoloLens have also helped to expand the use of gestures in many interaction contexts. Instead of using depth cameras, the Myo Armband uses 8 surface electromyography (EMG) to detect the user's hand movements and gestures through a wireless wearable device and muscle activity. The armband, however, is only able to detect a limited set of hand gestures [21]. Furthermore, gesture recognition is currently being used for augmented reality with the Microsoft HoloLens – mixed reality smartglasses that supports gaze, gesture, and voice commands for 2D and 3D applications. HoloLens' gesture recognition hardware features an inertial measurement unit which includes an accelerometer, a gyroscope, and a magnetometer, all in combination with depth camera [22]. Gestures such as "finger pinch" and "drag" can be used for selection and direct manipulation in augmented reality applications for instance.

Figure 3 Myo Armband (left) and Microsoft HoloLens (right)



2.5 Research Agenda

Despite the growing use of this interaction technique in many contexts (e.g. computer user, virtual reality, gaming, tele-medicine, and cars) and technical advancements, mid-air gesture interaction had not previously been studied systematically with regard to its actual use and usability for older adults (aged 60 and older). The closest research that explored this gap focused on investigating the intended use of full-body interactions by frail older adults [9, 11] in a leisure context. Therefore, the majority of research undertaken to advance the *state-of-the-art* of mid-air gesture interaction as an usable interaction technique has been focused on young and skilled users only. Little to no theoretical grounds of the role of age on mid-air gesture performance exist, making it difficult to think about this input method from the perspective of age-inclusiveness. Since ageing plays a fundamental role on technology use, the lack of empirical evidence from older adults makes it difficult to put this user group into perspective and contributes to further technological exclusion.

A much-needed research direction relates to gaining a better understanding on how older adults perceive and interact with interfaces based on mid-air gesture interactions. This includes gaining knowledge on how differently older adults interact with mid-air gestures in comparison with younger adults. There is also the need to understand where mid-air gesture interaction stands as an age-inclusive input method in comparison with traditional input methods such as mouse and touchscreen surfaces. Unanswered questions also include possible applications of mid-air gestures for improving the lives of older adults and how to make mid-air gesture interaction useful for older users in a computer-based context. Once there is an initial understanding regarding these fundamental issues, and a solid knowledge on the interaction challenges faced by older adults, then research can progress to explore more specific questions regarding age-inclusive gesture sets and gesture learning by the older population.

Insights from HCI literature on touchscreen gestures and older adults, or psychology literature on ageing and computers may be helpful to speculate about these questions. However, the work done in related areas is not sufficient to replace actual empirical knowledge regarding mid-air gestures and older users due to the particularities of this interaction technique and the psychomotor skills involved.

Furthermore, guidelines and design recommendations for developing usable gesture-based interfaces are often abstract and lack contextual use. This research aims to develop a set of practical and contextualised guidelines for designing usable and age-inclusive mid-air gesture interactions appropriate for both the research community but also for practitioners.

In the following chapters, the thesis presents users studies that aim to first gain comprehensive knowledge on how age affects mid-air gesture interaction and to identify key interaction challenges faced by older users (Chapter 3). After identifying these challenges, the research takes a more applied context in order to explore methods for minimising usability problems in mid-air gesture interfaces and enhancing age-inclusiveness by combining theory-driven and data-driven approaches (Chapters 4 to 7).

References

1. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266.

2. B. Laursen, B.R. Jensen, and A. Ratkevicius. Performance and muscle activity during computer mouse tasks in young and elderly adults. *European Journal Applied Physiology* 84 (2001), 329-336.

3. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78.

4. European Union statistics. 2018. Population Structure and Ageing. In *Eurostat Statistics Publication*. Retrieved September 2018.

5. Esben Warming Pedersen and Kasper Hornbæk. 2012. An Experimental Comparison of Touch Interaction on Vertical and Horizontal Surfaces. In *Proceedings of NordiCHI ’12*. ACM, New York, NY, USA, 370-379.

6. Genaro Motti, Lilian and Vigouroux, Nadine and Gorce, Philippe *Interaction techniques for older adults using touchscreen devices : a literature review.* (2013) In: 25eme conference francophone sur l'Interaction Homme-Machine (IHM 2013), 13 November 2013 - 15 November 2013 (Bordeaux, France).

7. Hiroyuki Umemuro. 2004. Lowering elderly Japanese users' resistance towards computers by using touchscreen technology. *Univers. Access Inf. Soc*. 3, 3-4 (October 2004), 276-288. http://dx.doi.org/10.1007/s10209-004-0098-6

8. H. Wandke, M. Sengpiel, and M. Sönksen. 2012. Myths About Older People’s Use of Information and Communication Technology. *Gerontology*. 58, 6, 564-570.

9. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. https://doi.org/10.1145/2325616.2325625

10. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346.

11. Kathrin Gerling, Ian Livingston, Lennart Nacke, and Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1873-1882. https://doi.org/10.1145/2207676.2208324

12. Michael W. Smith, Joseph Sharit, and Sara J. Czaja. 1999. Aging, Motor Control, and the Performance of Computer Mouse Tasks. *Human Factors*. 41, 3, 389-396.

13. Peter Gregor and Alan F Newell. 2001. Designing for dynamic diversity: making accessible interfaces for older people. In *Proceedings of the 2001 EC/NSF workshop on Universal accessibility of ubiquitous computing: providing for the elderly* (WUAUC'01). ACM, New York, NY, USA, 90-92. http://dx.doi.org/10.1145/564526.564550

14. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.

15. United Nations. 2017. World Population Ageing report. In *Department of Economic and Social Affairs, Population Division*. Retrieved September 2018.

16. Wei Lu, Zheng Tong, Jinghui Chu. 2016. Dynamic hand gesture recognition with the leap motion controller. *IEEE Signal Processing Letters*. 23, 9, 1188-1192.

17. Yao-Jen Chang, Shu-Fang Chen, Jun-Da Huang. 2011. A Kinect-based system for physical rehabilitation: A pilot study for young adults with motor disabilities. Research in Developmental Disabilities. 32, 6, 2566-2570.

18. Zahoor Zafrulla et al. 2011. American sign language recognition with the kinect. In *Proceedings of the 13th international conference on multimodal interfaces* (ICMI 11). ACM, New York, NY, USA, 279-286.

19. Zhengyou Zhang. 2012. Microsoft kinect sensor and its effect. *IEEE Multimedia*. April-June 2012. IEEE.

20. Zhou Ren, Jingjing Meng, Junsong Yuan, and Zhengyou Zhang. 2011. Robust hand gesture recognition with kinect sensor. In *Proceedings of the 19th ACM international conference on Multimedia* (MM '11). ACM, New York, NY, USA, 759-760. http://dx.doi.org/10.1145/2072298.2072443

21. Zainal Arief et al. 2015. Comparison of five time series EMG features extractions using Myo Armband. In *Proceedings of the 2015 International Electronics Symposium* (IES). IEEE.

22. Zhiwei Xiong et al. 2017. Computational depth sensing: toward high-performance commodity depth cameras. *IEEE Signal Processing Magazine*. 34, 3, 55-68.

3 *Investigating Age-Related Differences in How Novice Users Perform and Perceive Mid-Air Gestures as an Input Method for Computer Interaction*

Publication status:

* Excerpts of this chapter were peer-reviewed and published in:

Cabreira, A. T. and Hwang, F. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258. http://dx.doi.org/10.1145/2783446.2783599A

Cabreira, A. T. and Hwang, F. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. *In Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA, Article 122. https://doi.org/10.1145/2971485.2996757

* Full chapter is under peer-review in *Interacting with Computers* (IwC)

3 Investigating Age-Related Differences in How Novice Users Perform and Perceive Mid-Air Gestures as an Input Method for Computer Interaction

Abstract

We report the findings of a two-part study investigating differences between age groups in terms of how novice users perform and perceive mid-air gestures as an input method for computer interaction. We conducted a guessability study where participants were shown pre-defined commonly-used mid-air gesture names as referents and were then asked to propose how to make the named gestures, in order to assess the intuitiveness of these names for novice users. Participants were then asked to use mid-air gesture interaction to complete 5 computer tasks using a Leap Motion sensor. Our results show that even though younger and older adults had similar conceptual models for gesturing in-air, older users had poorer performance, and hand gestures based upon real-world interactions should be given preference over finger gestures based upon touchscreen paradigms. We also propose recommendations to guide the design of mid-air interactions that better accommodate the requirements of novice older users.

1 Introduction

Older adults (60 years and older) make up an increasing proportion of the world demographics, yet the majority of research in human computer interaction focuses mostly on younger users. As a consequence, older adults may be losing out on the possible benefits and opportunities from new technology and its applications. Moreover, older adults are still often not perceived as active users of technology and could potentially be put at a disadvantage in terms of their needs and abilities not being addressed within novel technologies and computer interaction methods. Therefore, unless there is an understanding of how older adults interact, perceive and face difficulties adapting to new technologies, successful use of novel interaction models will continue to be a challenge for the older population (Czaja and Lee, 2007; Dickinson et al., 2007).

Mid-air gesture interaction is a manner of interacting with a system by making in-air gestures which are then detected by motion sensors, and it has been increasing in popularity and diversity of applications with the emergence of commercially-available – and low cost - motion sensing platforms such as the Microsoft Kinect and HoloLens, Leap Motion and, more recently, Myo Armband. Interaction through touchless freehand gestures is deemed to be an effective way of reducing the learning curve and presents advantages over conventionally established interaction paradigms. Several authors suggest that the “naturalness” and “intuitiveness” of gesture production leads to better interaction, making the system more intuitive, usable and easy to use (Nielsen et al., 2003; Saffer, 2008; Wigdor and Wixon, 2011; Grandhi et al., 2011). It remains unclear, however, whether mid-air gesture interaction indeed facilitates technology use and adoption by older users with diverse capabilities, or whether the drawbacks involved in this physical embodied input method further decreases usability and accessibility of such interfaces for the older population.

Although it is widely known that older adults are increasingly making more use of technology, they are still seen by some as “non-users”. (Selwyn, 2004) argue that older adults move through different states of levels of technology (non)use depending on their circumstances and context and should not be seen as a homogeneous group of disempowered, under-resourced, under-skilled individuals. Similarly, (Moffatt, 2013) implies that age alone should not define this group of users and it should be rather defined by its common characteristics, hence older users may start to appreciate “seniorsensitive" designs at age 55, whilst others may have no interest in them at age of 80. In addition to that, (Charness and Boot, 2009) suggest that older adults may interact with and perceive novel interaction techniques differently than younger adults do, therefore age-related changes in sensory, cognitive and motor abilities should be carefully addressed when designing novel input methods (Fisk et al., 2009). If novel interaction techniques (e.g. mid-air gesture interaction) are not suitably designed with the older population in mind, this could bring a potential barrier to older users for adopting it and thus may prevent many older adults from benefiting from technological advances that could improve their independence and well-being (Coughlin et al., 2006).

One notable characteristic of mid-air gesture interaction is that it has the potential to allow direct manipulation, which incorporates the concept of physically manipulating objects within an interface in the same way as found in the "real world" (Shneiderman, 1982 & 1983; Te'eni, 1990). It is suggested that direct manipulation minimises cognitive effort if applied directly into a user's view or conceptual model of a specific task and promotes higher engagement, therefore making the system interface "transparent" and leading the user to build a sense of working with the actual interactive objects rather than just using a computer system (Hutchins et al., 1986). Direct manipulation derived from gesture interaction has the potential to help novice users learn basic functionality quickly as it incorporates a model of the task held by the user and presents instant on-going feedback as results of their interaction are shown as the action is taking place (Maes and Shneiderman, 1997; Shneiderman, 2010). On the other hand, (Norman and Nielsen, 2010) define gesture-based interaction as a step backwards in usability due to its lack of established guidelines for gesture control and minimal consistency across platforms. Additionally, (Grandhi et al., 2011) argue that some challenges around the implementation of this input technique are related to achieving accurate gesture recognition and identifying natural, intuitive gesture vocabularies appropriate for the tasks in question.

In relation to finding appropriate gestures that are consistent with different interaction contexts, (Wobbrock et al., 2005) suggested that it is possible to conceive a highly guessable symbol set by acquiring guesses from participants. Research has been done using guessability studies for gesture elicitation (Wobbrock et al., 2009; Ruiz et al., 2011; Findlater et al., 2012), a form of participatory design technique where users in propose gestures to inform the design and development of gesture-based systems (Wobbrock et al., 2005 & 2009). Gesture elicitation studies usually show participants the desired effect of an action (called referent) and ask users to propose a gesture command (called symbol) that would result in that action. Elicitation studies, combined with metrics such as subjective easiness and agreement amongst users, become powerful tools for informing user-friendly gesture sets by identifying patterns amongst different users (Rodriguez and Marquardt, 2017; Morris et al., 2014). Yet, one limitation of gesture elicitation studies is that gestures elicited using this method are merely hypothetical and the question of how translatable are these gestures to real interaction situations remains unanswered, unless the findings of these elicitation studies are somehow associated with a task-based study where the usability of those gestures are put to the test with real users. Unfortunately, the efforts of the research community in trying to find intuitive and usable gesture sets are currently not aligned with the practices seen in commercially-available applications. These gesture-based interfaces, made easily accessible by the popularisation of motion sensors, still lack established standard practices and cross-application consistency, which may affect how novice users learn how to make those gestures (Norman and Nielsen, 2010; Cabreira and Hwang, 2015 and 2016).

Nevertheless, mid-air gesture interaction is becoming largely ubiquitous and the applications range, for instance, from interactive public displays (Walter et al., 2013) to home-based leisure (Bobeth et al., 2012; Vatavu et al., 2012), medical surgery rooms (O'Hara, 2014), mobile interaction (Kratz et al., 2012), augmented reality (Kim et al., 2014) and virtual reality (Vosinakis et al., 2016). As the HCI research concerning the advancement of mid-air gesture interaction seems, for the most part, not to include the older population, questions regarding the suitability of mid-air gesture interaction arise as this novel input technique reaches a wider population, and whether the characteristics of mid-air gesture production are aligned with the needs and capabilities of the older population.

Therefore, this work reports the findings of a two-part mixed-method exploratory investigation of the intuitiveness and usability of freehand touchless gestures as an input method for novice younger and older users with no prior experience gesturing in mid-air in a computer interaction context. The first part of the study aimed to investigate the suitability of 15 current, commercially-used mid-air gesture names through a guessability study. The second part of the study aimed to evaluate how novice users - older adults in particular - execute, perceive and accept mid-air gestures when applied to 5 computer tasks. Finally, we propose system recommendations to guide the design and development of mid-air gesture-based interfaces that better accommodate the requirements of the older population with regards to user preference and overall usability.

2 Related Work

2.1 Older adults, gestures and motion control

2.1.1. Touchscreen gestures and older users. Previous investigations on mobile touchscreen gesture interaction and older adults have suggested that older adults are slower at performing finger gestures on touchscreen surfaces, but not necessarily less accurate, and that further factors such as user interface familiarity and intuitiveness play a greater role in influencing gesture performance than motor dexterity skills of older users (Stößel, 2009; Stößel et al., 2010; Piper et al., 2010). Additionally, (Findlater et al., 2013) conducted a comparison study of age-related differences in performance on desktop and touchscreen tasks, including: pointing, dragging, crossing, steering and pinch-to-zoom gestures. Results showed that whilst older adults were significantly slower than the younger participants in general, touchscreen gestures reduced the performance gap relative to mouse interaction, including decreased error rates and a significant movement time reduction of 35% over the mouse for older adults, in contrast to only 16% for younger adults. Furthermore, although there are increasing efforts to make touchscreen gesture interaction more accessible and usable for the older population, there is also a need for similar studies involving gesturing tasks in mid-air, where it is unclear if limited haptic feedback (i.e. no sense of touch), a lack of spatial steering guidance, and a heavy reliance on visual feedback could have a greater impact on performance by older users.

2.1.2. Motion control for TV and gaming. (Bobeth et al., 2012) conducted an evaluative study on performance and acceptance ratings by older adults using freehand gestures for smart TVs. Four types of gesture input techniques were explored in the study, and cursor-based interaction (pointing) was the input modality most-preferred by the older participants. Despite older users demonstrating initial positive attitudes towards freehand gestures for smart TVs, only one leisure task (i.e. menu selection) and a limited set of four gestures were assessed within this study and a better understanding of the influence of different tasks on performance and acceptance of gesture-based interactions is still necessary as a fundamental means of assessing the suitability of mid-air gesture interaction outside the scope of leisure contexts.

In addition, research has been done on motion sensing games for older adults using full-body interactions with regards to physical and social engagement. (Rice et al., 2011) investigated the usability and acceptability of a set of three gesture-based games by using a combination of pre-and-post game questionnaires, video analysis and group interviews. Their findings indicated that, although usable, gesture-based interactions were perceived as being in dissonance with the physical skills of the older gamers. Further work elaborates on how younger and older gamers differ in expectations and perceived interaction when using gesture-based games (Rice et al., 2013). In a similar manner, (Gerling et al., 2012) mention that most motion sensing games are not designed with age-related sensorimotor limitations in mind, which prevents games from being accepted by and usable for older adults. They further suggest that motion-controlled games have the potential to lead to positive effects on mood and can accommodate a variety of user abilities when designed to accommodate the skills and needs of the older population. These recommendations comprise, for instance, the inclusion of gestures that adapt to the player’s physical abilities and that closely relate to real-world activities. Despite the advancement of research in those applications areas, research concerning engagement and suitability of mid-air gesture interaction in non-gaming contexts such as public walk-up-and-use interfaces and daily non-gaming computer-based tasks is still needed.

2.2 Age-related declines and their potential challenges for mid-air gesture interaction

2.2.1. Motor Decline and Fatigue. Muscle strength begins to decline quite sharply from around the age of 50 (Huppert, 2003). Flexibility and adequate range of movement are also affected. (Chaparro et al., 2000) strongly suggest that older users can face greater difficulty using an input device that relies on motions of the wrist and grip strength (e.g. mouse) due to reduced range of motion. Moreover, individuals 60 years old and older present a decline of 25% in wrist flexion, wrist extension and ulnar deviation in comparison with younger adults (age 25-35). Also, a range of motion that is 60% of an average 30 years old individual is expected for an older adult at the age of 90.

Constant use of dextrous movements to perform gestures without frequent relaxation of the arms can lead to physical weariness and, consequently, impact consistency of performance, accuracy and user experience through the interaction. Although fatigue can appear in any user regardless of age, it has a more significant effect on older users due to their natural motor decline and muscular frailty, which includes decreased ranged of motion, less strength and less fine motor control (Hincapié-Ramos et al., 2014).

In an investigation of performance of older adults using short pointing-based freehand gestures for smart TVs, (Bobeth et al., 2012) noted that the body pose in which arm movements are performed has an influence on the appearance of fatigue and even if gestures may not be considered physically exhausting stand-alone, the entire interaction needs to be designed carefully to avoid the occurrence of fatigue. More than affecting the interaction as a whole, fatigue can also have significant influence on the gesture performance itself. In a study with younger adults using hand gesture interactions for remote control in a living room context, (Lee et al., 2013) observed increasing fatigue when, at the beginning of the experiment, most participants stretched their arms wide and started with large gestures, but over time the gestures became smaller until they turned into small gestures using just the wrist. Furthermore, (Vuibert et al., 2015) indicate that mid-air gesture interaction for direction manipulation becomes fatiguing when users need to keep their arms extended to manipulate the interface for longer periods of time, in the same way that, based on an experimental method for quantifying arm fatigue in mid-air interactions, (Hincapié-Ramos et al., 2014) recommend limiting gesturing motions between the hip and shoulders in order to reduce arm extension. However, despite of the increasing efforts of the HCI community to acknowledge means for minimising the influence of fatigue on performance and acceptance of full-body and gesture-based interaction methods, little work has included the older population and its motor capabilities as an additional challenge to be addressed, and therefore further work should be done on this topic.

2.2.2. Cognitive Decline, Learnability and Memorability of Gestures. Cognition refers to the set of mental abilities and processes related to comprehension, knowledge, attention and memory. These cognitive processes are triggered by the information that comes in from our senses, and are responsible for how we learn and remember, solve problems and make decisions (Huppert, 2003). Therefore, working memory is an important aspect to be considered regarding interface design, since several chunks of information have to be maintained and integrated to successfully complete tasks during an interaction sequence (e.g. selecting an option in a menu, typing login information, recalling a gesture) (Stößel, 2009). Older adults particularly have difficulties recalling information (e.g. remembering street address or the title of a book), and recognising the information when it is presented is a cognitive process that is easier to complete. Additionally, learning skills gradually decline after middle-age and older adults need to put more effort into learning compared to younger adults. Numerical skills and spatial abilities are also affected by ageing (Huppert, 2003). One design challenge concerning the learnability and memorability of gesture-based interfaces is regarding the choice of suitable gesture sets that accommodate the cognitive abilities of older users. According to (Nielsen et al., 2004), gestures should be appropriate to the corresponding task, easy to learn, perform and remember. (Stößel and Blessing, 2010) found that "good memorability", which is the quality of being easy to remember, was regarded by older users as the most important feature of good touchscreen gestures in a study on user-defined gesture set for completing tasks with an iPod Touch. (Nacenta et al., 2013) argue the importance of memorability, as forgotten gestures can lead to errors, increase frustration and may prevent the adoption of gesture-based user interfaces. Little work has been done on memorability of mid-air gestures for older adults and further studies should investigate the influence of cognitive changes in gesture learning, performance and recall.

2.2.3. Feedback, Sensory Decline and (lack of) Haptics. Ageing brings significant physiological changes that affect our senses and gradually reduce our sensitivity to incoming information (Huppert, 2003). These changes begin in our early adult life and are normal processes of ageing. Sensory and perception changes that occur with age have a significant effect on how older users perceive and interact with technology. Reduced vision is a main concern on how older users perceive and interact with different interactive systems, particularly touchless interfaces, since most interaction methods rely heavily on visual feedback (Fisk et al., 2009).

Reduced sensitivity to sound, according to (Huppert, 2003), is also an effect of ageing on hearing. These changes can affect understanding of speech, detecting high-pitched sounds, and separating selected sounds from background noise. Regarding usability standards, sound feedback should be carefully addressed in order to be effectively to benefit older users.

Lastly, touch is also an important sense when it comes to HCI. Haptic feedback from physical contact with an input device is present in most interactive systems (e.g. mouse clicks, key presses, touchscreen gestures, videogame controllers) and it plays a fundamental role for the user experience. Tactile perception, together with kinaesthetic proprioception, inform the user where fingers are located (e.g. on a keyboard, mouse, or touchscreen), and whether an action was successful (e.g. button press or tap) (Vitense et al., 2003; Emery et al., 2003; Stößel, 2009). As we age, our skin become less sensitive to pressure and there is a reduced ability to recognise different shapes and textures by touch, and the ability to perceive vibrations also gets diminished after the age of 50 (Huppert, 2003). Besides tactile sensitivity, tactile spatial acuity is also decreased and can affect tasks requiring fine manipulation (e.g. finger dexterity). (Stößel, 2009) also argues that decreased touch and tactile perception need to be mindfully considered when designing texture or pressure points of interface elements as well as button arrangement and vibrotactile feedback. Furthermore, mid-air gesture interaction usually offers limited to no haptic feedback, apart from that provided by the body making contact with itself (e.g. fingers touching or hands together). Further work should address how the lack of haptic feedback in mid-air gesture interaction affects performance of older users and how alternative feedback modalities could be used to support and enhance older adults' skills.

3 Methods

A two-part mixed-method exploratory study was conducted in order to investigate how younger and older users perceive and interact with mid-air gesture input for computer interaction for the first time. The first part of the study focused on the guessability and intuitiveness of common hand-based gesture names for novice users, whilst the second part focused on assessing how users perform mid-air gestures during task-based interactions, specifically in carrying out 5 computer tasks. The questions this study aimed to answer include:

- *How appropriate are the most common, currently-in-commercial use, gesture commands for novice older adults?*

- *How do novice older adults perform and evaluate mid-air gestures when they are used in the context of typical computer interactions?*

- *How do younger and older users differ in performance and expectations when using mid-air gesture interaction?*

3.1 Selecting the gesture vocabulary

In the first part of the study, the aim was to expose participants to common, currently-existing mid-air gestures which they may reasonably encounter in a real-world, "*walk-up-and-use*" scenario. In order to identify the most common gestures currently used in commercial applications, we conducted an analysis of three mid-air gesture interaction platforms (*Microsoft Kinect*, *Leap Motion* and *Myo Armband*) and their commercially-available applications (Cabreira and Hwang, 2015).

Searches were conducted in April 2015 for free "*ready to play*" apps for each platform, resulting in 250 applications being included in the analysis: 184 for the Leap Motion, 58 for Microsoft Kinect, and 8 for Myo Armband (see Table I). The imbalance in the number of apps for each platform is due to variation in the availability of free apps across these platforms. The applications were distributed across five different categories: Games (129), Education (21), Music (21), Experimental (38) and Computer Navigation (41).

Each app was analysed to identify the mid-air gestures that it used. The data was gathered directly from the official app stores for each platform (versus off third-party review sites), and the analysis included trialling demos, reviewing videos, and reading textual description data provided by app developers.

15 mid-air gestures emerged as the most common and recurrent gestures across the three platforms. As shown in Table 1, "*Pointing*" (cursor based) is the overall most recurrent gesture and was present in 134 (53.6%) of all 250 applications. "*Wave*" (used in 86 apps) and "*Swipe*" (used in 51 apps) were also commonly used gestures across platforms, whilst "Clap" was the least common gesture across the three platforms (2.4%, 6 apps out of 250). The gesture names shown in Table 1 reflect the nomenclature commonly used by app developers.

Table 1 Number of apps Number of apps for each platform that uses each mid-air gesture. N.A. means not applicable.

	Leap Motion (184)	***Microsoft Kinect (58)***	***Myo Armband (8)***	***Overall (250)***
1. Pointing	*112*	*18*	*4*	*134 (53.6%)*
2. Wave	*66*	*15*	*5*	*86 (34.4%)*
3. Swipe	*30*	*21*	*N.A.*	*51 (20.4%)*
4. Air tap	*38*	*9*	*N.A.*	*47 (18.8%)*
5. Hand rotation	*32*	*6*	*5*	*43 (17.2%)*
6. Hold hand still	*22*	*14*	*N.A.*	*36 (14.4%)*
7. Finger rotation	*30*	*N.A.*	*N.A.*	*30 (12%)*
8. Fist	*22*	*N.A.*	*4*	*26 (10.4%)*
9. Grab	*24*	*N.A.*	*N.A.*	*24 (9.6%)*
10. Spread hands	*20*	*3*	*N.A.*	*23 (9.2%)*
11. Fingers spread	*20*	*N.A.*	*3*	*23 (9.2%)*
12. Finger pinch	*22*	*N.A.*	*N.A.*	*22 (8.8%)*
13. Spread arms	*10*	*11*	*N.A.*	*21 (8.4%)*
14. Double tap	*4*	*N.A.*	*4*	*8 (3.2%)*
15. Clap	*4*	*2*	*N.A.*	*6 (2.4%)*

3.2 Participants

21 younger adults (20-29 years old, M=22.14; 10 female) and 21 older adults (55-80 years old, M=69.76; 11 female) were recruited through the University of Reading's Ageing Research database and from the local community. Inclusion criteria included not having any prior experience with mid-air gesture interaction (e.g. never used a *Microsoft Kinect*, *Leap Motion sensor* or a *Myo Armband* before), not having any diagnosed cognitive impairments (e.g. dementia), and not presenting physical impairments that would give rise to difficulties in making upper limb movements. After being introduced to the protocol and providing written informed consent, participants completed a demographic questionnaire on, for instance, frequency of computer use and type of devices regularly used as shown in Table 2. All participants were offered a reimbursement of £5 for their time and travel costs. The study has been reviewed by the University of Reading's Research Ethics Committee and has been given a favourable ethical opinion for conduct.

Table 2 Participant demographics.

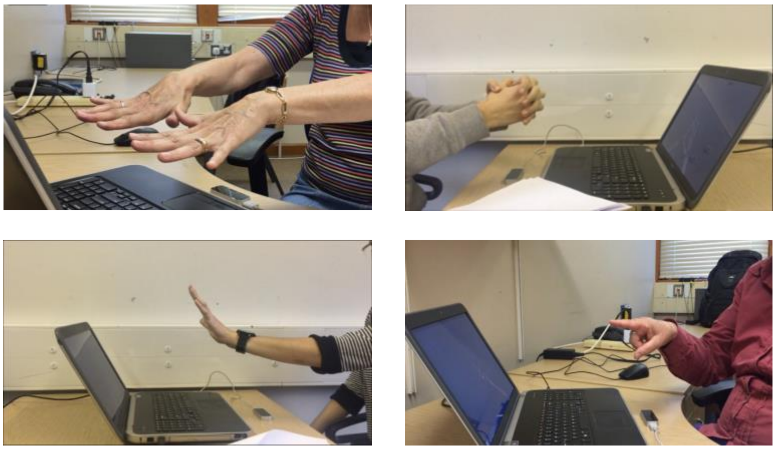
		Younger adults	***Older adults***
	N	*21*	*21*
Age	*M (SD)*	*22.14 (3.48)*	*69.76 (7.07)*
Gender	*# male*	*11*	*10*
	# female	*10*	*11*
Hand preference	*# right-handed*	*19*	*18*
	# left-handed	*02*	*03*
Eyesight	*# Normal*	*06*	*04*
	# Corrected-to-normal	*15*	*17*
Computer use*	*# Daily*	*21*	*21*
	# Other than daily	*00*	*00*
Type of devices regularly used	*# Desktop computer*	*10*	*11*
	# Laptop	*20*	*14*
	# Smartphone	*19*	*09*
	# Tablet	*10*	*10*
	# Smartwatch	*02*	*00*

**"Computer use" was described as use of desktop computer and/or laptop and/or mobile devices.*

3.3 Apparatus

Participants interacted, in a sitting position, with a Leap Motion sensor connected to a 17-inch Dell Inspiron 17R laptop with a 1600 x 900 screen resolution running Windows 8 64-bit. The sessions were conducted in a lab setting. The Leap Motion sensor was placed approximately 5 cm from the laptop's touchpad and 10 cm from the edge of the table (Figure 1). Both parts of the experiment were screen captured, and video recorded in order to capture hand and body movements, general behaviour, and verbal comments. Notes were also taken by the researcher throughout the sessions.

Figure 1 Study settings. Participants interacting with the Leap Motion sensor.



3.4 Procedure

3.4.1. Part 1: Guessability Study. Unlike previous elicitation studies (Wobbrock et al., 2009; Ruiz et al., 2011; Findlater et al., 2012) where participants were shown desired effects of an action and were then asked to propose gestures that would result in that action, our study uses pre-defined commonly used mid-air gesture *names* as referents and aims to elicit how differently participants without prior experience in making mid-air gestures would propose to make the named gestures. All 15 gestures identified in 3.1 were included in the guessability study (Cabreira and Hwang, 2015 and 2016).

Participants were first introduced to the Leap Motion sensor. To help acquaint the volunteers with the system and prime users to reflect about the capabilities of the sensing technology, the researcher asked the participants to interact with the sensor for a few minutes whilst the 3D model of the user's hands was being displayed on the screen (Figure 1).

Participants then were shown 15 boards one at a time, each displaying the name of a common mid-air gesture (Table 1). They were asked to perform each gesture in front of the screen. This was to enable us to assess a) the intuitiveness and appropriateness of current nomenclature for novice users and b) elicit how participants would propose gesture forms for each of the 15 mid-air gestures.

In other words, the symbolic referents used in our guessability study are the names of the mid-air gestures (versus the effects of their action (Wobbrock et al., 2009) and the proposals are then the gestures (i.e. the actual motion) made by the participants based on their understanding of these referents. Related to that, (Vatavu and Wobbrock, 2015) further explains "*say a practitioner wants to design a toolbar icon for an uncommon command in a spreadsheet program he calls "Shift." He asks 20 participants to draw an icon representing this command. The command itself is called a "referent" and the drawn icons are "proposals" for that referent".*

Participants were encouraged to attempt the task on their own, but they could ask for help if they felt they were unable to proceed. The researcher would then provide a hint, and if the query persisted, the researcher would give a demonstration. After proposing each mid-air gesture, participants were also asked to subjectively rate the easiness of guessing each gesture referent on a 5-item Likert item (i.e. how easy it was to make a certain gesture just by reading its name for the first time).

3.4.2. Part 2: Task-based Study. While the focus of the first part of this study was to investigate user preference and the appropriateness of different gesture nomenclature for novice users, the second part of the study focusses on the accuracy and efficiency of gesture execution by novice users. In order to assess intuitiveness and overall usability of mid-air gestures in a computer task-oriented context, participants were introduced to Leap Motion's *HandWave Software* (source: *https://gallery.leapmotion.com/handwave/*), a free application that uses mid-air gestures to perform computer tasks such as navigation (e.g. scrolling browser content, swapping windows) and media control (e.g. changing volume, controlling playback) when the computer is connected to a Leap Motion sensor. Participants were then asked to read the instructions on screen and complete 5 tasks using 5 different mid-air gestures (Table 3). Hand gestures used in this part of the study differed in terms of their involvement of gross versus fine motor skills, thereby enabling an assessment of participants' preferences for hand versus finger gestures.

Table 3 Computer tasks to be completed by the participant and corresponding gestures.

Task	***Gesture***
Select "start"	*Move your hand over the button then hold it steady to select it*
Scroll up and down	*Spread your fingers and tilt your palm up and down*
Turn the volume up and down	*Rotate your index finger using a clockwise / counter-clockwise gesture*
Stop / Play music	*Make a fist with your hand to stop the music, turn the music back on by making a fist again*
Select next and previous song	*Put your hand in the cube and swipe to the right or left*

Participants were encouraged to attempt the 5 computer tasks on their own, but they could ask for help if they felt they were unable to proceed. After completing the 5 tasks, participants were asked to complete System Usability Scale (SUS) (Brooke, 1996) and Technology Acceptance Model 3 (TAM-3) (Venkatesh and Bala, 2008) questionnaires regarding their first experience using mid-air gesture interaction. Both questionnaires received minimal wording alterations in order to become more specific about mid-air gestures. For instance, participants were asked to rate, on 5-point Likert items, the easiness of each task-gesture, confidence whilst using the system, indicating the presence of fatigue during their interaction and intention to use mid-air gestures for computer tasks in the future. Verbal responses, comments and annotations were also transcribed by the researcher for later analysis.

3.5 Analysis

3.5.1. Part 1: Guessability Study. After analysing all participants' videos, one researcher independently created categories for the proposed gesture forms based on motion distinctions proposed by (Grandhi et al., 2011), which are 1) number of hands used, 2) number of fingers used, and 3) dynamic vs static poses. Then, another two researchers independently distributed participants' proposed gestures into the defined categories, for all participants and all referents. The categorisation was done based on the first complete gesture form made by each participant for each of the 15 referents. It was up to the independent annotators to define what was the first gesture form made by each participant as some participants attempted multiple gesture forms for a referent, but we aimed to consider the first form that would come to their minds. Where the independent annotators disagreed about which category a particular gesture proposal belonged to, this was discussed in a group analysis involving two additional researchers until a consensus was reached. Following a group consensus, Vatavu and Wobbrock's equation for formalisation of agreement in guessability studies (Vatavu and Wobbrock, 2015) was applied to our data. Agreement scores were generated to identify and sort which of the referents received more homogeneous proposals amongst participants as an indication of intuitiveness of these gestures for novice users. Vatavu and Wobbrock's equation for calculating agreement scores in guessability studies (2015) extends Wobbrock's earlier equation (Wobbrock et al., 2005 & 2009) by adding two correcting factors depending on the number of participants and number of elicited proposals. The revised equation used in our analysis is presented below (Equation 1), where AR means Agreement Rate, and r is the referent in the set of referents R, P is the set of proposals for the referent r, and P_i is a subset of identical symbols from P. If all the proposed mid-air gestures are identical the agreement score is 1.00 (100%), whilst solely unique proposals produce a 0.00 (≈0%) agreement score (Vatavu and Wobbrock, 2015).

Equation 1 Formalisation of agreement in guessability studies as appears in (Vatavu and Wobbrock, 2015).

$$AR(r) = \frac{|P|}{|P|-1} \sum_{Pi \subseteq P} \left(\frac{|Pi|}{|P|}\right)2 - \frac{1}{|P|-1}$$

Mann-Whitney U Tests were then conducted to compare the results of the agreement scores and the subjective ratings of the two age groups for the 15 mid-air gestures. A Pearson's Correlation analysis was also conducted in order to investigate a possible correlation between the participants' responses on perceived easiness of a particular mid-air gesture (5-point Likert items scale) and their ability to be commonly guessable by many participants (overall agreement scores).

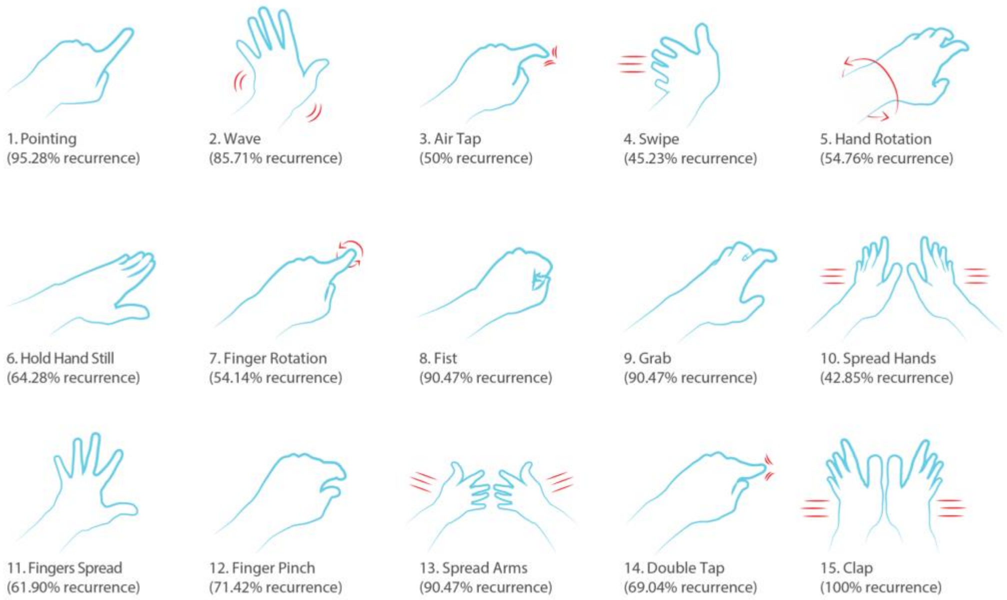
3.5.2. Part 2: Task-based Study. Completion times and number of gesture attempts were extracted through video analysis and Leap Motion's data. A Linear Mixed Model (LMM) analysis was conducted in order to investigate the effect of age group (younger, older) on task completion time for each of the 5 tasks (i.e. how many seconds needed to complete a specific task), the number of attempts to complete each of the 5 tasks (i.e. how many times the participant had to gesture in order to complete a specific task), and differences in reported difficulty between tasks. A Mann-Whitney U Test was also conducted to compare the two age groups in terms of their responses on the subjective questionnaires. Verbal responses and comments captured on video data, participants' written questionnaire responses and annotations made by the researchers were coded using the Thematic Analysis method for identifying, analysing and reporting patterns within qualitative data (Braun and Clarke, 2006).

4 Results – Part 1 (Guessability Study)

630 mid-air gestures (15 referents x 42 participants) were elicited and analysed in this part of the study. Simple hints were given to 2 younger participants for the "Air tap" referent. No demonstrations were needed.

Of all 15 referents, "Clap" was the only one eliciting a single gesture form by all participants (Figure 2). The most recurrent gesture forms elicited for each of the mid-air gesture referents used in our guessability study are illustrated in Figure 2:

Figure 2 Graphic representation of the most recurrent gesture forms elicited by 42 participants for each of the 15 mid-air gesture referents.



1. Pointing (95.28% recurrence)
2. Wave (85.71% recurrence)
3. Air Tap (50% recurrence)
4. Swipe (45.23% recurrence)
5. Hand Rotation (54.76% recurrence)
6. Hold Hand Still (64.28% recurrence)
7. Finger Rotation (54.14% recurrence)
8. Fist (90.47% recurrence)
9. Grab (90.47% recurrence)
10. Spread Hands (42.85% recurrence)
11. Fingers Spread (61.90% recurrence)
12. Finger Pinch (71.42% recurrence)
13. Spread Arms (90.47% recurrence)
14. Double Tap (69.04% recurrence)
15. Clap (100% recurrence)

4.1 Agreement Scores

Table 4 shows that referent mid-air gestures with the highest agreement scores amongst participants were “Clap”, “Pointing”, “Grab”, “Fist”, “Spread Arms”, “Wave” and “Finger Pinch”, with all the above gestures achieving more than 50% agreement amongst 42 participants. All other mid-air gestures had a score under 0.50 (less than 50% of agreement), which indicates significant variability amongst participants. A *post hoc* analysis did not reveal significant differences between the two age groups for their agreement scores ($p > 0.05$).

Table 4 Guessability Study Results: Mid-Air Gesture Agreement Scores.

Mid-Air Gesture Referent	***Younger Adults***		***Older Adults***		***Overall Agreement Score****
	Number of gesture forms	Group Agreement Score*	Number of gesture forms	Group Agreement Score*	
Clap	1	1.00	1	1.00	1.00
Pointing	2	0.90	2	0.90	0.90
Grab	2	0.90	3	0.72	0.81
Fist	3	0.81	3	0.81	0.81
Spread Arms	2	0.81	3	0.81	0.81
Wave	3	0.81	4	0.65	0.72
Finger Pinch	6	0.46	3	0.60	0.52
Hold Hand Still	5	0.36	4	0.65	0.46
Fingers Spread	4	0.43	3	0.50	0.45
Double Tap	4	0.64	7	0.35	0.40
Finger Rotation	4	0.31	4	0.52	0.38
Hand Rotation	5	0.41	4	0.36	0.37
Spread Hands	3	0.35	4	0.40	0.34
Swipe	5	0.42	5	0.47	0.33
Air Tap	6	0.35	8	0.28	0.32

** Agreement should be 1.00 (100%) when proposed symbols are identical, and 0.00 (≈0%) when they are unique (Wobbrock et al., 2005; Vatavu and Wobbrock, 2015).*

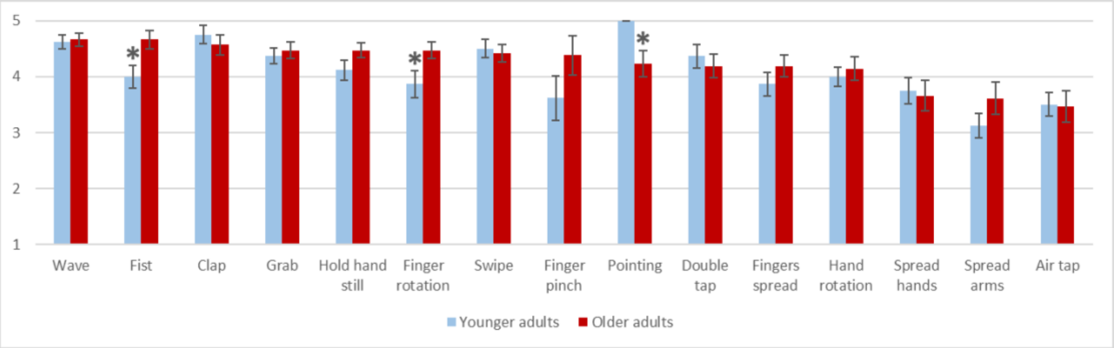
4.2 Perceived Easiness

Participants rated each of the 15 mid-air gestures in terms of their perceived easiness of gesture making. Although the majority of the gestures were rated similarly by both age groups, a main significant effect of age on perceived easiness was found for three mid-air gesture referents, as shown in Figure 2. The “Pointing” referent was rated “Very Easy” by all 21 younger participants and therefore perceived easier to perform than by older adults (U=72.95, Games-Howell post-hoc test adjusted p = 0.01).

The referents “Fist” and “Finger Rotation” were perceived easier to perform by older adults [(U=2.85, Games-Howell post-hoc test adjusted p = 0.05) and (U=4.25, Games-Howell post-hoc test adjusted p = 0.05) respectively].

Pairwise comparisons revealed that gesture referents “Wave”, “Clap”, “Grab” and “Swipe” were perceived as the easiest to make, whilst “Air tap”, “Spread arms”, and “Spread hands” were perceived to be significantly more difficult than the others (Games-Howell post-hoc test adjusted p = 0.01).

Figure 3 Group means of perceived easiness ratings for each mid-air gesture in part 1 of the study (5=Very easy, 1=Very difficult).



* Indicates a significant difference between age groups.

4.3 Guessability *vs* Perceived Easiness

Results showed that there was no strong correlation (Pearson's Correlation Coefficient r = 0.40) between the participants' responses on perceived easiness of a particular mid-air gesture (5-point Likert items) and their ability to be commonly guessable by many participants (overall agreement scores). However, gestures such as "Clap", "Pointing", "Grab", "Fist", and "Wave", presented a high guessability agreement score and were ranked well by participants of both age groups.

5 Results – Part 2 (Task-Based Study)

Following the guessability study in part 1, a task-based user study was conducted in order to explore the usability of mid-air gesture input for computer interaction. Participants in both age groups were asked to read instructions presented on the screen and complete 5 computer tasks by making 5 mid-air hand gestures.

5.1 Task completion times

Although the experiment focused on the discoverability of mid-air gesture interaction by novice users rather than performance efficiency, the time needed to complete each task was taken into consideration as a matter of assessing intuitiveness of different mid-air gestures when applied to a task-oriented context. Completion time results are shown in Table 5.

Table 5 Group means of completion time and (SD) in seconds for each task.

Task	***Mid-air gesture***	***Younger Adults***	***Older Adults***	***F value***	***p value***
Select start	*Point and hold*	5.81 s (3.41)	13.48 s (10.86)	20.82	0.004 *
Scroll up & down	*Tilt palm up & down*	7.62 s (12.56)	25.71 s (34.88)	9.78	0.005 *
Turn volume up & down	*Index finger rotation clockwise and counter-clockwise*	16.33 s (29.22)	38.71 s (40.05)	6.90	0.012 *
Stop music and play again	*Make a fist*	7.24 s (8.53)	6.19 s (4.56)	13.54	0.09
Browse items	*Swipe left & right*	18.33 s (32.13)	39.05 s (32.71)	2.00	0.04 *

** Indicates significant differences between age groups*

As expected, our results showed that older adults were in general slower than younger adults at completing computer tasks using mid-air gestures, completing those tasks on average in 24.63 seconds versus 11.06 seconds for the younger participants. A mixed-model analysis also showed a significant main effect of age on completion time for 4 out of the 5 tasks. Older adults spent more time at *selecting start* by pointing [F(5,42)=20.82, p = 0.004]; *scrolling* by tilting the palm up and down [F(5,42)=9.78, p = 0.005]; *turning volume up and down* by rotating the index finger [F(5,42)=6.90, p = 0.012]; and at *selecting songs* by swiping left and right in-air [F(5,42=2.00, p = 0.04]. No significant main effect of age was found for *stop playing music* by making a fist gesture.

5.2 Number of attempts per task

The number of gesture attempts participants had to perform to complete a task was counted in order to assess intuitiveness and easiness of each gesture (Table 6). Every gesture attempt was counted, even if it was a repeat of a previously attempted gesture form. Even though there was a large variation across participants, significant effects of age were found for the number of attempts necessary to complete task 1 (select start by pointing) [F=45.63, p = 0.001] and task 2 (scrolling by tilting palm up & down) [F=14.32, p = 0.05]. No significant effects of age were found for tasks 3-5 (p > 0.05).

Table 6 Mean number of attempts and (SD) per task for each age group.

Task	***Mid-air gesture***	***Younger Adults***	***Older Adults***	***F value***	***p value***
1. Select start	*Pointing and hold*	1.05 (0.22)	2.19 (1.44)	45.63	0.001 *
2. Scroll up & down	*Tilt palm up & down*	1.71 (2.00)	4.29 (5.82)	14.32	0.05 *
3. Turn volume up & down	*Index finger rotation clockwise and counter-clockwise*	2.95 (3.31)	4.29 (3.54)	20.55	0.2
4. Stop music	*Make a fist*	2.24 (2.07)	1.86 (1.74)	22.32	0.06
5. Browse items	*Swipe left & right*	6.48 (9.58)	8.29 (6.09)	15.78	0.8

** Indicates significant differences between age groups*

5.3 Help needed per task

Participants were encouraged to figure out how to make gestures and complete each task on their own with the instructions provided on the screen. If they were not able to proceed after multiple attempts (see Table 6 for reference) and verbally asked for help, the researcher would intervene by providing a hint on how to make the specific gesture. Task 5 - browsing through different songs by swiping the hand left and right - was the task in which most participants of both age groups asked for help (Table 7). However, no significant effects of age were found for this matter in a *post hoc* analysis (p > 0.05).

Table 7 Number of participants per group who needed help for each task.

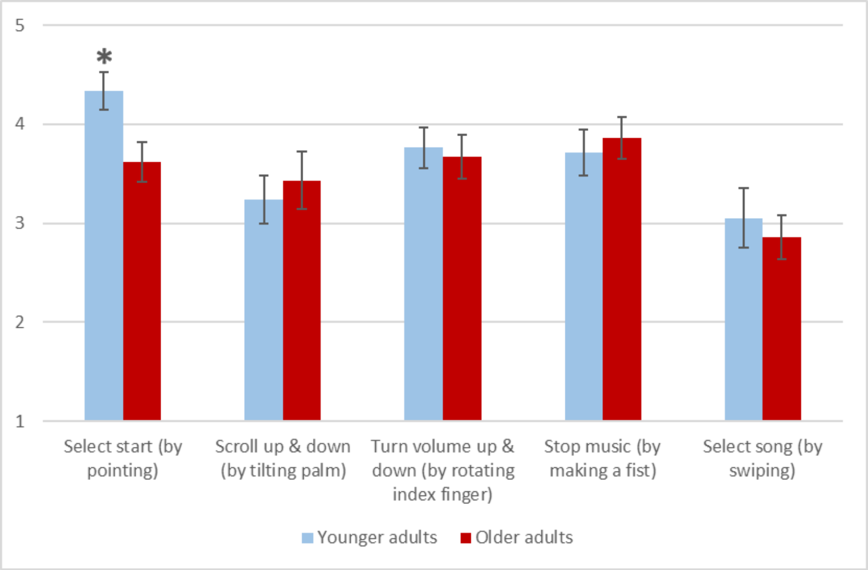
Task	*Mid-air gesture*	*Younger Adults*	*Older Adults*
Select start	*Pointing and hold*	0	2
Scroll up & down	*Tilt palm up & down*	2	6
Turn volume up & down	*Index finger rotation clockwise and counter-clockwise*	2	6
Stop music	*Make a fist*	2	1
Browse items	*Swipe left & right*	4	7

5.4 User Experience and Subjective Evaluation

5.4.1. Perceived easiness of each task. In accordance with the results of part 1 of the study (see section 4.2), a main significant effect of age and task on perceived easiness were found using a Mann-Whitney U Test (U = 123.00, p = 0.02). Younger adults found pointing to "select start" easier than older adults did in task 1 (Games-Howell post-hoc test adjusted p = 0.01). Selecting songs in a carousel-styled menu by swiping hand left and right in task 5 was perceived to be more difficult to perform than the other tasks included in this study by both age groups (U=13.45; Games-Howell post-hoc test adjusted p = 0.04) [Figure 4].

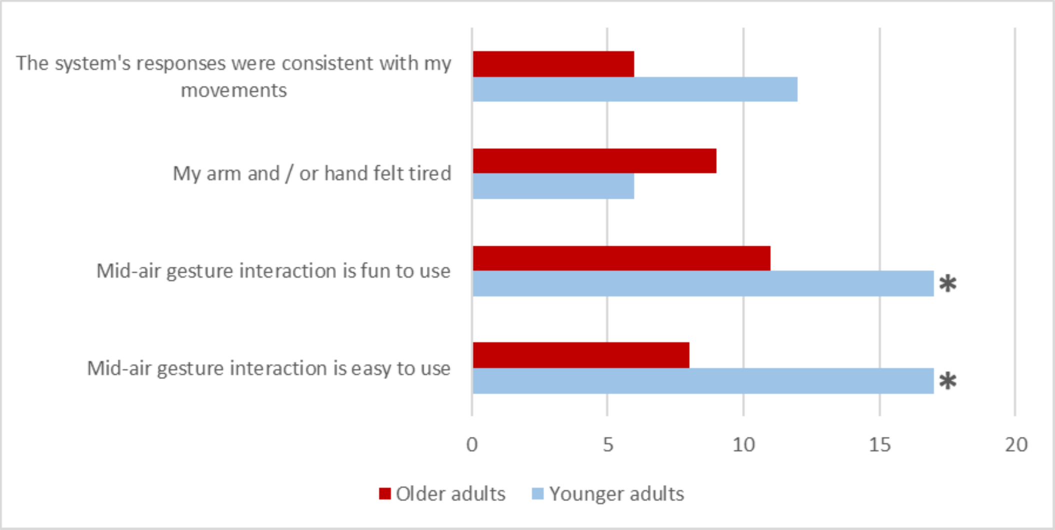
5.4.2. Experience ratings. A main effect of age on subjective rating was found using a Mann-Whitney U Test (U=128.50, p = 0.01). Gesturing in mid-air was found to be significantly "*easier to use*" (Games-Howell post-hoc test adjusted p = 0.02) and more "*fun*" (Games-Howell post-hoc test adjusted p = 0.01) to younger adults than to older adults as shown in Figure 5.

Figure 4 Group means of perceived easiness ratings for each task in part 2 of the study (5=Very easy, 1=Very difficult).



** Indicates a significant difference between age groups.*

Figure 5 Number of participants responding either “Strongly agree” or “Agree”.



** Indicates a significant difference between age groups.*

5.4.3. Positive aspects of mid-air gesture interaction. “Fun”, *“different”* and *“easy to use”* were recurrent terms chosen by younger adults to describe positive aspects of mid-air gestures in the questionnaire responses. The ability to explore the spatial and motion freedom was also welcomed by the younger group. A 22-year-old female participant found mid-air gesture interaction to be *"intuitive, easy to learn and feels natural to use when it responds accurately"*. Similarly, a 28-year-old female participant expressed that *"it's fun as long as it's used for less complex tasks"*. The fist gesture – used for stopping and start playing music again in task 4 - was deemed to be *"quicker"*, *"easier"* and *"more convenient"* than other mid-air gestures for three participants in the older group. In addition, for another three older participants (60, 71 and 73-year-old respectively), the possibility of using gestures in order to use the mouse less frequently whilst using the computer was also welcomed. *"These gestures could be used by people who have problems using a mouse"*, said a 60-year-old female participant.

5.4.4. Negative aspects of mid-air gesture interaction. The perceived inconsistency in the computer's ability to recognise some gestures was a common complaint amongst younger adults' responses. Additionally, a 55-year-old participant who particularly had great difficulties with browsing items through swiping and scrolling by tilting his palm up-and-down felt that *"there was nothing good about gestures, I didn't really find it a positive experience"*, whilst a 75-year-old female participant said she would prefer not to use gestures that involve multiple fingers (e.g. fingers spread, finger pinch). A 61-year-old male participant expressed that *"it was interesting to find different ways of doing things in the computer but I'm too used to holding a mouse and it would take time to readjust and learn new gestures"*. In addition, arm and shoulder fatigue and difficulty in keeping the correct distance from the sensor were also noted by many older adults, including *"an eventual physical strain on arm"* pointed out by a 73-year-old female participant and the time and physical effort taken *"to get used to positioning"* mentioned by a 57-year-old female and an 80-year-old male participant.

5.5 Observational findings

This section describes additional findings observed by the primary researcher throughout the study alongside inferential and qualitative data gathered through video analysis, note-taking and participants' responses. Some of recurrent issues faced by participants are listed below.

5.5.1. Presence of upper limb fatigue. Despite the absence of significant effects of age on self-report for fatigue, tiredness of upper limbs was a recurrent commentary amongst participants. 9 out of 21 older participants (42% of this group) felt their active hand and / or arm becoming tired in a determined moment during the experiment, in contrast with 6 out of 21 younger participants according to our questionnaire responses (as shown in Figure 5). These results reinforce the understanding that fatigue is an issue that needs to be considered when designing mid-air gesture interactions. A 60-year-old female participant said that mid-air gestures are *"quite tiring after only 10 minutes or so"* and a 64-year-old male participant said that he would prefer quicker interactions because mid-air gestures *"might be too tiring for longer use"*. Soft arm aches and physical strains were noted by 71 and 73-year-old female participants respectively. A 76-year-old female participant also suggested that the *"arm position needs to be at a comfortable height"* and proposed a *"padded surface"* to rest her arm whilst interacting through mid-air gestures. Meanwhile, a 20-year-old male participant suggested that mid-air gesture interaction *"might become tiring after extended periods of time, especially if my elbows are not supported on the desk"* and, in spite of his positive attitude towards mid-air gestures, a 22 year-old male participant said that *"my hand became slightly tired during the experiment, I imagine my hand would ache if this replaced a keyboard or mouse"*. Although upper limb fatigue seems to play a fundamental role over longer and more complex physical interactions, participants agreed that short and simple gesture interactions have not led to fatigue complaints.

5.5.2. Understanding the sensor's field of view and range of motion. According to our observations in part 1 and 2, a recurrent fundamental challenge for older adults was knowing where to place their hands in-air so that their gestures can be read by the sensing device. Unlike physical input methods such as touch surfaces, mouse and keyboard where users direct their input explicitly by touching, clicking or pressing a key, mid-air gesture interaction provides a less clear idea "where" to gesture which can lead the user to interact in a place where their hand movements cannot be detected by sensors. Despite the Leap Motion's 150º field of view with roughly 8 cubic feet of interactive 3D space, many older participants, in the beginning and throughout the experiment, had difficulties placing their hands within the view of the sensor. Some actions included placing their hands too close to the sensor (therefore occluding the infrared camera) or leaning forward and moving their hands too close to the screen (therefore making the sensor unable to detect their hand, only their wrist and upper arm). The oldest participant in this study (80-year-old, male) particularly found the range of the sensor *"too short"* and noted that *"it becomes easier once you know where to place your hand"*. Two older participants (69-year-old, male; 60-year-old, female) also shared thoughts about the difficulty in getting used to the sensor's field of view and the allowed range of motion. A 66-year-old male participant suggested that *"ideally, screen feedback would indicate if I was outside the Leap Motion's field of view. An icon could be made clear when in ideal position, and* *fuzzy when not”*. In contrast, only a few younger participants expressed difficulties with understanding the sensor’s field of view, however a 25-year-old male participant stated that interacting mid-air is *“sometimes a bit confusing because you’re not sure if the sensor is reading your movements”* whilst a 21-year-old female participant described the *“unclear range of motion”* as a negative aspect of sensor-based interaction.

5.5.3. Learnability – Matching system expectations. Our observations found that some gesture nomenclature (e.g. air tap; double tap; spread hands, fingers spread), icons and commands (e.g. tilt your palm up-and-down) can be rather misleading and vague, leading the participants to failed attempts. Older participants were more persistent in repeating a specific gesture form multiple times and seemed to feel more frustrated by failed attempts than the younger participants. Despite all participants being the same in terms of not having experience with interacting through mid-air gestures, younger and older participants presented different expectations. Younger participants were promptly willing to explore possible alternatives to the gestures, trying different forms until they succeeded in their action. In contrast, older participants would try what they believed was the correct gesture and persist in their choice, expecting the system to recognise it correctly and therefore were sometimes astonished when they were not able to complete their action. Concerning the mismatch between the system and the users’ expectations, a 68-year-old female participant stated that *“this system can be frustrating if the gesture is misleading because when I do it in a wrong way I don’t know how to make the gesture right afterwards”* whilst a 71-year-old female participant *“found that some of the gestures didn’t seem to relate to what I was trying to do with my hands and the need of repeating it multiple times until I get it right is rather frustrating”*.

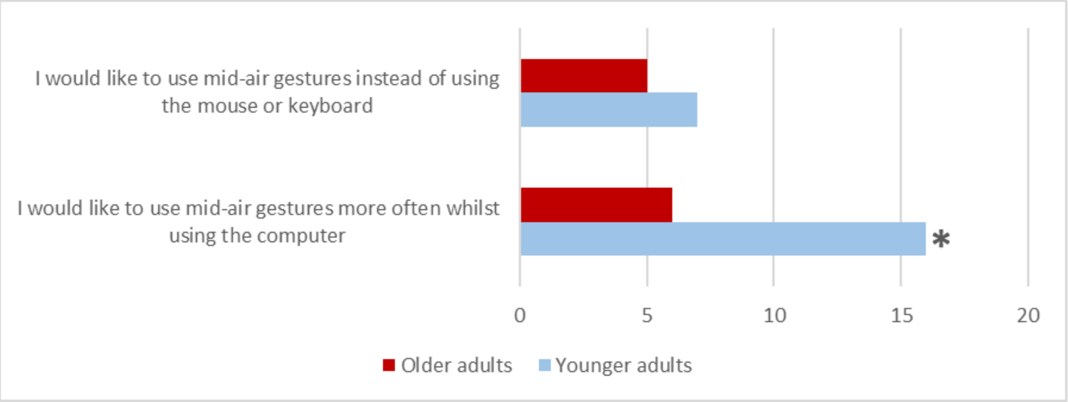
5.5.4. Gesture recognition accuracy and consistency. As participants were able to see a virtual representation of their hands during part 1 and 2 of this study, they were able to follow the sensor's tracking and recognition in real-time whilst interacting with Leap Motion, which claims to have up to 1/100th millimetres accuracy with no perceptible latency in detecting up to 10 fingers at the same time. However, regardless of its robustness, a common criticism amongst participants was the lack of perceived accuracy, especially in recognising gestures involving multiple fingers (e.g. finger pinch, fingers spread). *"Sometimes gestures weren't recognised as easily"*, *"very inconsistent in recognising gestures"* and *"sometimes not precise enough, technology can improve"* were recurrent commentaries amongst younger participants. Similarly, a 72-year-old female participant found that *"it's not accurate enough. I had to gesture 2 or 3 times to complete the action, uncomfortable using this!"* and, regarding inaccurate tracking, another 67-year-old female participant pointed out that *"it's frustrating when having to repeat gesture to achieve result"*.

5.6 Technology Acceptance and Intent-to-Use

In order to investigate the acceptance of mid-air gesture interaction after participants' first exposure, their attitude towards this input method and their intent for future use, we employed a modified-TAM3 questionnaire with 5-point Likert items alongside with open questions on the perceived usefulness of mid-air gestures, and possible contexts of use. As Figure 6 shows, a Mann-Whitney U Test comparing the responses of the two age groups regarding their intent to use mid-air gesture interaction as an input method revealed a significant main effect of age ($U = 92.00$, $p = 0.001$), with 16 out of 21 younger participants (76% of this group) answering that they would like to use mid-air gestures more often whilst using the computer, whereas only 6 of the 21 older participants (28%

of this group) agreed with this statement. On the other hand, only few participants agreed when asked if they would like to replace the mouse and keyboard with mid-air gesture interactions, and there was no significant difference between the age groups.

Figure 6 Number of participants responding either “Strongly agree” or “Agree”.



** Indicates a significant difference between age groups (p = 0.001).*

5.6.1. Perceived usefulness for computer interaction. Additional computer-based applications of mid-air gesture interactions were suggested by participants ßin addition to the five computer tasks they had to complete in part 2 of this study. For instance, amongst younger adults, recurrent responses included the use of mid-air gestures for video gaming (6 responses), doing presentations (3 responses), and swapping between screens, windows & tabs (5 responses). Unlike younger participants, older adults were less assertive about possible uses of mid-air gestures, and 11 out the 21 older participants were not able to think of any applications. A 60 years-old female participant wondered if mid-air gesture interaction could be useful as an alternative to using a mouse (e.g. to point at a button rather than drag a cursor and click it), and a 66 years-old male participant said he would like to use mid-air gestures for paging through documents the same way he does with physical documents, whilst a 75 years-old female participant answered that *"being new to this* (gesturing in-air*), I am somewhat prejudiced to the adoption of this technology as being unnecessary".*

5.6.2. Perceived usefulness outside the scope of computer interaction. Participants had different views when asked where they would like to use mid-air gestures in addition to computer interaction. Younger adults had much more diverse visions for applying mid-air gestures in their daily routines, including turning lights on and off without needing to leave the bed (4 responses), watching TV without needing a remote control (6 responses) and controlling house appliances (2 responses). A 26 years-old female participant who worked in a biology lab said that using mid-air gestures to operate her machines (including her computer) would be *"extremely"* useful to maintain asepsis of her hands without compromising the safety of the biological samples she has to work with. On the other hand, older adults presented more difficulty in proposing use scenarios for mid-air gestures in their daily lives; responses were limited to "operating TV" (3 responses) and "opening doors" (2 responses).

6 Discussion

6.1 Part 1 – Guessability of mid-air gestures

As (Wobbrock et al., 2005) define guessability in symbolic input as *"the quality of symbols which allows a user to access intended referents via those symbols despite the lack of knowledge of those symbols"*, our experiment used the names of common mid-air gestures - identified in a preliminary analysis - as symbolic referents in order to elicit how novice users in both age groups would propose gestures that are likely to be encountered in the real world. As shown in Table 4, the referents with the highest agreement scores amongst participants were *"Clap"*, *"Pointing"*, *"Grab"*, *"Fist"*, *"Spread Arms"*, and *"Wave"*, all ranging from 100% to 72% agreement amongst the 42 participants, respectively. This means little to no variability amongst participants and indicates that most or all participants followed the same conceptual model when proposing these gestures. On the other hand, mid-air gestures such as *"Finger Spread"*, *"Double Tap"*, *"Spread Hands"* and *"Air Tap"* had low agreement scores in our study and elicited a variety of proposed gesture forms across participants. This suggests that participants had different concepts of what the referents meant, resulting in different gesture proposals. Regarding conceptual models, (Norman and Wadia, 2013) state that conceptual models are not needed during usual operations but they become essential in two key HCI situations: for learning (how to use a new interface) and when things go wrong. People figure out how things work and how to proceed with their actions by forming mental models of their *"principles of operation"*, even if these models prove to be vague or turn out to be wrong in the end. In a hypothetical situation, where a gesture-based interface has been developed to recognise and expect a particular gesture form for a given gesture name, the gesture names with low agreement scores would prove more challenging for novice users to produce "correctly" at first. Users may interact with different interfaces quite skillfully without any underlying understanding of how they work, but when they face a novel situation (e.g. making mid-air gestures for the first time) the only way they can figure out what do is through a conceptual model of how it works (Norman and Wadia, 2013). Therefore, solid conceptual models lead to an intuitive interaction especially when the user interacts with a novel interface.

Accordingly, (Blackler et al., 2003) define intuitive interaction as a *"fast and generally non-conscious way of using a product or system, where people may not be able to explain* *how they made decisions, thus utilising knowledge gained through past experiences"*. This prior knowledge is passed on through *"image schemas"*, which are, according to (Johnson, 1987), *"abstract representations of recurring dynamic patterns of bodily interactions that structure the way we understand the world"*. They are based on each person's trajectory of interaction with the physical world, but tend to be fairly universal as the physical world operates in the same way for most people (Johnson, 1987). (Blackler and Popovic, 2015) suggest that because image schemas are based on prior experiences and sensorimotor skills, and because they are so well known and "universal" that they become unconscious, they can be defined as intuitive. (Hurtienne, 2009) argued that incorporating image schemas into interfaces can allow intuitive interaction, therefore resulting in better performance. Furthermore, performance using interfaces based upon image schemas (i.e. real-world interactions) should remain consistent across heterogeneous user groups, making them more ubiquitously applicable than *"familiar interaction paradigms"*, which may not be familiar to everyone and generally rely on experience with other products, leading to a legacy biased interaction.

Concerning legacy biased interaction, (Morris et al., 2014) define legacy bias as the tendency of users' gesture proposals and conceptual models to be frequently biased by their experience with prior interfaces and technologies, particularly the ones vastly popularised such as the standard WIMP interactions present in PCs and mobile devices. In elicitation studies where the aim is for participants to be innovative in proposing entirely new gestures, legacy bias *"may cause gesture elicitation methods to get caught in local minima, failing to uncover interactions that may be better suited for a given medium than those that leap readily to users' minds"* (Morris et al., 2014). When transitioning towards new forms of interaction, however, (Köpsel and Bubalo, 2015) argue that using the legacy bias *"smoothens rather than hinders the transition towards new forms of interaction"*. In our study, we did observe evidence of legacy bias. For instance, participants often proposed mid-air gestures based on their experience with touchscreen gestures commonly used on their mobile phones and tablets, simulating the same gesture but in-air as if they were touching an *"invisible surface"*. Thus, gestures such as *"Swipe"*, *"Air Tap"* and *"Double Tap"* were proposed by some participants using the index finger (as opposed to using the entire hand) with the common justification of *"that's how I would do on my phone!"*. At the same time, though, these gesture names elicited a low agreement score, indicating that not all participants were drawing on the same experiences. This suggests that mid-air gestures based on image schemas, that is, freehand gestures based on real-world interactions (e.g. Clap, Grab, Fist, Wave), should be given preference over mid-air gestures simply based upon touchscreen interaction paradigms (e.g. Swipe, Tap) in order to achieve a higher level of intuitiveness amongst participants with different technology expertise, especially older users.

6.2 Part 2 – Performance and acceptance of mid-air gestures in a task-based context

Older adults were slower than younger adults at completing computer tasks using mid-air gestures, for 4 out of 5 tasks, and this was not unexpected, given the data from other HCI studies with older adults (Walker et al., 1997; Ziefle and Bay, 2005; Ziefle et al., 2007; Moffatt and McGrenere, 2009; Stößel, 2009; Hwang et al., 2013; Findlater et al., 2013). Surprisingly, the fist gesture used for task 4 - *stopping the music* by making a fist – lead to a heterogenous performance across our participants and was highly accepted amongst the older group in parts 1 and 2 of the study.

On the other hand, tilting palm up-and-down for *scrolling* in task 2 (i.e. wrist flexion and extension) proved to be a great challenge for older adults and was widely rejected by both age groups. These results contradict the findings from Rahman's study with younger adults on the dexterity of wrist-based input for target selection using a hand-held device (Rahman et al., 2009) which suggested that users can control comfortably at least 16 levels on the pronation/supination axis and that using a tilt-based input method could improve user performance across all tilt axes. This reinforces the need of including older participants in HCI studies in order to also address their motor capabilities.

Furthermore, "swiping" left and right – used to *select items* in task 5, which was found to be the third most recurrent mid-air gesture across the commercial applications reviewed by (Cabreira and Hwang, 2015) and was perceived fairly easy by participants in our guessability study - scored badly in both performance and perceived easiness in comparison with other gestures when applied to a task-based context. Older adults seemed to have greater difficulties in generating a smooth and precise spatial trajectory (i.e. moving hand left to right in-air) in comparison with younger adults. A lack of clarity about where to start and stop the motion relative to the sensor and the screen, and how fast to move when performing a freehand swipe gesture was also a common complaint by older participants, with some participants inconsistently performing fast and abrupt motions whilst others would do it slowly with many pauses in hope of better chances for the motion to be detected by the sensor.

Moreover, the point-and-hold based input used in task 1, although dexterously performed and highly preferred by younger participants, was not performed as precisely by the older participants, who struggled at maintaining their hand steadily in-air at times for selecting the “start” target, resulting in accidental slip-offs and added attempts until successful target selection. These results are in accordance with the ones found by (Ketcham et al., 2002), who also argue that both the inability to scale velocity and control movement amplitude contribute to slower, more variable movements observed in older adults within target acquisition tasks.

Finally, our results add to the findings of (Stößel, 2009) and (Findlater et al., 2013) on the performance of older users in touchscreen gesture interaction and strengthen the common understanding that, generally, older adults exhibit poorer performance when using input techniques that heavily rely on precise motor control and additional work should be done on this matter. This issue can be also accentuated as a result of a mismatch between the expectations of both older users and the system.

Related to the intent-of-use and acceptance ratings of mid-air gestures for computer interaction by older adults, only 6 out of 21 older participants answered that they would, in the future, like to use mid-air gestures for interacting with a computer and therefore our findings contrast with the high acceptance ratings of freehand gestures for television control found by (Bobeth et al., 2012). This contrast raises the question if mid-air gesture interaction is more suitable for leisure contexts (e.g. video gaming, watching televison) in comparison with “serious” tasks (e.g. computer tasks) where the fun and immersive factor is limited and a focus on precision and directness is generally needed. However, it remains unclear if older adults would present a more positive attitude towards mid-air gesture input for computer interaction in favour of traditional input methods if some key challenges described in the current work could be overcome and therefore future work should investigate this further.

7 Design Implications

The findings of this exploratory study highlight differences between novice older and younger adults in terms of user preferences and performance of mid-air gesture interaction, and hence the design of mid-air gestures for a computer interaction context should take explicit consideration of the older population. We propose recommendations for designing age-friendly mid-air gesture-based interfaces for computer interaction that better accommodate the performance and expectations of older users. The recommendations are presented under the following headings: (1) *Designing Suitable Gesture Sets*, (2) *Physical Interactions and Ergonomics*, and (3) *User Interface Design*. Although these design recommendations may also benefit a greater population, we aimed particularly to expand on the understanding of the challenges of designing mid-air gesture interaction for older adults (Pullin and Newell, 2007).

7.1 Designing Suitable Gesture Sets

7.1.1. Provide cues about spatial freedom – Gesture kinematics. Mid-air gestures that provide spatial freedom are deemed to enhance the exploratory aspects of the interface and affect the user experience positively as a form of embodied interaction (Dourish, 2004; Grandhi et al., 2011). However, when some users make mid-air gestures such as pointing, swiping, air tapping and waving, that require specific kinematics, the actual system response may differ from their expectations due to a mismatch between the kinematics of the gesture made and those expected by the system. This problem is a result of novice users being unable to exactly execute the postures and gestures as the systems expects, due to vaguely-defined spatial and temporal trajectories (i.e. where does the gesture start and where does it finish? How quickly should the gesture be made?). Older adults face accentuated challenges on this matter as a consequence of age-related declines in motor control and range of motion, leading to imprecise and unsteady gesture making as observed in our study. The system should not assume that all users would make the gestures with the same kinematics, nor that they would easily learn what kinematics are required. Therefore, this challenge could be diminished by providing clear indications on how – and where – to perform the gesture, including cues for right direction, speed and range of motion. Another possible way of minimising this issue is by designing the gesture recogniser (i.e. what the system interprets as a certain gesture) to not be so restrictive, consequently increasing the sensitivity of the sensor and bridging the gap between the parameters expected by the system and the kinematics of the gestures made by the users as long as it does not lead to the so-called *"Midas Touch"* problem, where unintended movements are interpreted by the system as intentional commands (Wu and Wang, 2016).

7.1.2. Make use of real-world affordances. Affordances refers to perceived characteristics of an object that help guide the user in using that object correctly (Norman, 1998; Norman and Nielsen, 2010). Concrete affordances play a supporting role on the usability of gesture-based interfaces (Hartson, 2003). Providing affordances ensures that users understand what is possible to do within the interface and make it easier to anticipate how it can be done. Effective affordances make the interface easier to use and reduce error rates by persuading the user into making the right movements (McGrenere and Ho, 2000; Rogers, 2004; Kaptelinin and Nardi, 2012). Older users present less familiarity with gesture interaction paradigms and often base their actions on real-world assumptions rather than interaction conventions that are more easily assimilated amongst younger adults (e.g. finger pinch and spread to zoom in / out, finger swipe, air tap). In our study, older participants also preferred more relatable gestures such as grabbing, clapping, waving, and the fist gesture. Therefore, real-world affordances should be appropriated in order to make mid-air gesture interactions more usable for the older population. For example, bowling balls present indents suggesting two things: a) the ball should be grabbed, and b) the ball should be grabbed in a specific manner. Similar mechanisms are present in door knobs and push bars. The handles present in curtain rolls also indicate they can be reached and pulled up and down in order to be opened or closed. These affordances, for instance, could then be used as a foundation for designing interfaces that include the grab and push gestures as well as the pinch and drag gestures in a way older users can operate intuitively.

7.1.3. Minimise fine motor input. In accordance with the findings of related work on older adults and touchscreen gestures (Piper et al., 2010), in our study, mid-air gestures which involved entire hand movements and strokes (e.g. fist gesture, wave, clap, hold hand still, and grab) were either preferred or better performed by older participants, than finger gestures for which greater dexterity was required (e.g. fingers spread, finger pinch, and air tap). In order to avoid imprecise movements and accommodate older adults' motor skills, whole-hand gestures should be given preference over finger gestures.

7.2 Physical Interactions and Ergonomics

7.2.1. Allow interaction by either hand. Younger users have a clearer concept of using their hand as an input technique due to extensive familiarity with single hand interaction methods (i.e. by using a mouse or tapping their phones ubiquitously) (Ziefle and Bay, 2005). On the other hand, in our study we found that older users may not have this idea as clear as the younger population and swapped the active hand (i.e. the hand interacting with the system) more frequently due to various reasons, including upper limb fatigue or to make a gesture more easily. Current gesture-based systems expect a continuous interaction using the same hand as input but, in order to become more usable for older users, the system should not impose upon the user the need to use the dominant hand to make mid-air gestures for the entire course of interaction and should allow swapping hands as many times as they need.

7.2.2. Avoid user fatigue. Mid-air interactions are susceptible to upper limb fatigue and might lead to the so-called *"gorilla arm"* condition, which is a feeling of heaviness in the arms that can negatively impact the usability of this input method over time (Hincapié-Ramos et al., 2014; Ruiz and Vogel, 2015). Even though fatigue can affect users of all ages, our findings indicate that the presence of fatigue is accentuated amongst older users, especially when there was the need of sustaining and repeating the same gesture constantly without proper relaxation periods. In agreement with previous work (Hincapié-Ramos et al., 2014; Vuibert et al., 2015), one method for minimising fatigue is by combining different types of interactions. This combination allows the user to interact with the interface with different gestures and activate different muscle groups at a time. Constant more frequent gestures should be direct, simple, discreet and achievable through minimal effort whilst sporadic less frequent interactions can be more ample, complex and require more effort.

7.2.3. Allow inaccurate motions. Direct manipulation is one of the advantages of gesture interaction (Shneiderman, 1982 & 1983; Te'eni, 1990, Ruiz and Vogel, 2015). Pre-defined parameters in commercially available sensing devices (e.g. *Leap Motion*, *Microsoft Kinect*) are designed to set gesture recognisers to be fairly restrictive in order to avoid inaccurate motions, misdetections and the so-called *"Midas Touch"* problem leading to casual movements being interpreted by the system as intentional actions (Wu and Wang, 2016). However, for instance, due to sensorimotor restrictions, an older user may make a grab gesture next to an object rather than directly grabbing the object. Frequent target mis-selections and slip-offs when pointing and holding the hand in-air were also observed in older users during our task-based study. As a result, designing mid-air gesture interaction for older adults means that there will be the need of being reasonably forgiving of inaccurate motions. As an alternative, it could be possible to have the object snap into their hand. In addition, continuous visual feedback should be a fundamental factor for mid-air gesture interaction design in order to compensate for the lack of haptic feedback and inform the user about the status and progress of their motions (Delamare et al., 2016).

7.2.4. Compensate for the lack of haptics. Our results showed that older adults in general presented poorer execution and performance of mid-air gestures for computer interaction in comparison to younger adults. This difference may be explained by many factors, the lack of haptics in mid-air being one of them. The loss of tactile acuity in older adults is also accompanied by the deterioration of haptic performance and fine manipulative movements (Kalisch et al., 2008), and due to its touchless in-air nature, mid-air gesture interaction may present greater boundaries for older adults by providing limited haptic feedback and tactile involvement, which is a key human mechanism for perceiving unfamiliar objects and interacting with their surroundings. Similarly, (Smyth and Kirkpatrick, 2006) suggest that these boundaries, relative to the fluency of skills in their daily lives, are partly a consequence of unimodal interaction and limited to no haptic feedback present in mid-air gesture interaction. Furthermore, the precision of the movements sometimes required in mid-air gesture interaction prevent it from becoming second nature to the user if no haptic feedback is provided to support the transition from novice to skilled interaction (Oakley et al., 2000; Komerska and Ware, 2003; Smyth and Kirkpatrick, 2006). This issue could be minimised by making interactive elements reactive and responsive to casual movements alongside providing audio cues for indicating when and where interaction is taking place, therefore compensating for limited haptics by stimulating both visual and auditory exploration. This strategy could be useful to promote smoother interactions and support a rich set of gesture-based computer tasks in the absence of haptic feedback.

7.3 User Interface Design

7.3.1. Reduce unintended actions and adopt appropriate scaling. At times, older users in our study struggled to maintain their hand steady in-air for selecting targets and making directional motions such as the swipe gesture, resulting in accidental slip-offs, mis-selections and failed attempts. These accidental slip-offs may lead to the *"Midas Touch"* problem if their unsuccessful attempts to perform a certain gesture result in activating another function by mistake (Koutsabasis and Domouzis, 2016). Depending on the nature of the interface (e.g. menu based), the first object of a group to be selected can momentarily lock out all others. Group visual elements deliberately with enough space in between and adopt appropriate scaling so that older users do not accidentally trigger incorrect targets.

7.3.2. Define hand interactivity. Our findings showed that some users make pointing movements for selection using the index finger, whilst others prefer using the entire hand – older users in particular. Current interfaces usually employ one method or the other. Instead, make a single element of the hand, including itself, able to interact with buttons and other selectable elements – usually, with the tip of the index finger. At the same time, other nearby elements within the reachable area of the hand should not be interactive whilst the user is interacting with a specific object.

7.3.3. Provide multiple modes of consistent feedback. The lack of physical feedback in current mid-air gesture interactions leaves the task of informing the state of the interaction predominantly with the application's user interface. Efficient feedback should inform the user about three logical aspects of the interaction cycle: a) Where is the user now? b) Where should the user go? And 3) What does the user need to do to complete the interaction? (Buxton et al., 1983; Wigdor and Wixon, 2011). This usually happens through visual and sound feedback (Delamare et al., 2016). If proper feedback is missing, mid-air gesture interaction can fall into a loop of failed interaction attempts, as was observed with older adults in our study. One important aspect identified in our study is the need to clearly indicate when the user's hands become detectable by the sensor and when it is not. Visual feedback was provided when the user left the sensor's field of view but some older participants stated this was sometimes too subtle or insufficient for ensuring that they could proceed without hesitations. Furthermore, our study gathered useful information on what type of feedback novice users, especially older ones, expected to encounter when interacting with gesture-based interfaces for the first time, including some participants suggesting that all interactive elements should be easily distinguishable from the static ones, either by being highlighted in a different colour or shape. For instance, an older participant suggested that when someone tries to select a button by pointing or making another gesture, the item may compress and bounce back, with a colour state change suggesting that the item is now active. Alongside with visual feedback, unobtrusive sound cues could be used as a supporting indication that interaction was successful.

7.3.4. Avoid misleading instructions. As noted by (Gerling et al., 2012) many older adults have little experience of being instructed through a computer screen, and sometimes are dependent on other persons for assistance. This could be seen in our study, where a few older participants would wait for the researcher’s guidance before gaining enough courage to make a gesture by themselves, and they would seek the researcher’s confirmation afterwards even if their performed gesture was correct. Instructing 3D freehand movements for beginners can be a challenge either if attempting to represent mid-air gestures through 2D pictograms and simple animations or labels and written sentences because the user’s interpretation may differ from the gesture kinematics expected by the system. In our study we observed that, if unsure how to make a certain gesture, older adults will rigorously follow the provided instructions in order to proceed, therefore will feel frustrated if the instructions lead to unsuccessful attempts. This problem could be avoided by providing consistent and clear instructions and the investigation of new approaches to instructing novice users on how to perform gestures, including user tests of the instructions, could be helpful to increase the learnability of mid-air gestures and overall usability of gesture-based interfaces for older users.

8 Limitations and Future Work

In this study, we mainly investigated first impressions of hand-based mid-air gestures for a computer interaction context, in a sitting position. Many other interaction contexts such as public space "walk-up-and-use" interfaces, large interactive displays, virtual reality, and the use of full-body interaction could be explored in future work and may offer additional insights on how older adults engage with these physically embodied input methods in terms of user experience and social acceptance. Despite the increasing ubiquity of gesture-based interfaces, we are also aware of the fundamental role that culture and language play on eliciting gestures through symbolic referents and therefore the results of our guessability study may differ if applied in a different population. Also, even though we only recruited participants with no prior experience with mid-air gesture interaction, we acknowledge that our older participants all had past computer-mediated exposure and therefore older adults with little to no familiarity with interactive devices as well as individuals with physical impairments would probably raise additional questions and face greater difficulties which were not addressed in this study.

9 Conclusion

In this work, we conducted an exploratory study on how younger and older adults perceive and interact with mid-air gesture interaction for the first time. Our results indicated that even though younger and older adults presented similar conceptual models for gesturing in-air when the gestures were not associated with tasks, older users had a significantly poorer performance at task-associated gesture making and therefore their needs in terms of usability and accessibility warrant particular consideration when designing mid-air gesture-based interfaces. Our findings also suggest that mid-air gestures based upon real-world interactions (e.g. clap, grab, point, fist, wave) may be easier for older adults to produce consistently, compared with those based upon touchscreen paradigms (e.g. swipe, air tap, finger rotation and double tap), as indicated by guessability agreement scores and task-based performance, and therefore should be given preference in order to increase accessibility for older users with no familiarity with those devices. Hand gestures (e.g. fist, wave) were also preferred by older participants over finger gestures that involved fine manipulation (e.g. finger pinch, fingers spread). Furthermore, we propose a set of design recommendations for guiding the design of mid-air gesture-based interfaces that better accommodate the skills of older users. This work reinforces the need of representing older adults in HCI studies, especially in relation to novel interaction techniques, and by including the older population we intended to make a contribution to the expanded body of work on mid-air gesture input for computer interaction. Our findings suggest that a deeper understanding into how older users interact with mid-air gestures is fundamental for user-friendly interfaces and effective gesture recognition techniques. Finally, by being the first work to include both younger and older users with no prior experience using mid-air gesture interaction in order to investigate not only the acceptance and intuitiveness of commonly used gestures (through a guessability study), but also to investigate the execution, efficiency and intent-of-use of mid-air gestures for computer interaction (through a task-based study), this work makes a contribution to the research and practice of designing gesture-based interfaces that are suitable for a larger and more representative portion of the population.

References

Blackler, A., and Popovic, V. (2015). Towards Intuitive Interaction Theory. *Interacting with Computers*, 27(3), 203-209.

Blackler, A., Popovic, V. and Mahar, D. (2003). The nature of intuitive use of products: an experimental approach. *Design Stud.*, 24, 491–506.

Bobeth, J., Schmehl, S., Kruijff, E., Deutsch, S., Tscheligi, M. (2012). Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proc. of EuroiTV '12*, 35-44.

Braun, V., Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3, 77-101.

Brooke, J. (1996). SUS: a "quick and dirty" usability scale. In: Jordan, P. W., Thomas, B., Weerdmeester, B. A., McClelland, I. L. Eds.: *Usability Evaluation in Industry*, pp. 189-194. London: Taylor & Francis.

Buxton, W., Fiume, E., Hill, R., Lee, A., Woo, C. (1983). Continuous hand-gesture driven input. *Graphics Interface '83*, 191-195.

Cabreira, A. T., Hwang, F. (2015). An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258.

Cabreira, A. T., Hwang, F. (2016). How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA.

Chaparro A., Rogers M., Fernandez J., Bohan M., Choi S.D., Stumpfhauser L. (2000). Range of motion of the wrist: implications for designing computer input devices for the elderly. *Disabil Rehabil.* 2000 Sep 10-20;22(13-14):633-7.

Charness, N. and W.R. Boot, W.R. (2009). Aging and information technology use: potential and barriers, *Current Directions in Psychological Science* 18 (5), 253–258.

Coughlin, J.F., Pope, J.E., & Leedle, B.R. Jr. (2006). Old age, new technology, and future innovations in disease management and home health care. *Home Health Care Management & Practice*, 18, 196–207.

Czaja, S.J., and Lee, C.C. (2007). The impact of aging on access to technology. *Universal Access in the Information Society*, 5, 341-349.

Delamare, W., Janssoone, T., Coutrix, C., Nigay, L. (2016). Designing 3D Gesture Guidance:

Visual Feedback and Feedforward Design Options. In Proc. AVI '16. ACM.

Dourish, P. (2004). Where the Action Is: The Foundations of Embodied Interaction. MIT Press.

Emery, V.K., et al. (2003). Toward achieving universal usability for older adults through multimodal feedback. In *Proc. the 2003 ACM Conference on Universal Usability* (CUU03), 46–53.

Findlater, L., Froehlich, J.E., Fattal, K., Wobbrock, J.O., and Dastyar, T. (2013). Age-related differences in performancewith touchscreens compared to traditional mouse input. In *Proc. of CHI '13,* 343–346. ACM.

Findlater, L., Lee, B., and Wobbrock, J. (2012). Beyond QWERTY: augmenting touch screen keyboards with multi-touch gestures for non-alphanumeric input. In *Proc. CHI 2012*, 2679-2682. ACM.

Fisk A.D., Rogers A.R., Charness N, Czaja S.J., & Sharit J. (2009). Designing for Older Adults – Principles and Creative Human Factors Approaches. Boca Raton: CRC Press.

Gerling K., Livingston, I., Nacke L., and Mandryk, R. (2012). Full-body motion-based game interaction for older adults. In *Proc. CHI 2012,* 1873-1882. ACM.

Grandhi, S. A., Joue, G., Mittelberg, I. (2011). Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proc. CHI 2011*, 821-824. ACM.

Hartson, R. (2003). Cognitive, physical, sensory, and functional affordances in interaction design. *Behaviour & Information Technology*, 22:5, 315-338.

Hincapié-Ramos, J. D., Guo, X., Moghadasian, P., and Irani, P. (2014) Consumed endurance: A metric to quantify arm fatigue of mid-air interactions. In *Proc. CHI 2014,* 1063–1072. ACM.

Huppert, F.A. (2003). Designing for Older Users. In: PJ Clarkson, R Coleman, S Keates & C Lebbon (Eds) *Inclusive Design: Design for the whole population*. Springer Verlag, London.

Hurtienne, J. (2009). Image Schemas and Design for Intuitive Use. Technischen Universität Berlin, Berlin.

Hutchins E.L., Hollan, J.D. and Norman D.A. (1986) Direct manipulation interfaces. In: Norman & Draper (eds) *User centered system design: new perspectives on human-computer interaction*. Lawrence Earlbaum Associates, Hillsdale, NJ.

Hwang, F., Hollinworth, N., and Williams, N. (2013). Effects of target expansion on selection performance in older computer users. *ACM Trans. Access. Comput.* 5, 1, Article 1.

Johnson, M. (1987). The Body in the Mind. The Bodily Basis of meaning, Imagination, and reason. The University of Chicago Press.

Kalisch, T., Tegenthoff, M., and Dinse, H.R. (2008). Improvement of sensorimotor functions in old age by passive sensory stimulation. *Clin. Intervent. Aging* 2008; 3:673–90.

Kaptelinin, V., Nardi, B. (2012). Affordances in HCI: toward a mediated action perspective. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 967-976.

Kim, H., Takahashi, I., Yamamoto, H., Maekawa, S., Naemura, T. (2014). Mario: Mid-air augmented reality interaction with objects. *Entertainment Computing* 5, 4, 233 – 241.

Ketcham, C. J., Seidler, R. D., Van Gemmert, A. W.A., Stelmach, G. E. (2002). The Journals of Gerontology: Series B 57, 1, 54-64.

Komerska, R., Ware, C. (2003) Haptic task constraints for 3D interaction. In *Proceedings of IEEE HAPTICS 2003*, 270–277. IEEE.

Köpsel, A., and Bubalo, N. (2015). Benefiting from legacy bias. *interactions* 22, 5, 44-47.

Koutsabasis, P., Domouzis, C. (2016). Mid-Air Browsing and Selection in Image Collections. *International Working Conference on Advanced Visual Interfaces* (AVI) 2016. ACM.

Kratz, S., Rohs, M., Guse, D., Müller, J., Bailly, G. and Nischt, M. (2012). PalmSpace: continuous around-device gestures vs. multitouch for 3D rotation tasks on mobile devices. In *Proc. AVI '12*, 181-188.

Lee, S., et al. (2013). Towards more natural digital content manipulation via user freehand gestural interaction in a living room. In *Proc. UbiComp '13*, 617-626. ACM.

Maes, P., and Schneiderman, B. (1997). Direct manipulation vs. Interface agents: a debate. *Interactions* 4, 42–61.

McGrenere, J., Ho, W. (2000). Affordances: Clarifying and evolving a concept. In *Proceedings of the Graphics Interface 2000*, Canadian Human-Computer Communications Society: Toronto, 179 – 186.

Moffatt, K. A. and McGrenere, J. (2009). Exploring methods to improve pen-based menu selection for younger and older adults. *ACM Trans. Access. Comput.* 2, 1, Article 3. 1–32.

Moffatt, K. (2013). Older-adult HCI: why should we care? *interactions* 20, 4, 72-75.

Morris, M. R., Danielescu, A., Drucker, S., Fisher, D., Lee, B., and Wobbrock, J. O. (2014). Reducing legacy bias in gesture elicitation studies. *Interactions*, 21(3), 40-45.

Nacenta, M.A., Kamber, Y., Qiang, Y. and Kristensson, P.O. (2013). Memorability of pre-designed and userdefined gesture sets. *Proc. CHI 2013*. ACM.

Nielsen, M., Störring, M., Moeslund, T.B. and Granum, E. (2003). A procedure for developing intuitive and ergonomic gesture interfaces for HCI. *Int'l Gesture Workshop 2003*, LNCS vol. 2915. Heidelberg: SpringerVerlag, 409-420.

Norman, D. A. (1988). The psychology of everyday things. New York: Basic Books.

Norman, D. A., Nielsen, J. (2010). Gestural interfaces: a step backward in usability. *interactions* 17, 5, 46-49.

Norman, D.A., Wadia, B. (2013). Opportunities and Challenges For Touch and Gesture-Based Systems. In *2013 Society for Information Display conference*, Vancouver, Canada (May, 23).

Oakley, I., McGee, M., Brewster, S., Gray, P. (2000) Putting the feel in ‘look and feel’. In *Proceedings of ACM CHI 2000*, 415–422. ACM.

O’Hara, K., et al. (2014). Touchless Interaction Surgery. *Communications of the ACM*, 57, 1, 70-77.

Piper, A. M., Campbell, R., Hollan, J. D. (2010). Exploring the accessibility and appeal of surface computing for older adult health care support. *Proc. CHI 2010*, 907–916. ACM.

Pullin, G., Newell, A. (2007). Focussing on Extra-Ordinary Users. In: Stephanidis C. (eds) *Universal Acess in Human Computer Interaction*. Coping with Diversity. UAHCI 2007. Lecture Notes in Computer Science, vol 4554. Springer, Berlin, Heidelberg.

Rahman, M., Gustafson, S., Irani, P. and Subramanian, S. (2009). Tilt techniques: investigating the dexterity of wrist-based input. In *Proc. CHI '09*. 1943-1952. ACM.

Rice, M., et al. (2011). Evaluating gesture-based games with older adults on a large screen display. In *Proc. of the 2011 ACM SIGGRAPH Symposium on Video Games* (Sandbox '11), 17-24.

Rice, M., et al. (2013). The dynamics of younger and older adult's paired behavior when playing an interactive silhouette game. In *Proc. CHI 2013*, 1081-1090. ACM.

Rodriguez, I. B., Marquardt, N. (2017). Gesture Elicitation Study on How to Opt-in & Opt-out from Interactions with Public Displays. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (ISS '17). ACM, New York, NY, USA, 32-41.

Rogers, Y. (2004) New theoretical approaches for HCI. *ARIST: Annual Review of Information Science and Technology*, 38, 87-143.

Ruiz, J., Li, Y., and Lank, E. (2011). User-Defined Motion Gestures for Mobile Interaction. *Proc. CHI 2011*, 197-206. ACM.

Ruiz, J., Vogel, D. (2015). Soft-Constraints to Reduce Legacy and Performance Bias to Elicit Whole-body Gestures with Low Arm Fatigue. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15), 3347-3350. ACM.

Saffer, D. (2008). Designing Gestural Interfaces: Touchscreens and Interactive Devices. O’Reilly Media.

Selwyn, N. (2004). The information aged: A qualitative study of older adults’ use of information and communications technology, *Journal of Aging Studies* 18 (4) (2004) 369–384.

Shneiderman, B. (1982). The future of interactive systems and the emergence of direct manipulation. *Behavior and Information Technology*, I, 237-256.

Shneiderman, B. (1983). Direct manipulation: A step beyond programming languages. *IEEE Computer*, 16(8), 57-69.

Shneiderman, B. (2010). Designing the user interface: Strategies for effective human-computer interaction (5nd ed.). Reading, MA: Addison-Wesley.

Smyth, T. N., Kirkpatrick, A. E. (2006). A new approach to haptic augmentation of the GUI. *In Proc. ICMI ’06*. ACM.

Stößel, C. (2009). Familiarity as a factor in designing finger gestures for elderly users. In *Proc. MobileHCI '09*, Article 78.

Stößel, C., Wandke, H. and Blessing, L. (2010). Gestural interfaces for elderly users: Help or hindrance? *Gesture in Embodied Communication and Human-Computer Interaction*, Springer, 269-280.

Te'eni, D. (1990). Direct manipulation as a source of cognitive feedback: a human-computer experiment with a judgment task. *International Journal of Man-Machine Studies*, 33, 453-466.

Vatavu, R. (2012). User-defined gestures for free-hand TV control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12), 45-48. ACM.

Venkatesh, V., Bala, H. (2008). Technology acceptance model 3 and a research agenda on interventions. *Decision Sciences* 39 (2), 273–315.

Vitense, H., Jacko, J.A., and Emery, V.K. (2003). Multimodal feedback: an assessment of performance and mental workload. *Ergonomics* 46 (1–3), 68–87.

Vosinakis, S., Koutsabasis, P., Makris, D., Sagia, E. (2016). A Kinesthetic Approach to Digital Heritage using Leap Motion: The Cycladic Sculpture Application. *8th International Conference on Games and Virtual Worlds for Serious Applications* (VS-GAMES). IEEE.

Vuibert, V., et al. (2015). Evaluation of Docking Task Performance Using Mid-air Interaction Techniques. In *Proc. SUI '15*, 44-52. ACM.

Walker, N., Philbin, D. A., and Fisk, A. D. (1997). Age-related differences in movement control: Adjusting submovement structure to optimize performance. *J. Gerontology: Psychol. Sci.* 52B, 1, 40–52.

Walter, R., Bailly, G., Müller, J. (2013). StrikeAPose: Revealing Mid-Air Gestures on Public Displays. In *Proc. CHI 2013*, 841-850. ACM.

Wigdor, D., and Wixon, D. (2011). Brave NUI World: Designing Natural User Interfaces for Touch and Gesture. Morgan Kaufmann.

Wobbrock, J. O., Aung, H. H., Rothrock, B., and Myers, B. A. (2005). Maximizing the guessability of symbolic input. In *Proc. CHI'05 extended abstracts*, 1869-1872. ACM.

Wobbrock, J.O., Morris, M.R., Wilson, A.D. (2009). User-defined gestures for surface computing. In *Proc. of CHI 2009*, 1083-1092. ACM.

Wu, H., Jianmin Wang, J. 2016. A visual attention-based method to address the midas touch problem existing in gesture-based interaction. *Vis. Comput.* 32, 1 (January 2016), 123-136.

Ziefle, M., Schroeder, U., Strenk, J., Michel, T. (2007). How young and older users master the use of hyperlinks in small screen devices. In *Proc. SIGCHI Conference on Human Factors in Computing Systems 2007*, 307-316. ACM.

Ziefle, M., Bay, S. (2005). How older adults meet complexity: Aging effects on the usability of different mobile phones. *Behaviour & Information Technology*, Vol. 24-5. Taylor & Francis.

4 *Text or Image? Investigating the Effects of Instruction Type on Mid-Air Gesture Making with Novice Older Adults*

Publication status:

* Full chapter was peer-reviewed, revised and accepted for publication in:

Cabreira, A. T. and Hwang, F. 2018. Text or Image? Investigating the Effects of Instruction Type on Mid-Air Gesture Making with Novice Older Adults. *In Proceedings of the 10th Nordic Conference on Human-Computer Interaction* (NordiCHI '18). ACM, New York, NY, USA. https://doi.org/10.1145/3240167.3240222

(*in press*)

4 Text or Image? Investigating the Effects of Instruction Type on Mid-Air Gesture Making with Novice Older Adults

Abstract

Unlike traditional interaction methods where the same command (e.g. mouse click) is used for different purposes, mid-air gesture interaction often makes use of different gesture commands for different functions, but first novice users need to learn these commands in order to interact with the system successfully. We describe an empirical study with 25 novice older adults that investigated the effectiveness of 3 "on screen" instruction types for demonstrating how to make mid-air gesture commands. We compared three interface design choices for providing instructions: descriptive (text-based), pictorial (static), and pictorial (animated). Results showed a significant advantage of pictorial instructions (static and animated) over text-based instructions for guiding novice older adults in making mid-air gestures with regards to accuracy, completion time and user preference. Pictorial (animated) was the instruction type leading to the fastest gesture making with 100% accuracy and may be the most suitable choice to support age-friendly gesture learning.

1 Introduction

Mid-air gesture interaction has gained increasing popularity and diversification of applications in different contexts, including gaming, virtual reality, smart homes, intelligent vehicles and public interactive kiosks. Gesture-based interfaces usually use motion sensors such as the Microsoft Kinect, Microsoft HoloLens and the Leap Motion controller to allow users to make gesture commands to navigate the system and control objects on screen [1][24].

Recent studies have been focusing on finding coherent, easy and intuitive mid-air gestures for different interaction contexts [2][6][17][19] but little research has focused on investigating the most effective way of providing to novice users instructions on how to make those gestures once they have already been incorporated in an interface. As yet, the learnability of gesture commands by novice users is still a challenging aspect of gesture-based interfaces [9], and older adults (aged 60+) face even greater challenges when interacting with this novel input method [2].

Unlike traditional interaction methods where the same command (e.g. mouse click) is used for different purposes, gesture-based interfaces often make use of different gesture commands for different functions, but first the user has to learn these commands in order to interact with the system successfully. Clear interface instructions are a fundamental feedforward mechanism for guiding novice users in using novel technologies such as mid-air gesture interaction [6]. Demonstrating "where" and "how" the system is expecting users to make gestures, and therefore allowing novice users to successfully navigate through an interface can be a challenge due to two factors. First, mid-air gestures are three-dimensional motions per se but, in order to provide instructions to novice users on how to make these motions, gestures are usually represented on the screen which is fundamentally a 2-d environment. Furthermore, a 3-d gesture command usually translates into a two-dimensional result: for example, users need to swipe their hands left and right in mid-air, which involves a 3-d physical motion, in order to control a 2-d slider-style menu on screen. This incongruity between 3-d commands and 2-d interfaces, combined with vague gesture names can become a usability issue for users who are not familiar with this interaction method [6].

Second, the exact spatial trajectory and kinematics of different mid-air gestures expected by the system may sometimes differ from novice users' understanding and expectation of these gestures prior to the interaction, and, if instructions are vague, misleading, or the actual gesture is not "straightforward" then the mismatch between the user's and the system's expectations can lead to failed gesture attempts, frustration, and may affect the overall usability of the interface [2]. For instance, questions such as "A finger pinch involves which fingers exactly?", *"How fast should I swipe?", "Where should I point my finger to?", "Should I rotate my index finger clockwise or anti-clockwise?"* are not uncommon and could be precisely answered by providing instructions and guidance on-screen, however, the question of what is the most effective way of doing that for a novel input method as mid-air gesture interaction is still overlooked and unknown.

Although this uncertainty about knowing how to make gestures might affect all novice users with no prior experience in gesturing in mid-air, older adults (60+) face greater difficulties and are generally more reluctant to adopt new unfamiliar interaction concepts [15][17]. Previous work [2] suggests that some gesture commands (e.g. air tap, swipe, finger rotation) can be unfamiliar to older adults, therefore interface instructions on how to make certain gestures should be addressed carefully to avoid failed interaction attempts. Additionally, older adults experience additional challenges as a consequence of age-related declines in range of motion and motor control, leading to imprecise and unsteady gesture-making in comparison with younger users [6][15].

Therefore, our study aims to investigate effective methods for demonstrating to novice older adults how to make different gesture commands in mid-air for the first time (i.e. providing instructions on screen) when using a Leap Motion sensor. We compared three interface design choices for presenting gesture instructions: descriptive (text-based), pictorial (static), and pictorial (animated).

2 Background

This section first discusses the relationship between older adults and technology, and then reviews literature that focuses on theoretical and empirical research on pictorial versus text-based interfaces. Finally, work about the learnability of gestures and methods for providing gesture instructions to novice users is discussed. The body of work reviewed below was fundamental for guiding the design of our empirical study.

2.1 Older adults and unfamiliar interfaces

According to Arnott et al. (2004) [15], older adults (over the age of 60) often encounter two main obstacles to computer use: inexperience with interactive systems and unfamiliarity with novel technologies. Despite the significant growing numbers of older adults using - or interested in using - computers and technology advancements, little research had been conducted on the design of age-friendly interfaces and how to support an inclusive interaction for older users at that time. The authors designed an iconic “senior-friendly” e-mail interface and found that older users preferred literal conventional features over novel symbols and metaphors.

Gerling et al. (2012) [17] designed a motion-based game interface for older adults in nursing homes that uses full-body movements and a Microsoft Kinect sensor as a method for providing safe and engaging physical activity amongst sedentary older adults. Their findings indicate that easy gesture recall should be a fundamental aspect of an age-friendly gesture-based interface. The authors also explain that many older adults have little to no familiarity with being instructed through a computer screen, and therefore instructions should be carefully designed in order to support easy gesture learning by novice older users.

2. 2 Theoretical background of pictorial interfaces

Pictorial or iconic interfaces use images to represent actions, commands or objects that can be invoked or manipulated by a user [14]. Lodding (1983) [18] writes that different pictorial types may convey meaning in different ways. For instance, abstract icons are meant to convey abstract concepts, whilst representational icons, which are more commonly used for representing gestures, are meant to represent actual physical objects and actions.

Gittins (1986) [8] suggests that pictorial and text-based instructions are different in attentional, processing and memory demands, and advocates that recognition and categorisation processes may be faster for pictures than for text and that pictorial instructions may lead to enhanced performance due to the superior advantages of visual memory over verbal memory. Alongside recognition superiority, it is implied that “representational” pictorial instructions may be a better choice for assisting novice users in learning how to use a new system by providing a set of familiar objects from which inferences about the interaction can be made [14][8].

Despite the listed advantages of pictorial instructions, Ives (1982) [3] calls attention to the difficulty of designing interface icons that communicate the intended commands without producing other connotations, whilst Witten and Greenberg (1985) [13] indicate that mismatching user’s interpretations and the intended meaning of employed icons may lead to semantic errors and usability decrease. Furthermore, Lodding (1983) [18] suggests that ambiguity in iconic representations is a result of a lack of universal guidelines and principles for designing such interfaces.

2.3 Empirical studies and pictorial interfaces

There are relatively few studies that have evaluated the effectiveness of pictorial elements compared to text-based elements in interface design, however, empirical studies have been conducted for investigating abilities associated with pictorial use [10][23], for studying different interface design approaches [14][16], and for comparing forms of icons versus text commands [12]. No significant improvement in performance was found for novice users of iconic interfaces in those studies.

Egido and Patterson (1988) [4] investigated the effects of icons as a supporting aid for catalog browsing in comparison with text-based representations. In their findings, iconic representations led to slower browsing than “text” and “text plus labels”. Additionally, Kacmar (1991) [5] conducted a comparison study of text labels versus pictograms in matching programming concepts where it was found that both methods combined (text labels plus pictograms) led to greater accuracy, but there was no significant difference in time. Neither study reports an advantage in completion time or accuracy obtainable through the use of pictorial representations alone.

A more recent study conducted by Griffon et al. (2014) [20] investigated the application of an iconic system interface for Visualization of Concepts in Medicine (VCM) with 20 physicians. The interface contained a filter based on icons, and icons describing medical resources. Their findings demonstrated that VCM was highly accepted by end-users and significantly increased success of information retrieval tasks in comparison with a non-VCM interface, despite requiring more time to achieve it.

In general, these studies – mainly conducted with younger and medium-to-expert users – have not found a clear and definitive advantage of pictorial elements alone in comparison with text-based information. However, the question of whether pictorial instructions would improve accuracy of mid-air gesture making for novice older adults is still an important topic yet to be explored.

2.4 Learnability of gestures for novice users

Norman and Nielsen (2010) [9] argue that a challenging aspect of gesture-based interfaces is the learnability of new gesture commands for novice users. That is, novice users need to be informed about what gestures can be used for a list of interface commands and how to make them correctly in order to proceed with a successful interaction. Interface designers and developers alongside with HCI researchers have not yet employed consistent principles and practices concerning gesture learning. Although highly relevant, this question has been largely unexplored by the HCI community so far. Kurtenbach et al. (1994) [11] made use of auxiliary and contextual on screen animations to help novice users learn possible pen-based gesture commands within the interface, and how those gestures should be made. Similarly, Avrahami et al. (2001) [7] explored the suitability of Paper PDA, a paper-electronic interface that was designed to guide the making of single-stroke pen-based gestures.

Bau and Mackay (2008) [21] described OctoPocus, a novel concept that combined “on screen” guidance and feedback to help users learn, execute and remember mouse-based gesture commands by drawing path lines with the cursor. Despite initial positive results with medium-to-expert computer users, it is not possible to draw any conclusions on the suitability of this concept for novice users gesturing in mid-air.

3 Methods

We designed a study for investigating the effects of different “on-screen” instruction types on gesture making for novice older adults with regards to accuracy, completion time and user acceptance. A list of all gestures and instructions used in the study is available as a supplementary material.

We compared three interface design choices for presenting gesture instructions (Figure 1):

- **Descriptive**: Written gesture name plus a text-based instruction on how to make the gesture.
- **Pictorial (static)**: Written gesture name plus a static image depicting the gesture.
- **Pictorial (animated)**: Written gesture name plus a 3-frame animated gif simulating a hand making the gesture.

3.1 Design and materials

The study employed a within-subjects design. Each participant was asked to make 15 different mid-air gestures to a Leap motion sensor, based on one of the three instruction types provided on screen (Figure 1): 5 gestures were shown under a descriptive (text-based) instruction, 5 gestures were shown under a pictorial (static) instruction and 5 gestures were shown under a pictorial (animated) instruction. Gestures differed in complexity and number of hands involved. Gesture order and type of instruction provided were counter-balanced across participants using a balanced Latin square to minimise learning and fatigue effects (Figure 2). The number of gesture attempts (correct or incorrect) and time to make each gesture correctly (including instruction reading time) were the dependent variables.

Figure 1. Examples of on screen instructions type for the "finger rotation" gesture: (a) descriptive (text-based), (b) pictorial (static), and (c) pictorial (animated).

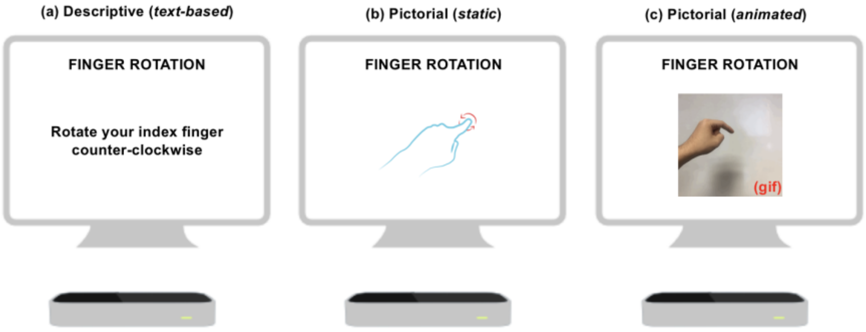
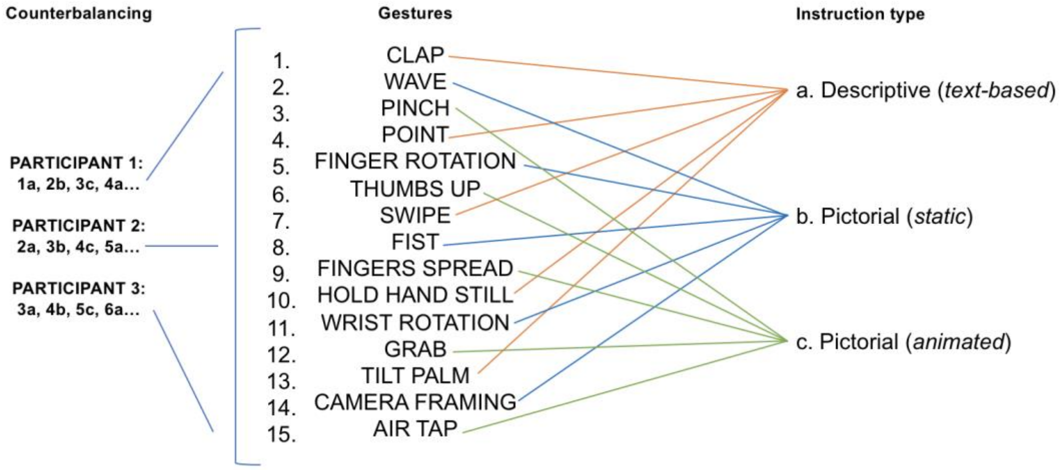


Figure 2. Study design diagram: gestures list and counterbalancing system.



Gestures were classified as either correct (the participant made the mid-air gesture shown on screen and the Leap Motion sensor recognised it) or incorrect (the participant made a mid-air gesture, but it was not the gesture described on the screen). We collected gesture data as well as initiation and finalisation times using a Leap Motion gesture recogniser [24]. Gestures were also video recorded and reclassified by the primary researcher in case of false negatives.

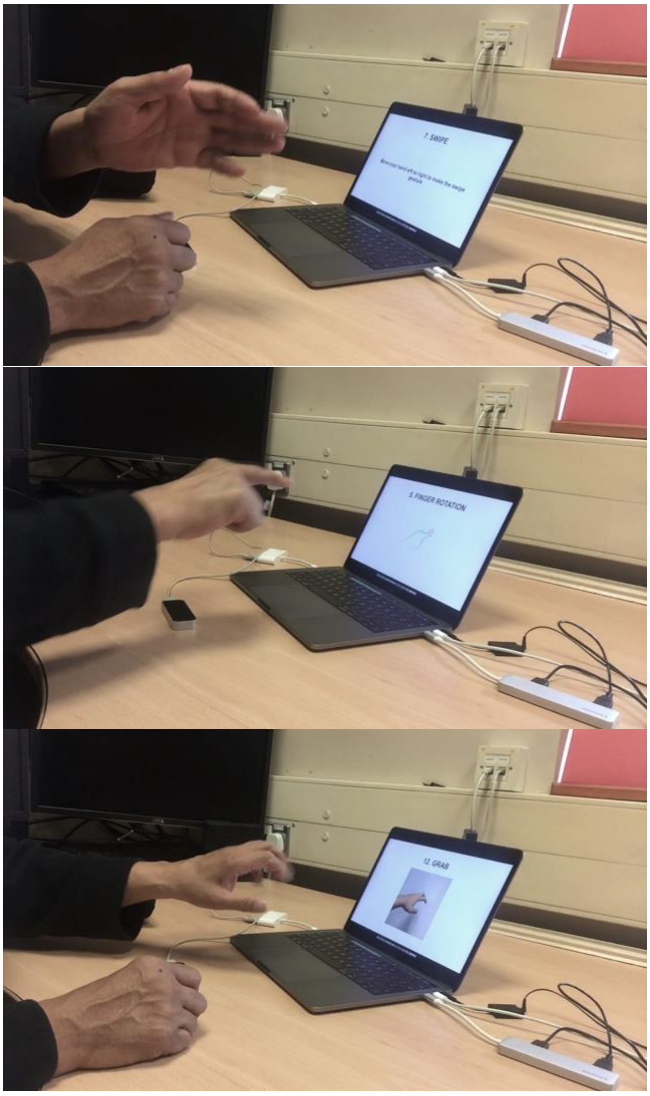
3. 2 Participants

25 older adults (12 female) were recruited for the study and the mean age was 67.04 years old (SD=6.71; range 60 to 83). All participants had previous computer experience (e.g. desktop, laptop) and little familiarity with touchscreen devices (e.g. smartphones, iPad) but none of them had significant previous experience with mid-air gesture interaction and motion sensing devices such as the Microsoft Kinect or the Leap Motion controller. All participants were assessed on their eye-hand coordination, motor function and manual dexterity using a Rolyan 9-hole peg test toolkit, which is considered an appropriate tool for measuring dexterity and motor skills across the age span [25]. The study has been reviewed by the University of Reading's Research Ethics Committee and has been given a favourable ethical opinion for conduct.

3.3 Procedure

Participants were shown one of the three instruction types on screen for 15 mid-air gestures one at a time (Figure 3a to 3c). Participants were then asked to make the gesture correctly in front of the screen as fast and accurately as possible in order to proceed to the next one. In case a participant struggled in making the correct gesture, the researcher would intervene after the 10th attempt by asking the participant to proceed to the next gesture. At the end of the study, participants were asked to rate their preference and perceived easiness of each of the three instruction types.

Figure 3a-3c. Participant making a “swipe” gesture based on a descriptive (*text-based*) instruction [top], a “finger rotation” gesture based on a pictorial (static) instruction [middle], and a “grab” gesture based on a pictorial (animated) instruction [bottom].



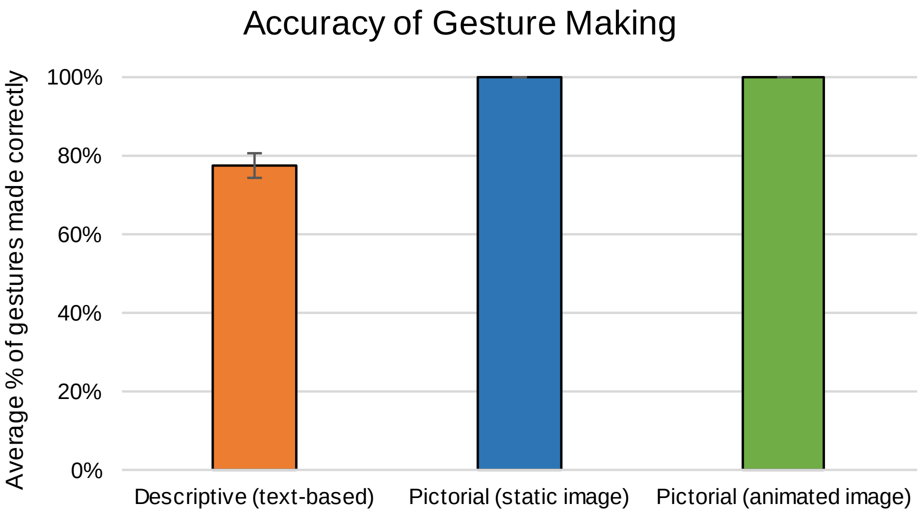
4 Results

403 (28 incorrect and 375 correct) mid-air gestures were collected and analysed in the study. This section describes our findings in regards to accuracy, completion time and subjective ratings for each of the three “on screen” instruction types: descriptive (text-based) and pictorial (static and animated). All participants were able to complete the study without help.

4.1 Accuracy

Gestures made based on descriptive (text-based) instructions achieved 77.6% accuracy, whilst pictorial instructions (static and animated) achieved 100% accuracy across all participants (i.e. all gestures were correctly made in one attempt). A repeated-measures ANOVA was conducted on the number of gesture attempts and the effects of three instruction types. Results showed that descriptive (text-based) instructions led to significantly lower accuracy in gesture making in comparison with pictorial (static and animated) instructions [F(2, 372) = 35.8; p <.0001; Cohen's d=0.87] (Figure 4).

Figure 4. Average percentage of mid-air gestures made correctly at first attempt based on three instruction types. Error bars indicate standard errors.



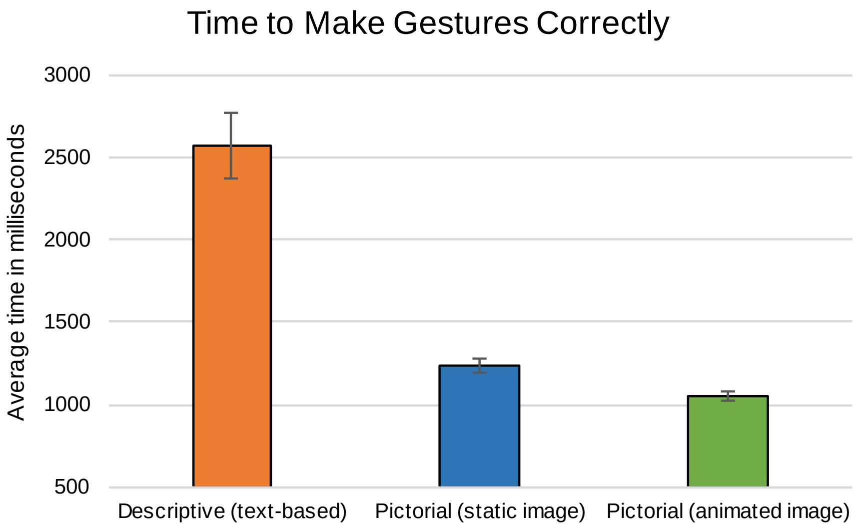
4.2 Time to make gestures correctly

Figure 5 shows the average time (ms) taken to read/view the instruction and make each of 15 gestures correctly based on three instruction types provided on screen.

The average time taken for a descriptive instruction (text-based) was 2.6s, whilst for gestures shown with pictorial instructions the average time was 1.2s for the ones depicted as static images and 1.0s for animated images.

A repeated-measures ANOVA showed a significant main effect of instruction type on time necessary to make correct gestures [F(2, 372) = 57.45; $p < .0001$; Cohen's d=1.03]. A post-hoc Tukey HSD test confirmed significant differences between all pairs and found that the time taken to make gestures correctly with a descriptive (text-based) instruction was significantly higher than the time taken to make gestures with a pictorial (static) instruction, and the time taken to make correct gestures with a pictorial (animated) instruction was significantly lower than the time taken with the two former instruction types (Figure 5).

Figure 5. Average time in milliseconds taken to make gestures correctly for each of the three instruction types. Error bars indicate standard errors.



4.3 Subjective ratings

Participants rated the perceived easiness (i.e. how easy it was to come up with a gesture based on the instruction displayed on the screen) for each of the three instruction types using a 5-point Likert item ranging from (1) Very difficult to (5) Very easy. Results show that all three instruction types were rated from "Easy" to "Very easy" on average (Figure 6). A one-way ANOVA found no significant differences between the three instruction types (p = 0.2).

Participants were also asked to order the three instruction types based on their personal preference. Figure 7 shows the number of participants responding to "most" to "least" preferred instruction type for making mid-air gestures. Pictorial (animated) was the overall most preferred instruction type (15 responses), in contrast with 7 participants choosing descriptive (text-based) and only 3 participants choosing pictorial (static) as their preferred instruction type.

Figure 6. Average perceived easiness ratings for each of the three instruction types (1 – Very difficult; 5 – Very easy).

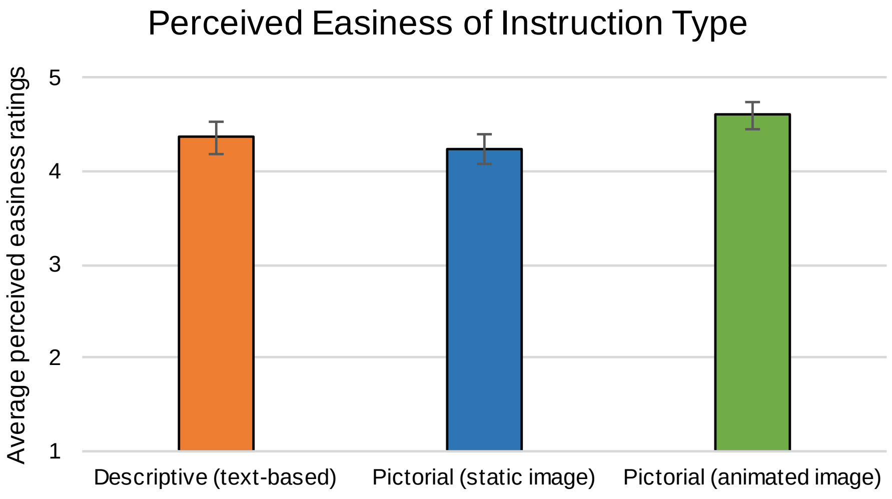
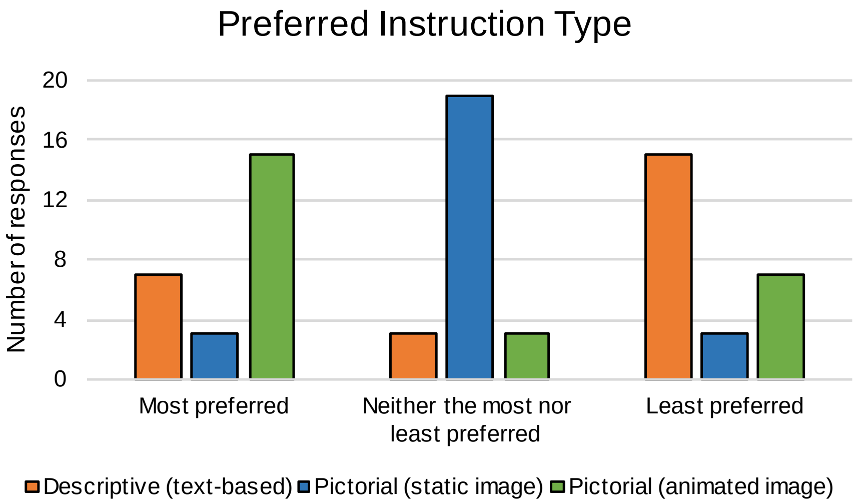


Figure 7. Number of participants responding to (1) most, (2) neither the most nor least, or (3) least preferred type of instruction for making mid-air gestures.



5 Discussion

Our study aimed to investigate the effects of three “on screen” instruction types for guiding novice users, older adults specifically, on making correct gestures in mid-air. In previous sections, we described the importance of not only choosing suitable gesture sets for a diverse population but also the need to consider effective interface design choices for supporting the learnability of these gestures. We investigated three instruction types: descriptive (text-based), pictorial (static) and pictorial (animated).

Despite being positively accepted by participants, our results found clear disadvantages of descriptive (text-based) instructions over pictorial instructions regarding completion time and accuracy of gesturing in mid-air. Our findings showed that the latter were more effective than the former, and highly accepted by novice older adults when applied to the context of mid-air gesture interaction. Pictorial (animated) instructions led to faster gesture making and 100% accuracy across participants and was considered the overall most preferred instruction type by older adults in our study.

Another interesting finding was that with text-based instructions, some participants would first only read the gesture label (e.g. “swipe”) to attempt making a gesture intuitively without specific guidance, and would only then read the actual gesture description if the attempted gesture was not made correctly (Figure 1). This is a possible explanation for a lower accuracy of gestures based on descriptive (text-based) instructions, as compared with the other two instructions type. It also suggests a higher visual hierarchy of images over text labels because the above issue was not observed in gestures shown with a pictorial instruction. Indeed, a 83-year-old participant said that she did not realise that pictorials were accompanied with written labels on the top, “I did not see that, I was just looking at the image”, said the participant.

Two participants (aged 66 and 70) expressed that they found the animated representations of gestures to be useful but preferred text instructions because they did not want to wait for the entire animation to be complete to make a gesture. Equally, other older adults may find animations too fast due to age-related declines in cognitive processing [17][19]. Regarding the use of on-screen animations and its impact on interaction, research on age-centred web design guidelines has hinted that animated images may indeed distract older users and may place too much strain on their cognitive capabilities in web navigations [22]. Our findings, however, provide empirical evidence that animated representations of gesture commands are a suitable and well accepted method for providing on-screen instructions on gesture making for older users unfamiliar to gesture-based interactions. Furthermore, although our animated pictorials consisted of a simple 3-frame gif, it may be worth considering the impact of temporal length of animated pictorials in different interaction contexts.

In relation to the generalisability of the findings, the results of this experiment found clear support for the use of pictorial instructions over mainly text-based descriptions for gesture-based interfaces that aim to be age-friendly. Pictorial representations of mid-air gestures are visual interface elements that could better guide older users in using gesture-based interfaces, therefore minimising the chances of failed gesture attempts and increasing the overall usability of the system. Even though we aimed to focus on the often marginalised learning challenges that older users face when using novel input methods for the first time, our results may also offer an indication of how younger users unfamiliar to gesture-based interfaces could benefit from these results.

5.1 Recommendations for On-Screen Instructions in Gesture-Based Interfaces

Despite the increasing prevalence of mid-air gesture interaction across different interaction contexts (e.g. interactive displays, intelligent cars, virtual reality and gaming), standard practices for user interface design that support novice users in learning the appropriate gesture commands is still insufficient and overlooked [1, 2, 9]. As found in the present study, both static and animated pictorials accompanied with gesture labels resulted in faster and more accurate gesture making than pure text-based instructions for novice older users. Based on our findings, a primary recommendation for the design of on-screen instructions for gesture-based interfaces would be to use either animated or static pictorials as visual guidance for supporting novice users on precise and correct gesture making. Depending on the gesture set used by a specific interface, static pictorials can be applied for representing gestures that involve a static pose (e.g. pointing, stop sign, thumbs up) and animated instructions can be applied for gestures that require more complex motions and orientation as well as direct manipulation (e.g. finger rotation, pinch and pull, swipe). For example, by depicting the required trajectory, motion, and location of a specific gesture command, animated instructions can provide spatial and temporal information of those gestures in a more elucidative way than a single static image or text descriptions are likely to achieve. An immediate implication of these recommendations is the benefit of assuring that the older population will be able to learn and interact with a gesture-based interfaces with more autonomy and less mistakes, and in a similar manner, younger users with little familiarity with gestures may also benefit from these design recommendations.

6 Future Work

In this work, we were mainly interested in investigating the fundamental task of effectively instructing novice users on making correct mid-air gestures by exploring the suitability of three instruction types to an older population. Choosing age-friendly interface instructions is a feedforward mechanism that can possibly lead to less frustrated and failed gesture attempts, improving the overall success of an interaction. However, this method could be possibly enhanced in future work by also exploring age-friendly feedback mechanisms for gesture making such as providing instructions on how to adjust the user's gesturing to the gesture kinematics expected by the system, once – and if – the user makes an incorrect gesture.

7 Conclusion

We have presented an empirical study that investigated the effectiveness of different "on-screen" instruction types for demonstrating to novice older adults how to make different gesture commands in mid-air for the first time. We compared three interface design choices for presenting gesture instructions: descriptive (text-based), pictorial (static), and pictorial (animated).

All three instruction types were highly accepted by participants, but our results showed a significant advantage of pictorial instructions (static and animated) over plain text-based instructions for guiding novice older adults in making mid-air gestures with regards to accuracy, completion time and user preference. Of the three types of instructions, pictorial (animated) was the instruction type that led to the fastest gesture making with 100% accuracy across participants and may be the most suitable interface design choice to support age-friendly learnability of gesture-based interactions. Although the focus of this work was to expand the understanding of how to design age-friendly gesture-based interfaces, the design implications of our findings may also benefit a greater population and may also contribute to the learnability of new gesture commands.

Acknowledgements

We thank all the volunteers for their participation and the University of Reading's Hugh Sinclair Unit for their help with recruitment. The research is funded by the Brazilian Science Without Borders Programme, an initiative under the Ministry of Education and CAPES Foundation. Project number BEX 13037-13-7.

References

1. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15), 257-258. http://dx.doi.org/10.1145/2783446.2783599

2. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16), 122-128. https://doi.org/10.1145/2971485.2996757

3. Blake Ives. 1982. Graphical user interfaces for business information systems. *MIS Quarterly*. 6, 4: 15-47.

4. C. Egido and J. Patterson. 1988. Pictures and category labels as navigational aids for catalog browsing. In *Proceedings of the Conference on Human Factors in Computing Systems* (CHI 88). 127-132.

5. Charles J. Kacmar. 1991. An experimental comparison of text and icon menu item formats. In J. M. Carey, Ed. *Human Factors in Information Systems: An Organization Perspective*. Ablex Publishing, Norwood, New Jersey, USA, 27-41.

6. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In Proceedings of the 11th *International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78. http://dx.doi.org/10.1145/1613858.1613950

7. Daniel Avrahami, Scott E. Hudson, Thomas P. Moran, Brian D. Williams. 2001. Guided gesture support in the paper PDA. In *Proceedings of the 14th annual ACM symposium on User interface software and technology* (UIST '01), 197-198. http://dx.doi.org/10.1145/502348.502385

8. David Gittins. 1986. Icon-based human-computer interfaces. *International Journal of Man-Machine Studies*. 24, 6: 519-543. https://doi.org/10.1016/S0020-7373(86)80007-4

9. Donald A. Norman and Jakob Nielsen. 2010. Gestural interfaces: a step backward in usability. *interactions* 17, 5 (September 2010), 46-49. https://doi.org/10.1145/1836216.1836228

10. Douglas Frye and Elliot Soloway. 1986. Interface design: a neglected issue in educational software. In *Proceedings of the SIGCHI/GI Conference on Human Factors in Computing Systems and Graphics Interface* (CHI '87), 93-97. http://dx.doi.org/10.1145/29933.30865

11. G. Kurtenbach, T. P. Moran, W. Buxton. 1994. Contextual animation of gestural commands. In *Proc. Eurographics Computer Graphics Forum*. 13, 5: 305-314.

12. G. Rohr and E. Keppel. 1984. Iconic interfaces: where to use and how to construct? In H. W. Hendrick and O. Brown, Eds. *Human Factors in Organizational Design and Management*. Elsevier, New York, 269-275.

13. Ian H. Witten and Saul Greenberg. 1985. User interfaces for office systems. In P. Zorkoczy (Ed.), *Oxford Surveys in Information Technolog*y. 2: 69-104. Oxford University Press.

14. Izak Benbasat and Peter Todd. 1993. An experimental investigation of interface design alternatives: icon vs. text and direct manipulation vs. menus. *International Journal of Man-Machine Studies*. 38, 3: 369-402. http://dx.doi.org/10.1006/imms.1993.1017

15. J. L. Arnott, Z. Khairulla, A. Dickinson, A. Syme, N. Alm, R. Eisma, P. Gregor. 2004. E-mail Interfaces for Older People. In *Proc IEEE Conference on Systems, Man & Cybernetics* (SMC 2004), 111-117.

16. John Whiteside, Sandra Jones, Paula S. Levy, Dennis Wixon. 1985. User performance with command, menu, and iconic interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '85), 185-191. http://dx.doi.org/10.1145/317456.317490

17. Kathrin Gerling, Ian Livingston, Lennart Nacke, Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 1873-1882. http://dx.doi.org/10.1145/2207676.2208324

18. Kenneth Lodding. 1983. Iconic Interfacing. *IEEE Computer Graphics and Applications*. 3, 2: 11-20. http://dx.doi.org/10.1109/MCG.1983.262982

19. Martin Mihajlov, Effie Lai-Chong Law, and Mark Springett. 2016. The Effect of Dyadic Interactions on Learning Rotate Gesture for Technology-Naïve Older Adults. In *Proceedings of the International Symposium on Interactive Technology and Ageing Populations* (ITAP '16), 99-108. https://doi.org/10.1145/2996267.2996277

20. Nicolas Griffon et al. 2014. Design and Usability Study of an Iconic User Interface to Ease Information Retrieval of Medical Guidelines. *Journal of the American Medical Informatics Association: JAMIA* 21.e2 (2014), 270–277.

21. Olivier Bau and Wendy E. Mackay. 2008. OctoPocus: a dynamic guide for learning gesture-based command sets. In *Proceedings of the 21st annual ACM symposium on User interface software and technology* (UIST '08), 37-46. https://doi.org/10.1145/1449715.1449724

22. Sri Kurniawan and Panayiotis Zaphiris. 2005. Research-derived web design guidelines for older people. In *Proceedings of the 7th international ACM SIGACCESS conference on Computers and accessibility* (ASSETS '05), 129-135. https://doi.org/10.1145/1090785.1090810

23. Susan T. Dumais and William P. Jones. 1985. A comparison of symbolic and spatial filing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '85), 127-130. http://dx.doi.org/10.1145/317456.317479

24. Wei Lu, Zheng Tong, Jinghui Chu. 2016. Dynamic Hand Gesture Recognition With Leap Motion Controller. *IEEE Signal Processing Letters*. 23, 9: 1188-1192.

25. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. *Journal of Hand Therapy*. 28, 1, 53-60.

5 *Movement Characteristics and Effects of GUI Design on How Older Adults Swipe in Mid-Air*

Publication status:

* Full chapter was peer-reviewed, revised and accepted for publication in:

Cabreira, A. T. and Hwang, F. 2018. Movement Characteristics and Effects of GUI Design on How Older Adults Swipe in Mid-Air. *In Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility* (ASSETS '18). ACM, New York, NY, USA. https://doi.org/10.1145/3234695.3241014

(*in press*)

5 Movement Characteristics and Effects of GUI Design on How Older Adults Swipe in Mid-Air

Abstract

We conducted a study with 25 older adults that aimed to investigate how older users interact with swipe-based interactions in mid-air and how menu sizes may affect swipe characteristics. Our findings suggest that currently-implemented motion-based interaction parameters may not be very well-aligned with the expectations and physical abilities of the older population. In addition, we find that GUI design can shape how older users produce a swipe gesture in mid-air, and that appropriate GUI design can lead to higher success rates for users with little familiarity with this novel input method.

1 Introduction and Background

Motion-based interaction through mid-air gestures has become increasingly popular with the advancement of motion sensors (e.g. Microsoft HoloLens, Leap Motion) and has been employed in a diverse range of applications such as interactive TV, vehicles, and public displays [9, 10, 13]. Research [4, 11] has found that older adults (aged 60 and older) may face greater challenges when interacting through mid-air gestures due to age-related decline in motor control, limited range of motion [5] and a lack of familiarity with this novel input method [6, 8, 12], however this issue is far from being tackled and fully understood. A particular challenge relates to the difficulty and inconsistency of how older adults perform the swipe gesture: a highly recurrent mid-air gesture that involves a lateral swiping motion of a finger or hand, that is mostly used for menu navigation and item selection [3, 15, 16]. To date, there are limited insights on how older users interact with mid-air gesture interaction and whether gesture-based systems take into account how older users gesture in mid-air. Consequently, the growing older population could be excluded from emerging interfaces that are employing mid-air gestures in different interaction contexts. One method yet to be explored for minimising this problem is by observing how older users intuitively swipe in mid-air in order to elicit movement data and improve sensing parameters. We report a study with 25 older adults that aimed to investigate how older users interact with swipe-based interactions in mid-air and how well the Leap Motion sensor is able to recognise those movements. Three on-screen carousel menu sizes were studied in our experimental design in order to investigate the possible effects of menu size on swipe characteristics. Our findings may contribute to the design and development of more inclusive sensing parameters and age-friendly gesture-based interfaces.

2 Experiment

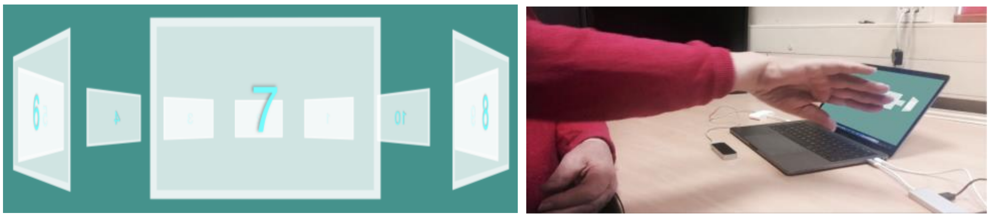
2.1 Participants

25 older adults (12 female) participated in the experiment. Participants were aged 60 to 83 (mean age: 67; SD=6.7) and had prior computer experience and some familiarity with touchscreen interaction. Little to no prior experience with motion sensing devices and mid-air gesture interaction was reported. Before the start of the experiment, participants had their manual dexterity and motor skills assessed using a Rolyan 9-Hole Peg Toolkit [17], which confirmed that all participants were within the norms for their age group.

2.2 Procedure and Apparatus

Participants were first introduced to the Leap Motion sensor. They were then asked to complete a task that involved navigating through a 10-item carousel menu by swiping their hand left and right in mid-air (Figure 1). This task was repeated for three different carousel sizes which were - in pixels - 2130x560 (large), 1800x480 (medium), and 1390x330 (small). Participants were encouraged to swipe intuitively and were not given specific demonstrations on how to gesture. The carousel moved to the next item independently from how participants swiped, in order to encourage participants to swipe in a manner that was natural to them without trying to conform to a gesture recogniser. Movement data was being automatically logged for later analysis. The order of presentation of menu sizes was counterbalanced across participants. The session was video recorded. The carousel was developed using javascript [1] and movement data was collected using the Leap Motion sensor [16]. Participants interacted in a sitting position with a Leap Motion sensor connected to a 13-inch MacBook with built-in retina display at 2560x1600 pixels resolution (227 ppi).

Figure 1. Carousel navigation and experimental set-up.



3 Results

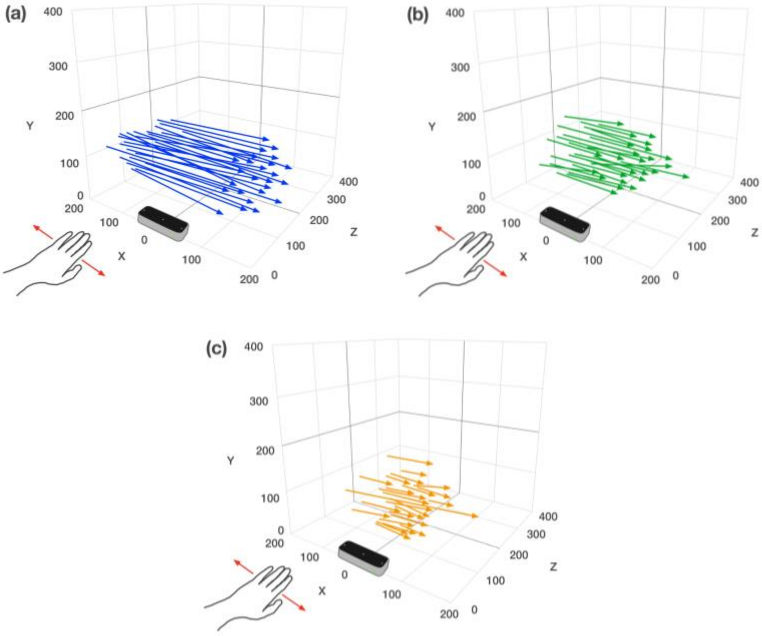
Table 1 shows average swipe characteristics for each carousel menu size. 395 out of 750 swipe trials (52.7%) were successfully recognised by the Leap Motion sensor.

Table 1. Movement characteristics of the swipe gesture made in mid-air by older adults for three carousel menu sizes.

Carousel menu size (pixels)	Swipe recognition rate	Average swipe length (mm)	Average swipe speed (mm/s)
Large 2130 x 560	90%	210.9 (SD=35.8)	889.1 (SD=57.8)
Medium 1800 x 480	50%	134.1 (SD=50.4)	482.7 (SD=61.5)
Small 1390 x 330	18%	97.8 (SD=80.2)	291.5 (SD =113.8)

Two participants chose to swipe using the index finger, whilst the other 23 participants swiped using the entire hand. Figure 2 shows, for each participant, the average starting and ending positions for their swipes, relative to the sensor for each menu size. A repeated measures ANOVA showed a significant main effect of carousel menu size on how older adults swipe in mid-air [F(2, 392) = 56.5; p =.0002]. A Tukey HSD post-hoc analysis found that carousel menu size had an effect on all dependent variables (swipe recognition rate, length, and speed). That is, the swiping motion was significantly longer (p=.0015), faster (p=.01), and better recognised (p=.01) when older adults were navigating through the larger carousel menu. In the same way, length, speed and recognition rates significantly decreased when interacting with the medium and small carousel menus respectively.

Figure 2. Swipe start and end positions (left to right) in mid-air for (a) large, (b) medium, and (c) small on-screen carousel-style menus. Arrows represent an average of 10 swipes per participant. Units are in mm within the Leap Motion's coordinate frame.



4 Discussion and Conclusion

The Leap Motion default parameters for a swipe gesture include a minimum swipe speed of 1000 mm/s and a minimum swipe length of 150 mm [15]. However, the results from the current study suggest that those parameters may not be age-friendly and may not have taken into consideration the psychomotor aspects of how older adults naturally swipe in mid-air. This mismatch between how older adults naturally swipe and how the system expects them to do it is likely to lead to a number of failed interaction attempts (see recognition rates in Table 1) and may affect the overall usability and accessibility of gesture-based interfaces Furthermore, we also found that carousel menu size affected how older adults produced a mid-air swipe gesture to a point where it was almost unrecognisable by the sensor. The large carousel menu (2130x560 pixels) was the menu with highest recognition rate (90%), whilst the smallest menu size (1390x330 pixels) achieved only 18% due to swipe lengths and speeds so low that the sensor was incapable of interpreting the motions as a recognised swipe. Our findings emphasise the role of GUI design in gesture-based systems, and how user interface choices can not only shape how older users produce a gesture in mid-air but also lead to higher success rates for users with little familiarity with this novel input method. Our findings suggest that currently-implemented motion-based interaction parameters may not be necessarily aligned with the expectations and physical abilities of the older population and we expect that our work will contribute to the implementation of gesturing parameters that take older users into account, leading to a higher success rate and greater accessibility for gesture-based interfaces.

Acknowledgements

We thank all the volunteers for their participation and the University of Reading's Hugh Sinclair Unit for their help with recruitment. The research is funded by the Brazilian Science Without Borders Programme, an initiative under the Ministry of Education and CAPES Foundation. Project number BEX 13037-13-7.

References

1. 3D Carousel Using TweenMax.js & jQuery. Available at: https://codepen.io/johnblazek/pen/nceyw
2. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266. https://doi.org/10.1007/s10209-010-0208-6

3. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15), 257-258. http://dx.doi.org/10.1145/2783446.2783599
4. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16), 122-128. https://doi.org/10.1145/2971485.2996757
5. Caroline J. Ketcham and George E. Stelmach. 2001. Age-Related Declines in Motor Control. In Birren, J. E. & Schaie, K.W. (Eds.), *Handbook of the Psychology of Aging*. Academic Press.
6. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78. http://dx.doi.org/10.1145/1613858.1613950
7. Darren Guinness, G. Michael Poor, and Alvin Jude. 2014. Gestures with speech for hand-impaired persons. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility* (ASSETS '14). ACM, New York, NY, USA, 259-260. http://dx.doi.org/10.1145/2661334.2661398
8. Donald A. Norman and Jakob Nielsen. 2010. Gestural interfaces: a step backward in usability. *interactions* 17, 5 (September 2010), 46-49. https://doi.org/10.1145/1836216.1836228
9. Gözel Shakeri, John H. Williamson, and Stephen Brewster. 2017. Novel Multimodal Feedback Techniques for In-Car Mid-Air Gesture Interaction. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (AutomotiveUI '17). ACM, New York, NY, USA, 84-93. https://doi.org/10.1145/3122986.3123011
10. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. https://doi.org/10.1145/2325616.2325625

11. Kathrin Gerling, Ian Livingston, Lennart Nacke, Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 1873-1882. http://dx.doi.org/10.1145/2207676.2208324

12. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346. DOI: https://doi.org/10.1145/2470654.2470703

13. Robert Walter, Gilles Bailly, Nina Valkanova, and Jörg Müller. 2014. Cuenesics: using mid-air gestures to select items on interactive public displays. In *Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services* (MobileHCI '14). ACM, New York, NY, USA, 299-308. https://doi.org/10.1145/2628363.2628368

14. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.

15. Swipe Gesture – Leap Motion Documentation. Available at: https://developer-archive.leapmotion.com/documentation/v2/python/api/Leap.SwipeGesture.html?proglang=python

16. Wei Lu, Zheng Tong, Jinghui Chu. 2016. Dynamic Hand Gesture Recognition With Leap Motion Controller. *IEEE Signal Processing Letters*. 23, 9: 1188-1192.

17. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. *Journal of Hand Therapy*. 28, 1, 53-60.

6 *Evaluating the Effects of Feedback Type on Older Adults' Performance in Mid-Air Pointing and Target Selection*

Publication status:

* Full chapter was peer-reviewed, revised and accepted for publication in:

Cabreira, A. T. and Hwang, F. 2018. Evaluating the Effects of Feedback Type on Older Adults' Performance in Mid-Air Pointing and Target Selection. *In Proceedings of the 6th ACM Symposium on Spatial User Interaction* (ACM SUI 2018). ACM, New York, NY, USA. https://doi.org/10.1145/3267782.3267933

(*in press*)

6 Evaluating the Effects of Feedback Type on Older Adults' Performance in Mid-Air Pointing and Target Selection

Abstract

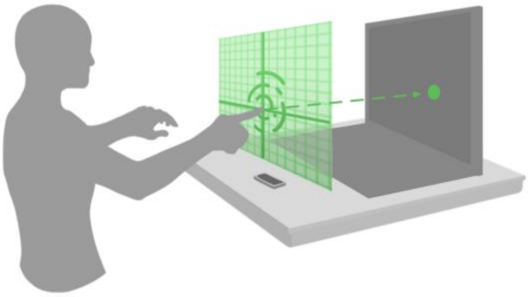
"Hands-free" pointing techniques used in mid-air gesture interaction require precise motor control and dexterity. Although being applied in a growing number of interaction contexts over the past few years, this input method can be challenging for older users (60+ years old) who experience natural decline in pointing abilities due to natural ageing process. We report the findings of a target acquisition experiment in which older adults had to perform "point-and-select" gestures in mid-air. The experiment investigated the effect of 6 feedback conditions on pointing and selection performance of older users. Our findings suggest that the bimodal combination of Visual and Audio feedback lead to faster target selection times for older adults, but did not lead to making less errors. Furthermore, target location on screen was found to play a more important role in both selection time and accuracy of point-and-select tasks than feedback type.

1 Introduction

Mid-air gesture interaction has been applied in a diverse range of interface applications over the past few years, mostly as a result of the growing number of currently existing motion sensing devices available to the general public such as the

Microsoft Kinect, Leap Motion controller, Myo Armband, and the Microsoft Hololens. Despite the variety of gestures supported by those sensor-based devices, point-based interaction is currently the overall most used input technique in mid-air across platforms [6]. That is, users need to move their fingers or hands in mid-air (as a pointer) in order to select interface elements whilst sensors track their physical movements and translate into 2D or 3D coordinates on screen (Figure 1). Tracking accuracy varies across devices but the point-to-select interaction paradigm remains the same. For instance, the Microsoft Kinect tracks hand movements as a single pointer [35] whilst the Leap Motion controller is able to track not only the hand trajectory but also individual fingers [36].

Figure 1 Point-to-select interaction paradigm example.



As mid-air gesture interaction becomes more present in different interaction contexts and this “hands-free” point-based input technique reaches a greater population, the need of assessing its suitability to a broad range of users is still needed. Successful use of pointing techniques requires precise motor control and dexterity [8, 17]. Using point-to-select input techniques can be a challenge and become a burden for users that experience temporary, sporadic or gradual changes in pointing abilities due to ageing, physical impairments, or other situational conditions [5].

The number of older adults (aged 60 and older) has tripled since the year of 1950 and it is estimated that the older population will reach over two billion worldwide by the year of 2050 [3, 30]. However, little research has looked into older adults' needs and expectations for mid-air interaction and point-to-select input techniques. Older adults are known to experience age-related decline in motor, cognitive and sensory abilities that can affect their daily tasks, including the way they interact with technology [3, 8, 24]. Older adults experience natural changes in motor dexterity and muscular strength that may affect pointing abilities due to loss of hand mobility and decreased range of motion [18, 30]. If these physical limitations are not anticipated by the system design, then older users may come across failed interaction attempts, leading to frustrating interaction experiences and further hindrances to technology use.

It is already known that older adults often struggle with traditional mouse-based "point-and-click" input techniques, with common problems including - but not limited to - the need of cursor relocation, double-clicking, accidental target slip-offs, and click-to-drag tasks [3]. In order to avoid transferring these issues to the mid-air medium, interfaces that make use of point-to-select input techniques should provide additional support for users that experience changes in pointing abilities. However, researchers have yet to identify effective and accessible methods for doing so.

Because mid-air pointing techniques often offer limited to no natural haptic feedback and usually rely solely on unimodal visual feedback through hand-GUI coordination [29], it is pertinent to question if multimodal feedback could support and even improve older adults' "point-and-select" abilities in mid-air. Prior research has suggested possible benefits of providing multimodal feedback for older users in mouse-based “drag-and-drop” tasks [23], touchscreen mobile interaction [22], and gaming [24, 35], but given the “hands-free” and touchless nature of mid-air interaction, the effects of multimodal feedback on older adults’ pointing and selection performance in mid-air are still not widely understood.

As “hands-free” interaction starts to appear in a growing number of interaction contexts (motion-based games, smart homes, intelligent car interfaces, virtual and augmented reality, interactive walls and more), it is essential to understand if this novel input method is aligned with the abilities and needs of the growing older population and further explore possibilities for supporting usable and accessible interactions. Therefore, we report the findings of a target acquisition experiment in which older adults had to perform “point-and-select” gestures in mid-air whilst different feedback types were being provided. We compared performance and subjective workload ratings of 6 feedback conditions: visual only, audio only, haptic only, visual-and-audio, visual-and-haptic, and audio-and-haptic. Our results contribute to a better understanding of how feedback modality may improve the usability and accessibility of mid-air gesture interaction for older adults with diverse abilities.

2 Related Work

2.1 Age-related Changes in Pointing Abilities

The natural course of ageing leads to gradual decline in sensory, cognitive and motor functions [8, 30]. These natural changes affect how older adults engage with all aspects of daily activities, including computer-mediated tasks [8, 24]. For instance, research has been conducted to better understand the role of age-related changes in mouse aptitude [3], web browsing [34], and touchscreen performance [11, 25]. It was also observed in older adults a decreased ability of controlling movement amplitudes and scale velocity that contributed to slower, more variable movements within target acquisition tasks [9]. However, older adults' pointing performance in mid-air – including means of supporting it - is a topic yet to be fully addressed and understood. Recent research on how older adults use freehand gestures for TV menu control [20] and computer tasks [7] found empirical evidence that older adults – unlike younger users - indeed struggle at "point-and-select" tasks in mid-air, however this issue was not deeply explored in those studies and the question about how can we design age-friendly mid-air interactions that support pointing and selection abilities of older users is still unanswered.

There are many ageing factors that compromise the pointing abilities of older users. Muscle strength begins to gradually decline from the age of 50 [18], leading to easy fatiguing, decrease in motor control, limited range of motion and slower reaction times [8, 24]. As a matter of comparison, an older adult at the age of 90 is expected to have a range of motion that is only 60% of the range of motion of an average 30 years old individual [8, 18]. Furthermore, continuous use of hand and arm movements for pointing in mid-air, without proper and frequent relaxation of the arms, can lead older users to physical tiredness and may largely impact accuracy and steadiness of movements, performance consistency, and user experience throughout the interaction [7, 24, 33]. Age-related health conditions such as Arthritis and Parkinson's disease may also create further impediments for older individuals [8, 24, 30].

Gradual decline in sensory and cognitive functions may also affect the pointing abilities of older users in mid-air. Reduced visual perception is a main contributing factor on how older users perceive and interact with different interfaces, specifically touchless interfaces, since most interaction methods rely heavily on visual feedback [6, 11]. Older adults may face greater difficulties at following cursor movements, locating targets on screen, and perceiving GUI changes due to limited visual acuity, which can also affect reaction times once they make a gesture [18, 20, 30]. Aged hearing function and reduced sensitivity to sound [18] can also affect the effectiveness of sound cues and audio feedback in cases where these are provided. Despite limited haptics in mid-air, reduced tactile sensitivity and acuity may also contribute to poorer "point-and-select" performance. The skin of older individuals become less sensitive to pressure after the age of 50 and there is a reduced ability to perceive vibrations and recognise different shapes and textures by touch [18, 30]. Besides tactile sensitivity, tactile spatial acuity is also affected and may affect tasks requiring orientation and hand dexterity [11, 18]. Reduced touch and tactile perception need to be taken into account when choosing GUI arrangements and pressure points for interface elements as well as haptic feedback for mid-air interactions [11]. Natural age-related decline in cognitive functions may also be involved in greater efforts for motor learning and motor recall which can jeopardise motor-based interaction in mid-air [8, 18, 24].

2.2 Uni-and-Multimodal Feedback in Mid-air

2.2.1 Visual feedback. To date, most gesture-based interfaces rely heavily – and sometimes exclusively – on visual feedback [14]. Visual feedback provides useful support and most users will expect some form of visual information to rely on. For instance, user interfaces based on pointing gestures may provide continuous visual feedback about hand position [1, 10] as well as indicate the outcomes of gesture commands on screen [7]. However, unimodal visual feedback can bring some fundamental issues: virtual elements and transitions can be easily occluded by the hand during the course of the interaction [29], feedback may become imperceptible on small screens or at a distance (for large gesture-based interactive walls) [2], and may be inaccessible for users with visual impairments [19]. Age-related decline in visual processing and acuity may also be a contributing obstacle for older users interacting with gesture-based interfaces that exclusively rely on visual feedback [7, 18].

2.2.2 Audio feedback. Although not as widely used as visual feedback, audio feedback is mostly used to support visual feedback and indicate whether gesturing in mid-air has been successful [32]. Literature regarding the exploration and effectiveness of audio feedback for gesturing in mid-air is rather limited. In [31], users receive audio feedback after selecting items by tapping on the palm of their hand, while BoomRoom [21] uses real objects to augment audio feedback for emitting sounds after the user gestures in mid-air. Despite the usefulness of providing audio feedback after the user's input, [14] argue that functional feedback gives no insight into how users are being sensed. Indeed, research has suggested that providing feedback for indicating whether the user's hand is being sensed and whether they are gesturing in the right place can be of great use for older users and should be explored in more depth [7, 15].

2.2.3 Haptic feedback. Interaction in mid-air provides limited to no haptic feedback due to its touchless nature. Haptic feedback has been implemented on an experimental level using two methods: through contact-based vibrotactile stimulation [4, 14] and through non-contact force [32]. Although the benefits of providing haptic feedback in mouse-based target acquisition tasks [2, 28] have been suggested in prior research, the benefits of implementing haptic feedback in mid-air are still not well known. It is also unclear if the inclusion of haptic feedback may improve the performance of older adults in pointing and selection tasks.

2.2.4 Multimodal feedback. Research has indicated that multimodal feedback improved older adult's performance in completing drag-and-drop tasks on a computer [23] and during touchscreen interaction [22]. Providing multimodal feedback in mid-air may be useful in supporting older users who experience different levels of visual, auditory or tactile processing decline. However, research on the effects of different multimodal feedback combinations has not been widely explored yet.

2.3 Empirical Studies on Pointing in Mid-air

Haque et al. [16] described *Myopoint*, a barehand pointing and clicking technique using forearm mounted electromyography and inertial motion sensors. *Myopoint*'s accuracy and speed were evaluated with young adults using Vogel and Balakrishnan's [13] experiment design that consisted of freehand pointing and clicking tasks on a large display. Winkler et al. [12] investigated the effectiveness of mid-air pointing interaction on projector phones with 12 young adults. Their findings suggested that interaction techniques that integrate touch and mid-air pointing may enrich projector experiences.

Nancel et al. [26, 27] explored mid-air pointing on ultra-walls (wall-sized displays). Novel pointing techniques were designed based on the theoretically assumption that high precision pointing on ultra-walls. All the empirical studies described above contributed to some aspect of advancing mid-air pointing techniques. However, studies involving older users (60+ years old) are still necessary in order to understand if pointing techniques are aligned with the physical abilities of the older population. Older users may be excluded from technology advancements in the field if their physical abilities and preferences are not taken into account. Furthermore, the role of feedback on the performance of mid-air pointing techniques and target selection has not been largely explored yet and might contribute to the usability of pointing interactions for the older population.

3 Experiment

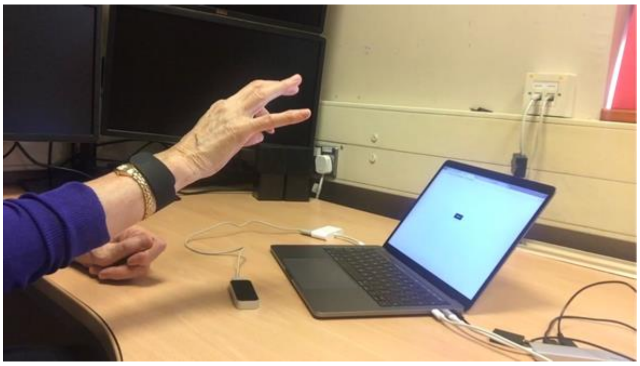
3.1 Participants

25 older adults (12 female) participated in the experiment. Participants were aged 60 to 83 (mean age: 67; SD=6.7) with normal-to-corrected vision and had prior computer experience with some familiarity with touchscreen interaction. Little to no experience with motion sensing devices and mid-air pointing interaction was reported. Before the start of the experiment, participants had their manual dexterity and motor skills assessed using a Rolyan 9-Hole Peg Toolkit [37], which confirmed that all participants were within the norms for their age group. Two participants were left-handed. The study has been reviewed by the University of Reading's Research Ethics Committee and has been given a favourable ethical opinion for conduct.

3.2 Task

After being introduced to the Leap Motion sensor, participants were made aware that they were able to control the cursor on-screen by moving their hand in mid-air. After understanding the interaction, participants were told they were able to select the target shown on screen by making a pinch gesture once they located the target with the cursor on it (Figure 2). Then, participants were given a practice session of 10 trials and were asked to select the following targets as fast as possible whilst visual feedback was being provided. The practice session served to make participants familiar to the Leap Motion's spatial field of interaction and gesturing in mid-air as well as minimising learning effects for the following sessions.

Figure 2. Participant pointing in mid-air and selecting an on-screen target by making a pinch gesture while receiving haptic feedback through a wearable wristband.



After completing the practice session, participants were asked to complete a target acquisition task consisting of 21 targets shown randomly on screen. The first target was not included in the analysis because it usually involved repositioning of the hand and finding a comfortable posture. Participants were asked to locate the target by pointing and select it by making a pinch gesture as fast as possible, while being given feedback. Participants repeated the task for 6 feedback types, 3 were unimodal feedback (*Visual* or *Audio* or *Haptic*) and 3 were multimodal feedback (*Visual-and-Audio*, *Visual-and-Haptic* or *Audio-and-Haptic*). The order was counterbalanced across participants to minimise fatigue and learning effects. After each round, participants were asked to complete a NASA TLX (Task Load Index) questionnaire about the subjective workload of each feedback type.

3.3 Apparatus

Participants interacted in a sitting position with a Leap Motion sensor connected to a 13-inch MacBook with built-in retina display at 2560x1600 pixels resolution (227 ppi) as shown in Figure 2.

3.4 Targets

Target size was 115 pixels for width and 50 pixels for height. Target location was defined randomly and shown to participants within the on-screen thresholds in Table 1. Target distances were counterbalanced across trials and Index of Difficulty (ID) ranged between 1 and 1.7 for all possible target position combinations in the study [28].

Table 1: Random possible target positions (in pixels). Zero is top left of the screen.

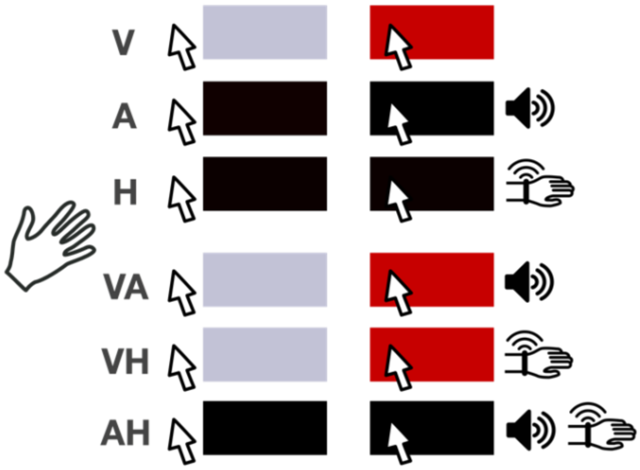
x-axis	y-axis
50	70
600	1200
500	50
100	1100
300	650
680	40
50	1200
200	200
660	1200

3.5 Feedback Design

Feedback was designed to help older adults in point-and-select tasks in mid-air (Figure 3). Feedback was provided when users located a target on-screen and also for as long as users kept the cursor within the target area. After locating the target (first step: point), users were only able to select the target by making a pinch gesture while still hovering it (second step: select). Users were able to see the cursor location on all 6 feedback types. The feedback conditions used in our experiment are explained below:

- **Visual Feedback (V)**: An on-screen target change in colour and contrast is provided when the user locates a target. From grey (hexadecimal #C2C2D6) to red (#C70000).
- **Audio Feedback (A)**: A continuous tone cue of 44100 Hz (32-bit) is provided when the users locates a target.
- **Haptic Feedback (H)**: On-skin vibrotactile feedback is provided through a wearable wristband. The wristband is built with a micro *bluetooth* subwoofer that provides continuous vibrations at 55Hz when users locate a target. The development of the haptic engine was informed by [14] and [4].
- **Visual-and-Audio Feedback (VA)**: A combination of Visual only and Audio only feedback at the same time.
- **Visual-and-Haptic Feedback (VH)**: A combination of Visual only and Haptic only feedback at the same time.
- **Audio-and-Haptic Feedback (AH)**: A combination of Audio only and Haptic only feedback at the same time.

Figure 3: Target selection and feedback type scheme.



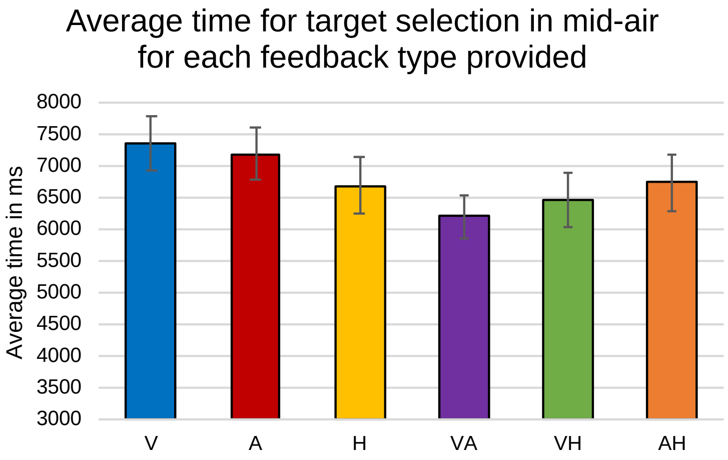
4 Results

3000 trials (20 targets x 6 feedback conditions x 25 participants) were analysed in the experiment. This session report our findings.

4.1 Target Selection Time

Figure 4 shows the average time taken to select a target for each feedback type in mid-air. Target selection time presented great variability across trials, with targets being selected as fast as 1 second and as slow as 1 minute due to multiple target mis-selections and slip-offs. Participants receiving different feedback types achieved average target selection times between 6.2 seconds (*Visual-and-Audio* feedback) and 7.4 seconds (*Visual* feedback only). The average selection time across participants – regardless of feedback type – was 6.8 seconds per target. A repeated-measures ANOVA on time to select targets for 6 feedback types showed a significant main effect for feedback type on selection time [F(5, 2994)=2.25, p=0.03]. Post-hoc pairwise Tukey HSD tests showed that the time taken to select targets on multimodal *Visual-and-Audio* feedback (6.2 seconds) was significantly lower than the time taken on unimodal *Visual* feedback (7.4 seconds, p=0.02) and *Audio* feedback (7.2 seconds, p = 0.03). No significant differences were found for the remaining feedback types (p > 0.05).

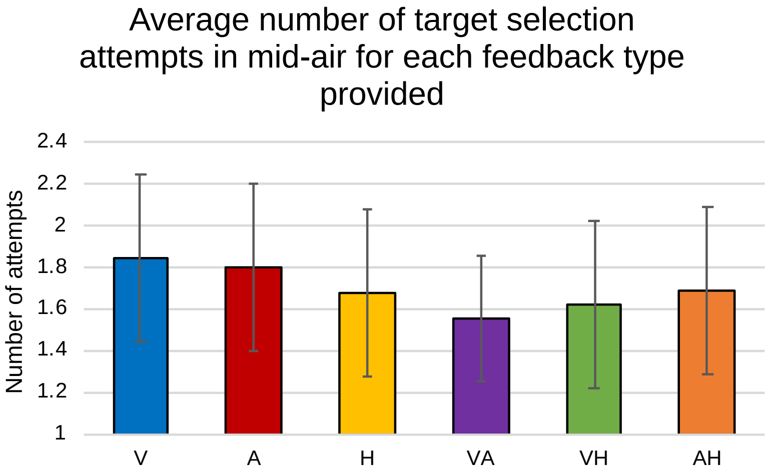
Figure 4: Average time (ms) for selecting on-screen targets (n=20) by making a pinch gesture in mid-air. Error bars represent S.E.



4.2 Accuracy

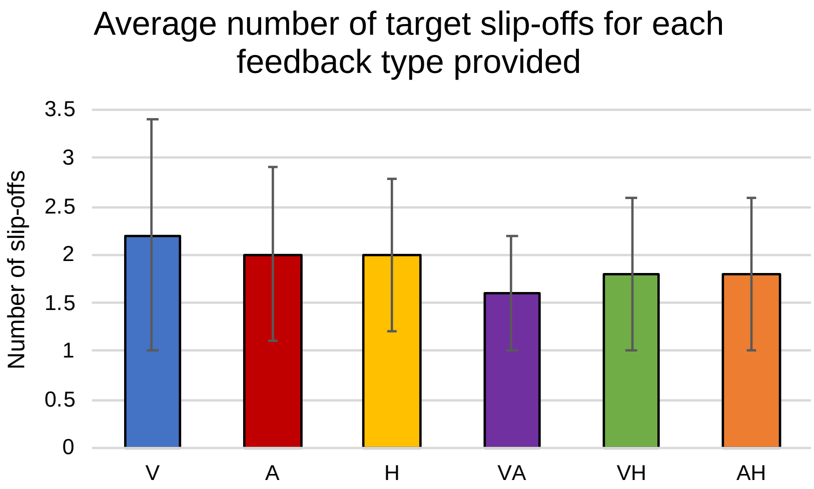
Participants achieved a successful target selection after 1.7 gesture attempts on average (i.e. how many times they had to make a pinch gesture to select a specific target). Average number of target selection attempts ranged between 1.5 attempts on *Visual-and-Audio* feedback (VA) and 1.84 attempts on *Visual* feedback only (V) (Figure 5). A repeated-measures ANOVA was performed on the number of gesture attempts for target selection and feedback type, however no significant differences were found across all 6 feedback types [F(5,5094=2.21, p=0.39).

Figure 5: **Average number of gesture attempts participants had to make to select a target successfully. Error bars represent S.E.**



Although not presenting great issues at cursor relocation from one target to another, older adults presented substantial difficulties at keeping the cursor within the target once they located it. Lack of hand steadiness lead to multiple unintended target slip-offs and mis-selections, especially when participants attempted to make the pinch gesture to select the target (Figure 6). A great variability was observed across participants, but the average number was 1.9 slip-offs per target (i.e. how many times they exited the target without successfully selecting it). A repeated-measures ANOVA was performed on the number of target slip-offs and feedback type, however no significant differences were found across all 6 feedback types ($p > 0.05$).

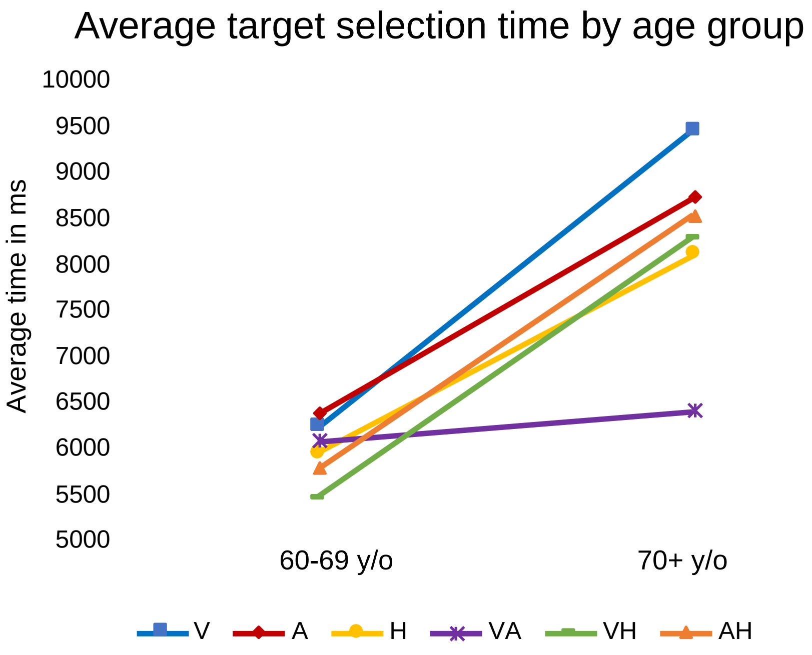
Figure 6: **Average number of target slip-offs for each feedback type provided. Error bars represent S.E.**



4.3 Effects of Age

A two-way repeated-measures ANOVA was performed on the average selection time, comparing the effects of age group (60-69 and 70+) and all 6 feedback types [F(5, 2994)=3.34, p=0.039]. Post-hoc pairwise Tukey HSD tests found no significant differences in average selection times among all feedback types provided in the first age group (60-69) [5.5 to 6.3 seconds, p > 0.05]. However, significant differences were found between the average selection time on bimodal *Visual-and-Audio* feedback (VA) and the remaining 5 feedback types in the older group (70+). That is, selection time on all 6 feedback types were not significantly different for participants in the 60-69 group, but selection time on *Visual-and-Audio* feedback (VA) was significantly faster (6.4 seconds) than on other feedback types (8.1 to 9.4 seconds) for participants in the 70+ group (p = 0.003), as shown in Figure 7.

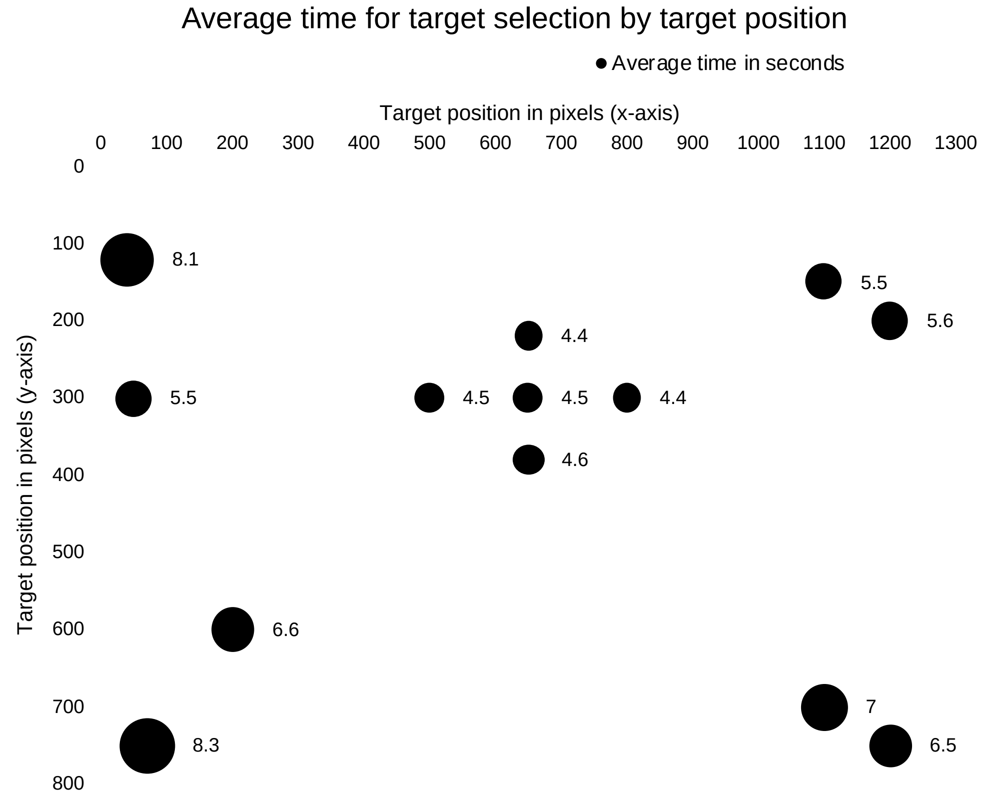
Figure 7: **Average target selection time (ms) by age group for each feedback type.**



4.4 Effects of Target Location

Selection times were isolated by location on-screen as shown in Figure 8. Average times were affected by location, number of target slip-offs and mis-selections but most importantly the number of times participants had to repeat the selection gesture once they located the target. Distance travelled between targets showed no significant effect on time.

Figure 8: **Average target selection time (ms) by target position on-screen (in pixels).**



4.5 Subjective Workload

The results of the NASA TLX (Task Load Index) questionnaires are shown in Table 2. Scores ranged from 1 (lowest) to 20 (highest). *Visual-and-Audio* feedback (VA) showed the lowest overall task load index of 9.5, whereas the other 5 feedback conditions achieved higher scores of 10 and above. An one-way ANOVA was performed on overall task load index scores for all 6 feedback types, however no significant differences were found between all 6 conditions [F(5,894)=1.25, p=0.28)].

Further investigation using a two-way ANOVA on the effects of age (60-69 y/o and 70+ y/o) on subjective task workload for all 6 feedback conditions found a significant difference between age groups (p=0.028). Post-hoc pairwise Tukey HSD tests found no significant differences among overall TLX scores of all 6 feedback conditions in the 60-69 y/o group, however a significant difference was found between the average TLX score for bimodal *Visual-and-Audio* feedback (VA) and the other feedback conditions in the 70+ y/o group (p=0.02). Similar to the results of section 4.3, participants aged 70+ found the target acquisition task under bimodal *Visual-and-Audio* feedback (VA) to have a lower subjective workload (overall TLX score of 8.1) in comparison with other feedback conditions (overall TLX scores between 9.2 and 10).

Table 2: Average scores (1 to 20) from NASA TLX questionnaires for each feedback condition.

	V	**A**	**H**	**VA**	**VH**	**AH**
Mental demand	10	9.7	10.2	8.9	9.9	9.4
Physical demand	10.3	10	9.7	9	10.1	9.6
Temporal demand	10.7	9	9	8.3	8.8	8.5
Performance	12	11.6	11.2	10.9	10.7	11.3
Effort	11.3	12.4	12	10.1	10.8	10.4
Frustration	11	10.8	11.4	9.8	11.4	11
Overall TLX	**10.9**	**10.6**	**10.6**	**9.5**	**10.3**	**10**

Table 2 headings:

V: *Visual feedback only* / **A**: *Audio feedback only* / **H**: *Haptic feedback only* / **VA**: *Visual-and-Audio feedback* / **VH**: *Visual-and-Haptic feedback* / **AH**: *Audio-and-Haptic feedback*

5 Discussion

5.1 Effects of feedback type on pointing tasks

Our findings indicate that the combination of *Visual* and *Audio* feedback (VA) lead to faster target selection in comparison with providing only visual or only audio feedback. *Visual-and-Audio* feedback, however, did not lead to a lower number of gesturing and selection mistakes in mid-air. Multimodal *Visual-and-Audio feedback* also achieved a lower subjective workload score in comparison with unimodal feedback types. Despite of older adults taking less time for selecting targets on multimodal *Visual-and-Audio* feedback, we were not able to find significant differences between the other 5 feedback types.

Furthermore, the inclusion of haptic feedback in mid-air did not improve older adults' pointing and gesturing performance in our experiment. It is still unclear, however, if feedback type (uni or multimodal) may improve task completion time or error rates for older users in different contexts of mid-air interaction. Research indicated that level of experience [23] and type of task [4] may play a role in the usefulness of different feedback modalities.

User preference varied among participants, unimodal *Audio* feedback seemed to be preferred over unimodal *Visual* feedback. Many participants, including a 73-years-old noted that with audio feedback *"I could find the target even with my eyes closed, it feels easier"*. Unimodal *Visual* feedback, however, received complaints when the participant's hand would occlude their view of the target in a way participants had to frequently change their posture to solve the problem. Furthermore, some participants found the "buzzing" coming from the wristband that provided *Haptic* feedback to be too disturbing, while others said they were indifferent about the vibration.

In relation to ageing, some older users may present a higher decline in vision processing, whereas others may present higher declines in auditory or tactile processing, therefore multimodal feedback should be given preference over unimodal feedback in order to minimise the effects of ageing in mid-air pointing tasks.

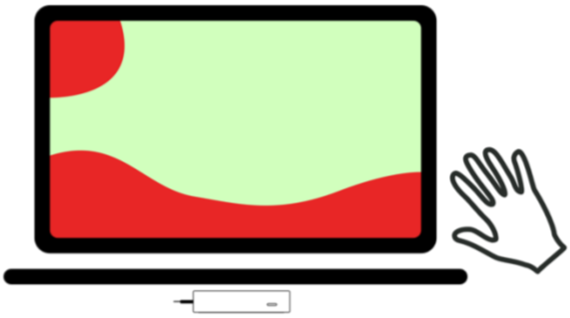
5.2 Age

Age affected time for selecting targets regardless of feedback type provided. Older adults with ages between 60-69 (n=13) selected targets in 6 seconds on average, while older adults aged 70+ (n=7) needed 8.2 seconds on average to make a successful target selection. Decreased movement control and pointing steadiness as well as more frequent target slip-offs were observed in the older group. Upper arm fatigue was also noted by some participants regardless of their age, and this issue reflected on the subjective workload responses (NASA TLX) as participants judged that pointing in mid-air required high physical demand (average score of 12.3 out of 20, across all feedback types). Issues with the Leap Motion not being able to recognise the pinch gesture for selecting targets was also judged by older adults as “more frustrating” than pointing and locating a target. Our findings indicated that minimising the need of constant or repetitive gesturing plays a more important role for the usability of pointing interfaces than the feedback type provided. Therefore, we suggest that future work could possibly explore more efficient and age-friendly “selection gesture” options for point-and-select tasks.

5.3 Target Location

On-screen target location affected both the selection time and accuracy of target selection by older adults (Figure 8). Targets located on the bottom (left and right) and top left of the screen were highly problematic, leading to more slip-offs and mis-selections than targets located in other coordinates. This issue was possibly due to older adults leaving the Leap Motion sensor's field of view when trying to select those targets (i.e. placing their hand too high or too forward). Instead of moving their hand left-and-right and up-and-down just above the sensor, older adults would try to reach the screen and place their hand forward to a point where the hand would leave the Leap Motion's field of view. Participants expressed frustration when trying to reach those targets unsuccessfully. A 80-years-old participant said *"my shoulder started to get uncomfortable trying to reach that target on the bottom left, it did not seem to like me"*. Targets located on the central area and top right of the screen, however, did not present as many issues as the top left and bottom areas. Effects of hand laterality were also not observed. Therefore, based on older users' behavior and sensor capabilities, we suggest that targets should be placed within central area or top right of the screen to ensure that mid-air point-and-select input methods are age-friendly. Screen areas in red (Figure 9) should be avoided.

Figure 9: Representation of on-screen areas to avoid placing targets for point-and-select tasks in mid-air (in dark red), whereas areas in bright green should be chosen for age-friendly interfaces.



6 Conclusion

In this work, we report the findings of a target acquisition experiment that investigated the effects of different 6 feedback conditions on how older adults performed point-and-select tasks in mid-air. Combined bimodal *Visual-and-Audio* feedback lead to faster target selection (6.2 seconds on average) in comparison to unimodal *Visual* or *Audio* feedback (7.4 and 7.2 seconds respectively). Mid-air point-and-select tasks on bimodal *Visual-and-Audio* feedback also achieved a lower subjective workload among participants aged 70 and older. Effects of other feedback combinations on target selection time were not significant. Accuracy of pointing and selection gestures were not affected by feedback modality. Furthermore, target location on screen showed to be a more decisive factor for older adults' pointing and selection performance in mid-air than feedback modality. Our findings contribute to the advancement of mid-air pointing techniques and to a better understanding of how feedback modality may improve the usability and accessibility of mid-air gesture interaction for older users who experience changes in pointing abilities.

Acknowledgements

We thank all the volunteers for their participation and the University of Reading's Hugh Sinclair Unit for their help with recruitment. The research is funded by the Brazilian Science Without Borders Programme, an initiative under the Ministry of Education and CAPES Foundation. Project number BEX 13037-13-7.

References

1. Alex Butler, Shahram Izadi, and Steve Hodges. 2008. SideSight: multi-"touch" interaction around small devices. In *Proceedings of the 21st annual ACM symposium on User interface software and technology* (UIST '08). ACM, New York, NY, USA, 201-204. DOI: https://doi.org/10.1145/1449715.1449746

2. Andy Cockburn and Stephen Brewster. 2005. Multimodal feedback for the acquisition of small targets. *Ergonomics*. 48, 9, 1129-1150.

3. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266. DOI: https://doi.org/10.1007/s10209-010-0208-6

4. Anne Köpsel, Päivi Majaranta, Poika Isokoski, Anke Huckauf. 2016. Effects of auditory, haptic and visual feedback on performing gestures by gaze or by hand. *Behaviour & Information Technology*. 35, 12: 1044-1062.

5. Aqueasha Martin-Hammond, Foad Hamidi, Tejas Bhalerao, Abdullah Ali, Catherine Hornback, Casey Means, and Amy Hurst. 2017. The Participatory Design of an Adaptive Interface to Support Users with Changing Pointing Ability. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility* (ASSETS '17). ACM, New York, NY, USA, 343-344. DOI: https://doi.org/10.1145/3132525.3134810

6. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258. DOI: http://dx.doi.org/10.1145/2783446.2783599

7. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA. DOI: https://doi.org/10.1145/2971485.2996757

8. Caroline J. Ketcham and George E. Stelmach. 2001. Age-Related Declines in Motor Control. In Birren, J.E. & Schaie, K.W. (Eds.), *Handbook of the Psychology of Aging*. Academic Press.

9. Caroline J. Ketcham, Rachael D. Seidler, Arend W.A. Van Gemmert, and George E. Stelmach. 2002. Age-Related Kinematic Differences as Influenced by Task Difficulty, Target Size, and Movement. *The Journals of Gerontology: Series B*. 57, 1, 54-64.

10. Chris Harrison and Scott E. Hudson. 2009. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology* (UIST '09). ACM, New York, NY, USA, 121-124. DOI: https://doi.org/10.1145/1622176.1622199

11. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09). DOI: http://dx.doi.org/10.1145/1613858.1613950

12. Christian Winkler, Ken Pfeuffer, Enrico Rukzio. 2012. Investigating mid-air pointing interaction for projector phones. In Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces (ITS '12), 85-94. DOI: https://doi.org/10.1145/2396636.2396650

13. Daniel Vogel and Ravin Balakrishnan. 2005. Distant freehand pointing and clicking on very large, high resolution displays. In Proceedings of the 18th annual ACM symposium on User interface software and technology (UIST '05), 33-42. DOI: http://dx.doi.org/10.1145/1095034.1095041

14. Euan Freeman, Stephen Brewster, and Vuokko Lantz. 2014. Tactile Feedback for Above-Device Gesture Interfaces: Adding Touch to Touchless Interactions. In *Proceedings of the 16th International Conference on Multimodal Interaction* (ICMI '14). ACM, New York, NY, USA, 419-426. DOI: https://doi.org/10.1145/2663204.2663280

15. Euan Freeman, Stephen Brewster, and Vuokko Lantz. 2016. Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 2319-2331. DOI: https://doi.org/10.1145/2858036.2858308

16. Faizan Haque, Mathieu Nancel, Daniel Vogel. 2015. Myopoint: Pointing and Clicking Using Forearm Mounted Electromyography and Inertial Motion Sensors. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15), 3653-3656.

17. Faustina Hwang, Simeon Keates, Patrick Langdon, and P. John Clarkson. 2003. Multiple haptic targets for motion-impaired computer users. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '03). ACM, New York, NY, USA, 41-48. DOI: http://dx.doi.org/10.1145/642611.642620

18. Felicia Huppert. 2003. Designing for Older Users. In: P. John Clarkson, Roger Coleman, Simeon Keates, and Cherie Lebbon (Eds.), *Inclusive Design: Design for the whole population*. Springer, London. DOI: https://doi.org/10.1007/978-1-4471-0001-0_2

19. Holly S. Vitense, Julie A. Jacko, and V. Kathlene Emery. 2002. Multimodal feedback: establishing a performance baseline for improved access by individuals with visual impairments. In *Proceedings of the fifth international ACM conference on Assistive technologies* (Assets '02). ACM, New York, NY, USA, 49-56. DOI: http://dx.doi.org/10.1145/638249.638260

20. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. DOI: https://doi.org/10.1145/2325616.2325625

21. Jörg Müller, Matthias Geier, Christina Dicke, and Sascha Spors. 2014. The boomRoom: mid-air direct interaction with virtual sound sources. In *Proceedings of the*

SIGCHI Conference on Human Factors in Computing Systems (CHI '14). ACM, New York, NY, USA, 247-256. DOI: https://doi.org/10.1145/2556288.2557000

22. Ju-Hwan Lee, Ellen Poliakoff, and Charles Spence. 2009. The Effect of Multimodal Feedback Presented via a Touch Screen on the Performance of Older Adults. In *Proceedings of the 4th International Conference on Haptic and Audio Interaction Design* (HAID '09). Springer, Berlin, Heidelberg, 128-135. DOI: https://doi.org/10.1007/978-3-642-04076-4_14

23. Julie Jacko, V. Kathlene Emery, Paula J. Edwards, Mahima Ashok, Leon Barnard, Thitima Kongnakorn, Kevin P. Moloney, and François Sainfort. 2004. The effects of multimodal feedback on older adults' task performance given varying levels of computer experience. *Behaviour & Information Technology*. 23, 4, 247-264. DOI: https://doi.org/10.1080/01449290310001659213

24. Kathrin Gerling, Ian Livingston, Lennart Nacke, and Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 1873-1882. DOI: http://dx.doi.org/10.1145/2207676.2208324

25. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346. DOI: https://doi.org/10.1145/2470654.2470703

26. Mathieu Nancel, Emmanuel Pietriga, Olivier Chapuis, Michel Beaudouin-Lafon. 2015. Mid-Air Pointing on Ultra-Walls. ACM Trans. Comput.-Hum. Interact. 22, 5. DOI: https://doi.org/10.1145/2766448

27. Mathieu Nancel, Julie Wagner, Emmanuel Pietriga, Olivier Chapuis, Wendy Mackay. 2011. Mid-air pan-and-zoom on wall-sized displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11), 177-186. DOI: https://doi.org/10.1145/1978942.1978969

28. Motoyuki Akamastu, I. Scott MacKenzie, Thierry Hasbrouc. 1995. A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. Ergonomics, 38, 816-827.

29. Peng Song, Wooi Boon Goh, William Hutama, Chi-Wing Fu, and Xiaopei Liu. 2012. A handle bar metaphor for virtual object manipulation with mid-air interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1297-1306. DOI: http://dx.doi.org/10.1145/2207676.2208585

30. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.

31. Sean Gustafson, Christian Holz, and Patrick Baudisch. 2011. Imaginary phone: learning imaginary interfaces by transferring spatial memory from a familiar device. In Proceedings of the 24th annual ACM symposium on User interface software and technology (UIST '11). ACM, New York, NY, USA, 283-292. DOI: https://doi.org/10.1145/2047196.2047233

32. Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (UIST '13). ACM, New York, NY, USA, 505-514. DOI: https://doi.org/10.1145/2501988.2502018

33. Vanessa Vuibert, Wolfgang Stuerzlinger, and Jeremy R. Cooperstock. 2015. Evaluation of Docking Task Performance Using Mid-air Interaction Techniques. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction* (SUI '15). ACM, New York, NY, USA, 44-52. DOI: https://doi.org/10.1145/2788940.2788950

34. Vicki L. Hanson and Susan Crayne. 2005. Personalization of Web browsing: adaptations to meet the needs of older adults. *Universal Access in the Information Society*. 4, 1, 46-58. DOI: https://doi.org/10.1007/s10209-005-0110-9

35. Wijnand Ijsselsteijn, Henk Herman Nap, Yvonne de Kort, and Karolien Poels. 2007. Digital game design for elderly users. In *Proceedings of the 2007 Conference on Future Play* (Future Play '07). ACM, New York, NY, USA, 17-22. DOI: http://dx.doi.org/10.1145/1328202.1328206

36. Wei Lu, Zheng Tong, Jinghui Chu. 2016. Dynamic Hand Gesture Recognition With Leap Motion Controller. IEEE Signal Processing Letters. 23, 9: 1188-1192.

37. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. Journal of Hand Therapy. 28, 1, 53-60.

7 *Investigating the Suitability and Effectiveness of Mid-Air Gestures Co-Designed By and For Older Adults*

Publication status:

* Full chapter was submitted to CHI 2019.

(*under review*)

7 Investigating the Suitability and Effectiveness of Mid-Air Gestures Co-Designed By and For Older Adults

Abstract

This work explores the design and suitability of mid-air gestures as an input method for facilitating computer use for older adults. First, we report the results of a co-design study with 25 older adults in which participants were asked to envisage mid-air gestures that they would find useful for completing computer microinteractions in a quicker and easier way than using traditional input methods such as mouse interaction. Older adults designed 372 mid-air gestures across 69 microinteractions and 10 computer activities. We then conducted a usability study with 18 older adults that compared these co-designed mid-air gestures for computer-based interactions with unimodal mouse interaction and off-the-shelf mid-air gestures (i.e. that do not necessarily take into consideration the needs and skills of older users). Our findings suggest that mid-air gestures co-designed by and for older adults, compared with off-the-shelf gestures, achieved higher acceptance rates, faster task completion times and fewer errors.

1 Introduction

Computer-based interactions occupy an essential part of our modern daily lives. At work or at home, we interact with computers with the purpose of accomplishing an ever-growing range of tasks. Over the past decades, a significant body of HCI research has focused on investigating means of making computer methods more efficient, easier to use, and, in recent times, more natural. Despite the general advancements of computer-based interfaces in terms of usability and accessibility, a distinguished portion of the society has been historically underrepresented in HCI studies: the older population [33, 34, 37]. Although the number of people aged 60 and over is expected to double by 2050 and to triple by 2100 (reaching 3.1 billion worldwide) [56], currently established input methods (e.g. mouse-based point-and-click interactions) often fail to support older adults in using computers [4, 12, 21, 27, 42, 43]. Older users frequently face many barriers to computer use [4, 44], and some known challenges preventing older users from interacting effectively with computers include lack of familiarity with computer interfaces and natural age-related decline in motor, cognitive and sensory abilities [14, 50]. Therefore, research concerning the design and employment of suitable and appropriate interaction methods that take into account the needs and capabilities of the older population is still an essential topic to be explored within the HCI community.

It is well-known that the needs and skills of "ordinary" older users (i.e. those without specific disabilities) are seldomly considered or incorporated in the design and ideation of computer interaction methods meant to be used by all ages [21, 33, 34]. Older adults are, in general, an underrepresented user group in HCI, with exceptions to research undertaken to envisage particular interfaces meant to serve as assistive technologies for older individuals with acquired health conditions, for instance to compensate for loss of a specific function [36]. Assistive technologies are indeed important assets to improving the accessibility of computers for older individuals with acquired health conditions (e.g. Glaucoma, Dementia, Parkinson's disease) [38, 45], however, older adults with no health-related impediments also need to have their range of skills and particularities accommodated in the conception and development of computer interfaces in order to minimise the digital exclusion of those citizens as well as encourage and support those individuals in their computer-mediated endeavours [52].

Even though some older adults may not consider themselves "old" or "unfit" to use computers and technology in general, their needs and range of skills can vastly differ from the needs and skills of younger users [33]. Computer interaction methods are either designed based on the needs and abilities of a typical young user, or assume that the needs and abilities of all users are similar [45]. Furthermore, older adults are still seen, for the most part, as non-users of technology, however, evidence over the years is demonstrating otherwise [50]. Older users may present less familiarity with computers in comparison with younger individuals [11, 14, 39, 43], but that does not necessarily mean that older adults do not present any less interest or will to use and benefit from technology [7, 8, 40]. For this reason and on the grounds of an ageing population, natural and gradual age-related decline in motor, cognitive and sensory functions should be better taken into consideration within the design and development of computer-based interactions. Additionally, the investigation of more "age-friendly" interaction methods that support – and possibly enhance – the skills of older users is still necessary within HCI research.

Regarding means to better support older users in using computers and provide easier interaction methods, current research trends have been exploring the concepts of intuitive embodied interaction [5] and natural user interfaces (NUI) [15, 53] with the aim of exploring means to augment – or even replace – traditional input methods (e.g. mouse interaction) and offer enhanced interaction techniques for a greater number of target users and interaction contexts [20, 22, 25]. Novel embodied input techniques such as touchless gestures (also known as mid-air or in-air gestures) are deemed to be more "intuitive" and "natural" to users than standard computer methods (e.g. mouse-based point-and-click paradigm) [15, 54], however it still is not clear if these advantages apply to the older population, or even if these so-deemed "natural" input techniques are "natural" to older users at all [11, 14, 18, 30]. Indeed, Lindsay et al. (2012) has suggested that novel interaction techniques can cause a number of problems that older users experience, rather than being a solution [52].

Furthermore, despite the increasing popularity of gesture-based interfaces, the lack of standard practices for designing and implementing touchless gestures makes it difficult to assume that current commonly-employed gestures are aligned to the range of skills or the needs of older users [10, 29, 18]. It is well documented that older adults are sometimes reluctant to adopt new technology [2, 4, 11, 50] and may be hesitant to try novel input methods that could potentially help them in using computers [44]. Therefore, even supposing that gesture-based interaction can be a suitable method for improving older users' computer performance in comparison with traditional input methods [39], it does not necessarily mean that older users will accept the radical change.

This paper proposes the design and use of mid-air gesture input to facilitate the completion of computer-based microinteractions for older users (+60) through two empirical studies: a co-design session and a task-based study. Microinteractions are defined as single interaction events that happen within a main computer task and serve a single purpose (Saffer, 2013) [16, 19]. For instance, scrolling to the next page of a pdf file while reading a document is considered a microinteraction, as well as typing a password to log in, or confirming an item is added to the cart when doing online shopping. According to Oulasvirta et al. (2005) and Ashbrook (2010) [9, 17, 26] microinteractions are input interactions that take less than 4 seconds to initiate and complete, so the user can quickly move on or progress in their computer activity.

2 Related Work

This session explores related work on ageing and computer interaction, participatory design methods and user-defined gestures.

2.1 Older adults and Computer Interaction

A person's abilities change as they get older and so does their relationship with technology [45]. It is well known that computer use can be challenging older adults that suffer natural and gradual age-related decline in cognitive, sensory and motor abilities [4, 21, 50]. Computer interactions relies heavily on input methods such as mouse interaction. Research, however, has indicated, however, that age affects mouse control [4, 12]. Older users present more difficulty with clicking and double-clicking, cursor repositioning, target selection and more complex mouse manipulations [43]. Age-related decline in motor control and visual processing were found to affect mouse movement times and lead to higher cursor slip-offs [42]. Prior work has suggested that older adults (60+) are willing to adopt new technologies as long as their usability and perceived usefulness outweighs the initial unfamiliarity and complexity of interaction [14, 36]. Furthermore, the suitability and efficacy of alternative input methods for supporting older users in using computers is still a topic requiring further attention [42] and research towards design interventions for age-friendly interfaces are still needed.

2.2 Participatory Design Methods and Older Users

Researchers and HCI practitioners often apply participatory design methods for designing novel interactive systems that are more intuitive and relatable to target users [40, 52]. Older adults are often overlooked and underrepresented in HCI studies that aim to conceive and improve interaction methods with which older users have little familiarity [2, 7, 31, 32, 52]. Through participatory and co-design methods, there is an opportunity to involve older users in the design of emerging interaction methods with the intent of envisaging interactive systems that better accommodate the needs and skills of the older population [8].

Although guidelines for involving older adults in co-design are scarce, considerations include providing more than one method for collecting data and suggest alternative activities, and focus on designing tangible concepts [1, 26]. Another possible challenge for including older adults in the design process is the appearance of design fixation [31, 32], which is described as the act of mimicking existing designs and concepts without introducing novelty and challenging existing paradigms. Even though design fixation may hinder the variety of co-design results, it can also smooth the transition towards new forms of interaction, similarly to legacy bias [6, 29, 41].

2.3 Designing Age-Friendly Mid-Air Gesture Interaction

Participatory design methods have engaged users to define input techniques with the intent of creating gesture sets that feel familiar and intuitive to target users. Wobbrock et al. (2009) [28] reported the findings of user-defined gestures for surface computing where the researchers prompted users with referents (i.e. effects of an action) and elicited how participants would propose the causes of those actions. This method for eliciting user-defined gestures has been employed in many studies [13, 19, 22, 55], however, the inclusion of older participants in gesture elicitation studies has not been extensive, and the suitability and effectiveness of user-defined gestures for the older population is still unknown. Prior research has suggested that bimanual input combined with mid-air gesture interaction may lead to faster interaction [3, 23, 24, 25, 47, 48, 49, 58], but little is known about its effectiveness for older users.

Furthermore, it is fundamental to better understand if user-defined gestures would be beneficial to older users, in the same way that they are deemed to be to younger users, and if user-defined gestures offer greater support for older adults in using interactive systems in comparison with regular gesture sets.

3 Study 1 – Co-Designing Mid-Air Gestures for Microinteractions with Older Adults

In order to better understand the extent to which older users would find mid-air gestures to be useful as an add-on in computer interaction and investigate the appropriateness of bimanual interaction, a co-design study was conducted for eliciting mid-air gestures and matching them with computer microinteractions that could be achieved either by using standard input methods (e.g. mouse-based point-and-click actions) or by using mid-air gestures.

That is, instead of completely replacing traditional computer input methods (i.e. mouse and keyboard interaction) as explored in prior work [11, 15, 51], mid-air gestures could give older users the option of completing specific computer tasks through one method or the other, with mid-air gestures being a secondary input method activated only when necessary. The co-design study aims to answer two questions: 1) What mid-air gestures to use as an auxiliary input method, and 2) in what computer activities they could be useful for older users.

3.1 Co-Design Methods

This section describes the co-design study design and experimental set-up.

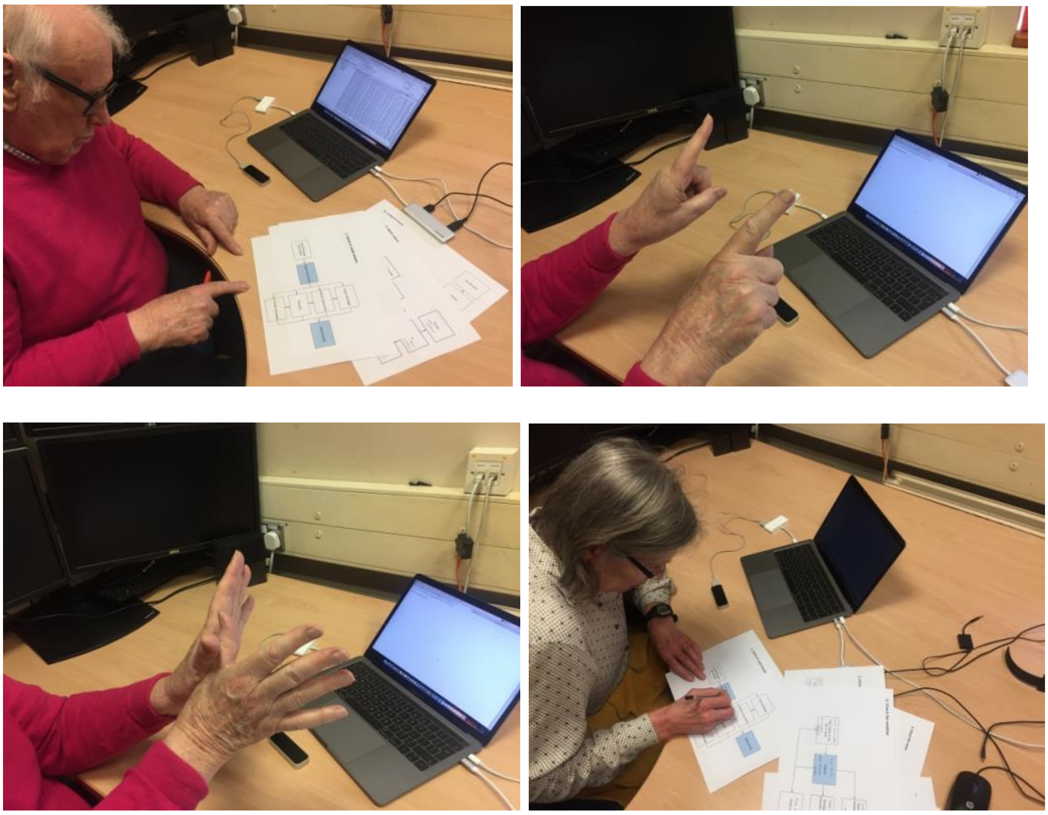
***3.1*.1 *Participants*.** 25 older adults (12 female) participated in the co-design session. Participants were aged 60 to 83 (mean age: 67; SD: 6.7) and had prior computer experience with some familiarity with touchscreen interaction (e.g. smartphones, tablets). All participants reported using computers regularly (e.g. desktop, laptop). No prior experience with motion sensing devices and mid-air gesture interaction was reported. Before the start of the session, participants had their eye-hand coordination, manual dexterity and motor skills assessed using a Rolyan 9-Hole Peg Toolkit (Wang et al., 2015) [59], which confirmed that all participants were within the norms for their age group. The study was reviewed by the University of Reading's Research Ethics Committee and was given a favourable ethical opinion for conduct.

***3.1*.2 *Procedure and Materials*.** Participants were first asked to complete an inventory questionnaire regarding the type of tasks they regularly do when using a computer (e.g. internet browsing, social media, video streaming), including level of perceived difficulty and frequency of use. The computer activities included in the questionnaire were informed by [46] (Table 1). After reviewing the answers with the participant, the primary researcher presented an illustrative flowchart demonstrating the breakdown of the microinteractions needing to be completed for achieving each of the computer tasks indicated by the participant. The primary researcher then asked the participant to envisage what mid-air gesture command could be useful for replacing one of the microinteractions shown in the flowchart, usually completed with mouse or keyboard commands (Figure 1). If unable to create their own gesture, participants were given the choice to pick from a list of gestures. Gestures created by participants were photographed, video recorded and catalogued into the flowcharts alongside additional annotations made by the researcher.

Table 1 - List of computer activities used as a basis for the co-design session

Computer activities inventory
1. Send and read e-mails
2. Use a search engine to find information
3. Online shopping
4. Read the news
5. Check the weather
6. Watch videos or films (Youtube, Netflix)
7. Online banking
8. Play games (specify)
9. Social media (Facebook, Twitter)
10. Video calls with family or friends (Skype, Facetime)
11. Listen to music
12. Work related computer activities (specify)
13. Other computer activities (specify)

Figure 1 – Participants analysing task flowcharts and demonstrating their mid-air gestures during the co-design study



3.2 Co-Design Results

372 mid-air gestures across 69 microinteractions and 10 computer activities were elicited by older adults in the co-design session. This session reports the main findings of the study.

***3.2*.1 *Most recurrent elicited mid-air gestures by computer activity*.** Table 2 shows the most recurrent mid-air gesture designed by older adults for different computer activities. The “hand up and down” gesture for controlling the scroll bar was the most recurrent mid-air gesture in 6 out of 12 computer activities.

Table 2 - Most recurrent mid-air gestures elicited by older adults in the co-design session

Computer activity	Number of mid-air gestures elicited	Most recurrent mid-air gesture
Send and read e-mails	74	Hand up and down for scrolling
Use a search engine to find information	61	
Online shopping	50	
Read the news	39	
Check the weather	32	
Online banking	26	
Listen to music	25	Palm facing the screen (stop sign) for pausing music
Video calls	24	Fingers together + pull up or down for controlling volume
Watch videos	18	Palm facing the screen (stop sign) for pausing video
Other computer activities (2)	15	Hand wave for opening menu (1) / Swipe left for locking computer (2)
Social media	8	Thumbs up (ok sign) for sending message

3.2.*2 ***Most recurrent elicited mid-air gestures by function. Elicited gestures were highly variable across participants. The most recurrent elicited mid-air gestures for computer navigation include “hand up and down” for scrolling (appeared 59 times), “lateral hand swipe” for navigating between pages or tabs (14 times), and “finger pinch and pull up / down” also for scrolling (9 times). Recurrent gestures elicited for single triggering actions include “hand stop sign” for pausing music or video (appeared 15 times), and continuous gestures such as “fingers together + pull up and down” for controlling the volume (8 times).

4 Study 2 – Comparing the Suitability and Effectiveness of Co-Designed Mid-Air Gesture Input with Standard Interaction Methods

Following the co-design of gestures, a study was conducted to investigate the suitability and effectiveness of mid-air gestures designed by and for older users (aged 60 and older) and whether those gestures can contribute to easier computer use for the older population in comparison with a) gestures not designed with older users in mind, and b) standard input methods such as mouse interaction.

4.1 Methods

4.1.1 Participants. 18 participants (7 female) were recruited for the study and randomly divided into two groups: 9 participants were allocated to co-designed gestures and 9 participants were allocated to off-the-shelf gestures. Participants were aged 61 to 79 (mean age: 68 years old, SD: 5.4) and all had prior computer experience. All participants passed a manual dexterity test using a 9-hole Rolyan peg toolkit [59]. Further participant information is shown in detail in Table 3.

Table 3 – Participant information (n = 18)

Participant information		n (18)
Handedness	Left	1
	Right	17
Eyesight	Corrected	18
Frequency of computer use	Every day	15
	Every 2 – 3 days	3
Touchscreen experience	Little to no experience	6
	Fairly experienced	10
	Very experienced	2
Mid-air gesture experience	Little to no experience	18
Devices regularly used	Desktop	12
	Laptop	10
	Tablet	8
	Smartphone	11
	Interactive TV	2

4.1.2 Mid-Air Gestures and Microinteractions. Table 4 shows the 5 microinteractions and the mid-air gestures included in the study design. Co-designed mid-air gestures (condition A) were based on the findings of the co-design sessions with older adults and "off-the-shelf" mid-air gestures (condition B) were chosen based on real world commercially available applications that offer mid-air gesture interaction and may not take into consideration the older population [10, 11, 19, 26].

Table 4 – Mid-air gestures and microinteractions included in the study design

Task	**Microinteraction**	**Condition A** *(co-designed mid-air gestures)*	**Condition B** *(off-the-shelf mid-air gestures)*
1. Open and scroll to page 4 of a pdf file	Scroll (up and down)	Hand up and down	Tilt wrist up and down
2. Play a song on spotify	Change volume (up and down)	Index finger up and down	Index finger rotation clockwise and counter-clockwise
3. Play a video	Stop video	Stop sign (palm facing the screen)	Air tap (finger)
4. Menu navigation	Open menu	Hand wave	Swipe left
5. Lock and shut down computer	Lock computer	Swipe left	Hand down

4.1.3 Procedure and Materials. The lab-based study was conducted with participants sitting in front of a laptop connected to a Leap Motion sensor (Figure 2) . After reading the information sheet, signing the consent form and answering a brief questionnaire on age, gender, dominant hand and computer experience, participants were introduced to the Leap Motion sensor and the primary researcher explained the 5 computer-based microinteractions that participants had to complete under either condition A (co-designed mid-air gestures elicited by older adults in study 1) or B (off-the-shelf mid-air gestures). Participants received training and instructions before completing the tasks. After completing the tasks, participants were asked to complete a SUS (System Usability Scale) and a NASA TLX (Task Load Index) questionnaire about using mid-air gestures for computer microinteractions. Half of the participants then repeated the 5 tasks using only the mouse or keyboard as they would do at home, whereas the other half completed the tasks with the mouse first (i.e. condition order was counterbalanced across participants in order to minimise learning effects). Although the computer tasks were relatively simple, participants were told that they could ask for the researcher's assistance at any time during the study. Data regarding time to complete each task, success rates and subjective evaluation were collected. At the end of session 1, participants were asked to book a day and time to return for session 2.

During session 2, the focus was to explore the learnability and memorability of the mid-air gestures used in session 1 after the first interaction. Participants were welcomed back in the lab after 3 to 7 days of participating in session 1 and were asked to repeat the 5 computer tasks completed in session 1. This time, participants were asked to remember the gestures used in the last session on their own and did not receive additional training or instructions. If the participant was unable to remember any of the gestures, the researcher would help and take note of the gesture.

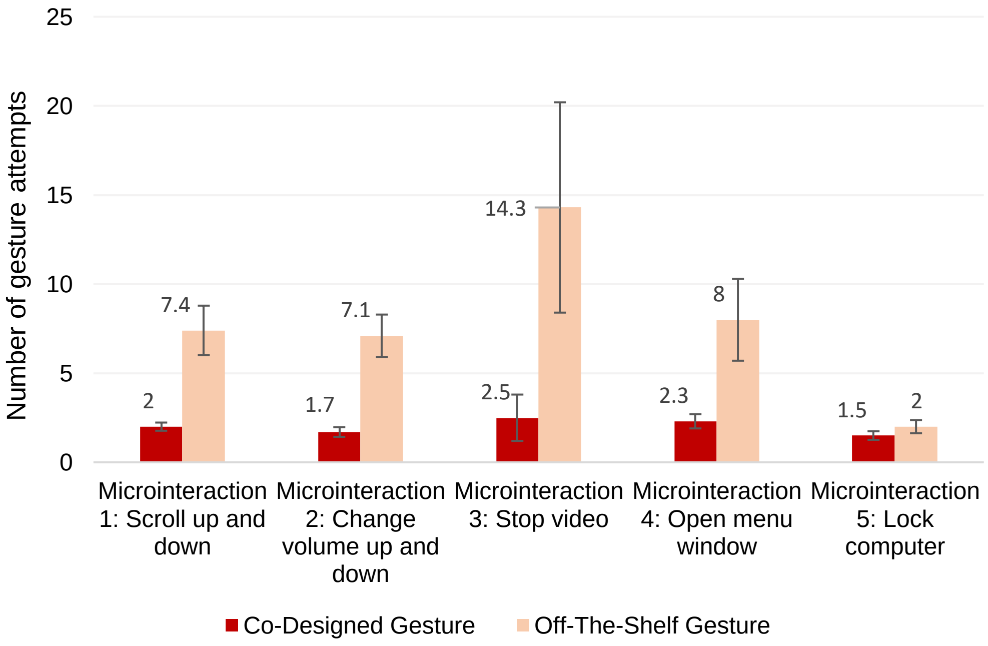
In session 2, participants were free to choose between completing the tasks using the mid-air gestures of session 1 (condition A or B) or standard input methods. In the end, participants were encouraged to explain what factors led them to choose between gestures or not, and were asked to complete the SUS and NASA TLX questionnaires one more time. Data collected in session 1 and session 2 were compared in order to investigate if there are noticeable changes in usability and user experience over time. The two sessions were video recorded.

Figure 2 – Study set-up and participant using the co-designed mid-air gesture (hand up and down) for scrolling

4.2 Results of Session 1

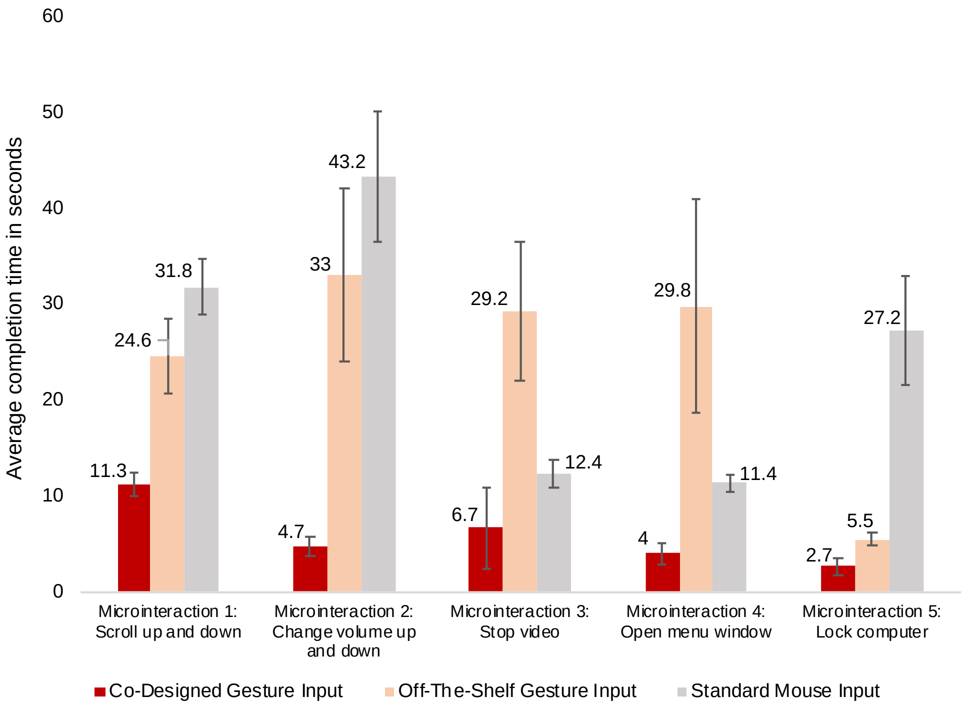
4.2*.1 *Number of gesture attempts. The number of gesture attempts older users had to make to complete each computer microinteraction differed between the two gesture input methods (Figure 3). A Student's t-test found a significant difference between the number of gesture attempts that participants had to make in order to complete each microinteraction successfully in session 1 [t(1, 88) = 4.1, p =.000062]. Tukey HSD pairwise comparisons confirmed that co-designed mid-air gestures led to fewer gesture attempts in comparison with off-the-shelf mid-air gestures for all computer microinteractions, except for the 5th microinteraction: locking the computer, in which the number of gestures attempts for both groups was not significantly different.

Figure 3 – Mean number of gesture attempts necessary for completing each computer microinteraction. Error bars represent S.E.



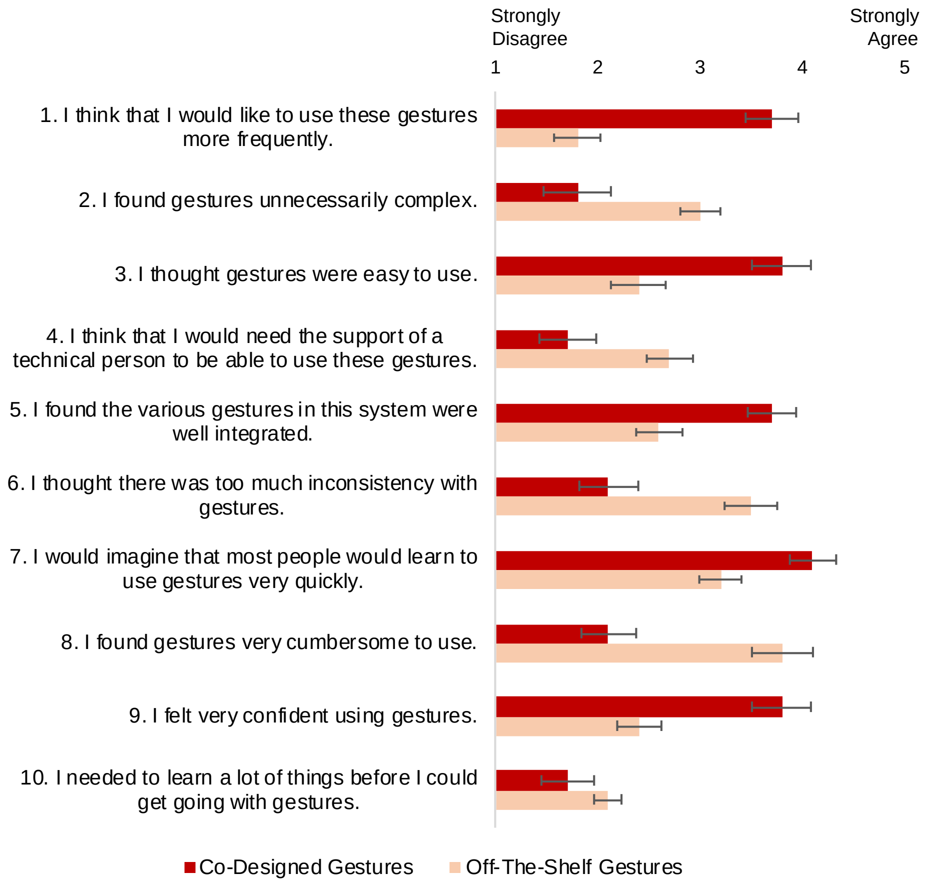
4.2.*2 ***Microinteraction completion time. Microinteraction completion time results are shown in Figure 4. Older adults completed computer-based microinteractions on average in 5.8 seconds with co-designed mid-air gestures versus 24.4 seconds with off-the-shelf mid-air gestures and 25.2 seconds with standard mouse-based input. An one-way ANOVA revealed a significant main effect of input type on completion time of computer-based microinteractions [F(2,177)=25.81, p=.000024]. Tukey HSD pairwise comparisons found that co-designed gesture input achieved faster completion time than both off-the-shelf gestures ($p < .00001$) and standard mouse input ($p < .00001$), regardless of the task.

Figure 4 – Mean completion time (seconds) for each input method and microinteraction. Error bars represent S.E.



***4.2*.1 *SUS Responses*.** After completing the 5 computer microinteractions by using either co-designed or off-the-shelf mid-air gestures, participants were asked to answer the SUS questions (Figure 5) regarding their subjective evaluation of using mid-air gesture input for computer interaction. Tukey HSD pairwise comparisons found a significant difference between the two gesture input methods for questions 1 to 9 ($p < 0.05$).

Figure 5 – SUS responses (means) for co-designed and off-the-shelf mid-air gestures. Error bars represent S.E.



4.2.1 ***Subjective Workload***. Table 5 shows the NASA Task Load Index results for each input method used to complete the computer microinteractions in session 1. A one-way ANOVA found a main effect of input method on subjective task load index [F(2, 213)=14.8, p=.0025]. Tukey HSD pairwise comparisons found that both co-designed mid-air gestures (p=.0003) and standard mouse interaction (p=.0056) achieved a lower task load index than off-the-shelf mid-air gestures.

Table 5 – NASA TLX results for each input method.

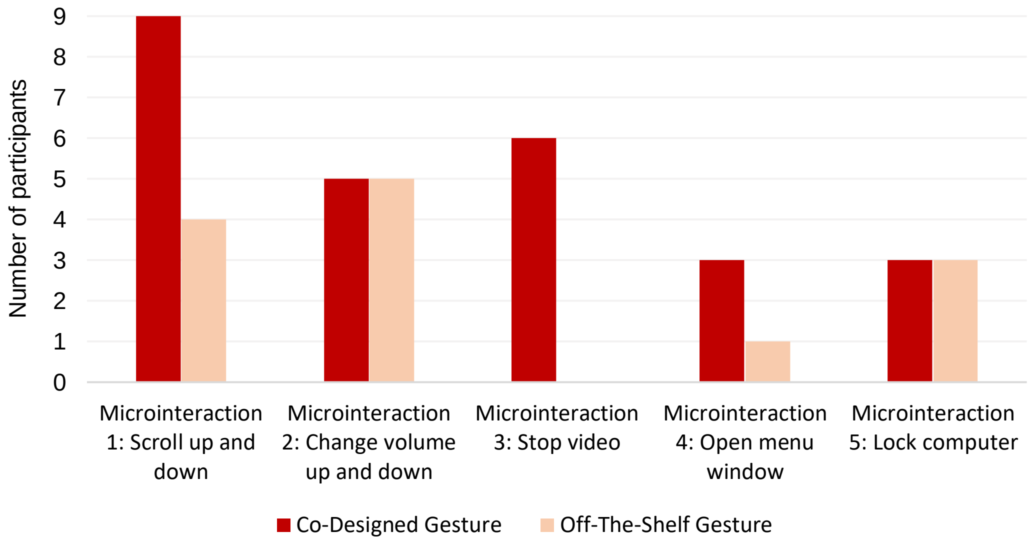
	Co-Designed Gestures	Off-The-Shelf Gestures	Standard Mouse Interaction
Mental demand	3.8	6.4	3.2
Physical demand	3.8	7.4	3.1
Temporal demand	2.7	8.2	4.5
Performance	11.4	5.6	15.6
Effort	4.5	11.4	4.2
Frustration	4	12	3.9
Overall TLX	5	8.5	5.7

4.3 Results of Session 2

Participants returned for a second study session after 6 days of the first session on average.

***4.3*.1 *Memorability rate*.** In the beginning of session 2, participants of both groups (co-designed versus off-the-shelf mid-air gestures) were asked to remember and demonstrate the mid-air gestures used for each of the 5 microinteractions of session 1. A Student’s t-test found a significant difference between the number of participants who were able to remember the mid-air gestures they used in session 1 [t(1, 88) = -2.8, p =.0026]. As shown in Figure 6, participants using co-designed mid-air gestures presented a higher gesture memorability rate than participants using off-the-shelf mid-air gestures.

Figure 6 – Number of participants who were able to remember and demonstrate the mid-air gestures used in session 1.

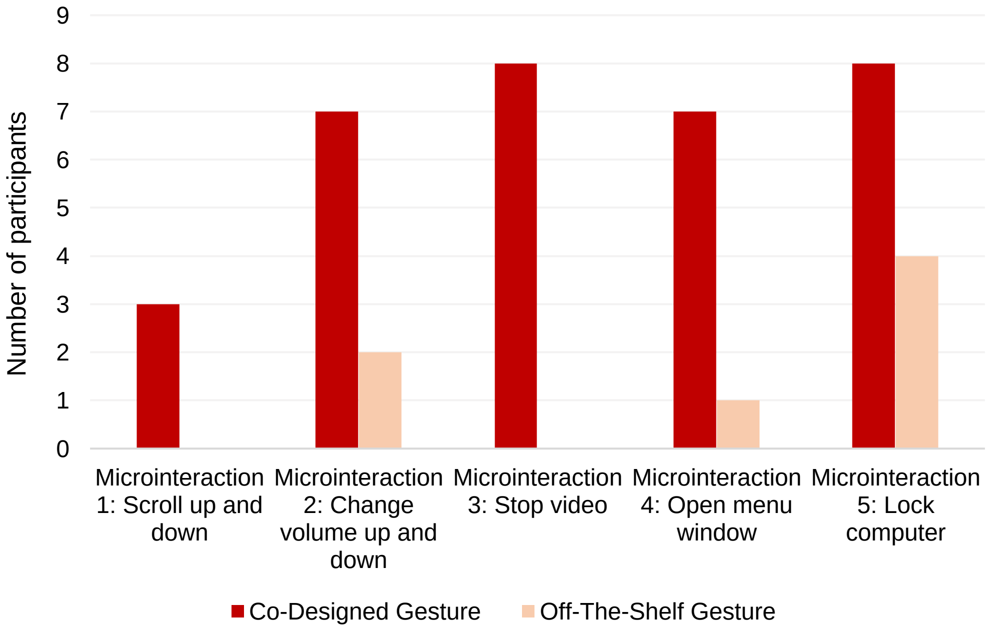


4.3.2 Microinteraction completion time, error rates, and subjective ratings (SUS and NASA TLX results). As participants repeated the 5 microinteractions of session 1, task completion times, number of gesture attempts, and subjective responses (SUS and NASA TLX questionnaires) were reassessed in session 2. Unlike session 1, participants did not receive training for completing the 5 tasks and were free to choose between using either the group's mid-air gestures or standard input (mouse interaction). A repeated-measures ANOVA found no significant differences between the results of completion times, error rates, and subjective ratings reported in session

1 and the results of session 2 ($p > 0.05$ for all metrics). Therefore, participants' performance and views remained unaltered after the first exposure.

***4.3*.3 Preference over mouse interaction**. A Student's t-test found a significant difference between the number of participants who answered that they would prefer using mid-air gestures for completing the 5 computer microinteractions over using standard mouse input in the future [$t(1, 88) = -6.7$, $p < .0001$]. As shown in Figure 7, preference rates were higher amongst participants using the co-designed mid-air gestures (above 50% preference rate over mouse interaction), and lower amongst participants using off-the-shelf mid-air gestures (below 50% preference rate). Tukey HSD pairwise comparisons found that co-designed mid-air gestures achieved higher preference over mouse interaction in all 5 computer microinteractions, in comparison with off-the-shelf mid-air gestures (p values between 0.0001 and 0.003).

Figure 7 – Number of participants responding that they would prefer using mid-air gestures for completing each of the microinteractions below in comparison with standard mouse input.



5 DISCUSSION

This session discusses the findings of both co-design study with older adults and the usability study that aimed to compared the mid-air gestures co-designed by older users with traditional mouse interaction and off-the-shelf mid-air gestures.

5. 1 Co-Designing Mid-Air Gestures for Microinteractions

The productiveness of the co-design sessions varied amongst older adults. Some participants told the primary researcher that they were either *“too used to the mouse, and could not think of many gestures that would be useful”* or *“learning new gestures seems* *to be hard work"*, whereas other participants were quite inventive and tried to envisage mid-air gestures that would be useful for their own needs. The nature of the computer microinteractions for which older adults chose to design mid-air gestures included, for instance, gestures that facilitated mouse-based tasks in which precise and continuous control is necessary (e.g. cursor dragging, scrolling, fine-positioning, and multiple clicking). Prior work has showed supporting evidence that older adults indeed present more difficulties in performing the above mouse tasks due to age-related changes in psychomotor abilities on mouse control [12, 42, 43]. In the co-design study, older adults were mindful of these difficulties and tried to design mid-air gestures for specific microinteractions that rely heavily on mouse input. "Hand up and down" for scrolling was the overall most recurrent designed mid-air gesture across all participants (appeared 59 times within different contexts). Participants explained that selecting and dragging the scrolling bar can be both difficult and slow using a mouse, and completing the same task with a mid-air gesture could be useful and more efficient for long documents or contexts that require constant scrolling. *"I can scroll with my other hand if this one gets tired",* said a 65-year-old female participant while explaining her rationale.

Furthermore, although legacy bias is deemed to smooth the transition towards new forms of interaction [6] and was observed in some participants' rationale for designing mid-air gestures that were similar to finger gestures used on touchscreen devices (e.g. finger pinch, finger tap), older adults generally preferred designing mid-air gestures that involved mostly hand movements and not reliant on finger dexterity.

5.2 The Suitability and Effectiveness of Co-Designed Mid-Air Gestures

The findings of our task-based study show supporting evidence that mid-air gestures co-designed by and for older adults, compared with off-the-shelf gestures and mouse input, achieved higher memorability and acceptance rates, faster task completion times and fewer errors. Acting as a "shortcut" for completing the microinteractions included in our experimental design, co-designed mid-air gestures were found to lead to a faster and effective way for supporting older adults in using computers. On the other hand, off-the-shelf mid-air gestures (i.e. mid-air gestures that were based on gestures available within commercial applications and may not take older users into consideration) did not improve computer interaction, led to a high number of failed gesture attempts, and had poor acceptance amongst participants. Unlike the co-designed gesture set, off-the-shelf mid-air gestures did not present advantages over unimodal mouse input and may offer further hindrance for older adults when using computers.

Microinteractions such as "opening the menu" and "locking the computer", although conceptually simple, require a sequence of mouse-based actions: cursor relocation, menu exploration, and selection (clicking). In our study, older adults spent on average 11.4 seconds in order to open a menu successfully and 27.2 seconds for locking the computer. By turning the sequence of mouse-based actions into a single "triggering" action with the co-designed mid-air gesture input, these times were reduce to 4 and 2.7 seconds respectively. Furthermore, by shortening the time and number of interaction steps required to complete these microinteractions, mid-air gesture input can also reduce the proneness of older users in making mistakes during the course of computer interaction.

Our findings are in accordance with the findings of Findlater et al. (2013) [39] that suggested that touchscreen gestures helped older users in reducing movement time and error rates compared to traditional mouse input. The possibility of bimanual input by either using mid-air gestures or mouse input was generally accepted amongst older adults, which can relate to the findings of [25] that found that younger users also prefer two hands for using bimodal input methods. Therefore, gesture-based interaction seems to offer usability advantages when designed to accommodate the needs and psychomotor skills of the older population and may become a suitable input method for supporting older users in using computers as long as the interface also allows bimodal interaction (i.e. mouse input plus another modality) and is designed with proper considerations of older adults.

5.3 User Acceptance and Intent-to-Use

Older adults using off-the-shelf mid-air gestures described mid-air gesture interaction as being "*very laborious*", "*a bit of hit and miss*", "*not consistent nor responsive enough*". Unlike the off-the-shelf gesture set, older adults using co-designed mid-air gestures stated that mid-air gestures can be "*simpler*" and "*require less precision*" than using the mouse. In relation to that, a 70-year-old female participant described that "*I feel like I have more control with the gestures*" and a 67-year-old male participant stated that "*gestures get easier once I get used to it*". Additionally, a 74-year-old female participant explained her views on mid-air gestures acting as single "triggering" actions: "*gestures are easier because you don't need to find the buttons and icons on screen, you can just do it*". On the other hand, some of the reservations that older users shared in relation to mid-air gesture interaction included the perceived lack of consistency and reliability, as older adults said that it is important that gestures work at first attempt. Other factors include the perceived physical effort needed for some mid-air gestures and the use of precise fine motor skills. Furthermore, some participants shared concerns about the learnability and memorability, with a 70-year-old participant saying that she "*would write down the gestures so I can remember them*".

Although it is known that some older users may be adverse to adopting new technology [1, 4, 45, 50], our SUS questionnaire responses indicate that older adults are willing to use age-friendly mid-air gestures more frequently in the future and are inclined to accepting mid-air gesture interaction as long as it contributes to their computer interaction and do not impose further impediments.

6 Conclusion

This paper first investigated the use of participatory and co-design methods for eliciting mid-air gestures as an input method for facilitating computer microinteractions for older adults. Older adults chose to design mid-air gestures, for instance, to replace multiple-step mouse-based interactions, such as scrolling, dragging and selecting options. From the 372 mid-air gestures elicited during the co-design sessions, older adults generally designed gestures that used hand movements over gestures that required finger dexterity. Secondly, we conducted a usability study that compared the suitability and effectiveness of 5 of these co-designed mid-air gestures with unimodal mouse interaction and off-the-shelf mid-air gestures (i.e. that do not necessarily take into consideration the needs and skills of older users). Our findings provide empirical evidence that mid-air gestures co-designed by and for older adults, compared with off-the-shelf gestures, achieved higher acceptance rates, faster task completion times and fewer errors. Besides the natural hesitations regarding the reliability of gesture-based interfaces, older adults showed more approval and willingness to adopt co-designed mid-air gestures as an input method for computer use, compared to off-the-shelf gestures.

Taking into consideration the cost-benefit of conducting co-design sessions with older adults, participatory design methods were demonstrated to be a suitable choice for conceiving gesture sets that better accommodate the preference, needs and psychomotor skills of older users.

Acknowledgements

We thank all the volunteers for their participation and the University of Reading's Hugh Sinclair Unit for their help with recruitment. The research is funded by the Brazilian Science Without Borders Programme, an initiative under the Ministry of Education and CAPES Foundation. Project number BEX 13037-13-7.

References

1. Alan Newell, John Arnott, Alex Carmichael, and Maggie Morgan. 2007. Methodologies for Involving Older Adults in the Design Process. In: Stephanidis C. (eds) *Universal Acess in Human Computer Interaction* (UAHCI 2007). Lecture Notes in Computer Science, vol 4554. Springer, Berlin.

2. Amanda Lazar, Raymundo Cornejo, Caroline Edasis, and Anne Marie Piper. 2016. Designing for the Third Hand: Empowering Older Adults with Cognitive Impairment through Creating and Sharing. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (DIS '16). ACM, New York, NY, USA, 1047-1058.

3. André Kunert, Alexander Kulik, Anke Huckauf, and Bernd Fröhlich. 2007. A comparison of tracking- and controller-based input for complex bimanual interaction in virtual environments. In *Proceedings of the 13th Eurographics conference on Virtual Environments* (EGVE'07), Bernd Fröhlich, Roland Blach,

and Robert van Liere (Eds.). Eurographics Association, Aire-la-Ville, Switzerland, Switzerland, 43-52. http://dx.doi.org/10.2312/EGVE/IPT_EGVE2007/043-052

4. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266.

5. Anna Macaranas, Alissa N. Antle and Bernhard E. Riecke. 2015. What is Intuitive Interaction? Balancing Users' Performance and Satisfaction with Natural User Interfaces. *Interacting with Computers*. 27, 3, 357-370.

6. Anne Köpsel and Nikola Bubalo. 2015. Benefiting from legacy bias. *interactions*. 22, 5, 44-47. https://doi.org/10.1145/2803169

7. Anne Marie Piper and Amanda Lazar. 2018. Co-design in health: what can we learn from art therapy? *interactions*. 25, 3, 70-73.

8. Anne Marie Piper, Ross Campbell, and James D. Hollan. 2010. Exploring the accessibility and appeal of surface computing for older adult health care support. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10). ACM, New York, NY, USA, 907-916. https://doi.org/10.1145/1753326.1753461

9. Antti Oulasvirta, Sakari Tamminen, Virpi Roto, and Jaana Kuorelahti. 2005. Interaction in 4-second bursts: the fragmented nature of attentional resources in mobile HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '05)*. ACM, New York, NY, USA, 919-928. https://doi.org/10.1145/1054972.1055101

10. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258. http://dx.doi.org/10.1145/2783446.2783599

11. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA, Article 122, 6 pages. https://doi.org/10.1145/2971485.2996757

12. Caroline J. Ketcham and George E. Stelmach. 2001. Age-Related Declines in Motor Control. In Birren, J.E. & Schaie, K.W. (Eds.), *Handbook of the Psychology of Aging*. Academic Press.

13. Christian Kray, Daniel Nesbitt, John Dawson, and Michael Rohs. 2010. User-defined gestures for connecting mobile phones, public displays, and tabletops. In *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services* (MobileHCI '10). ACM, New York, NY, USA, 239-248. https://doi.org/10.1145/1851600.1851640

14. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78.

15. Dan Saffer. 2008. Designing Gestural Interfaces: Touchscreens and Interactive Devices. O'Reilly Media, Inc.

16. Dan Saffer. 2013. Microinteractions: Designing with Details. O’Reilly Media, Inc.

17. Daniel L. Ashbrook. 2010. Enabling Mobile Microinteractions. *Ph.D. Dissertation*. Georgia Institute of Technology, Atlanta, GA, USA.

18. Donald A. Norman and Jakob Nielsen. 2010. Gestural interfaces: a step backward in usability. *interactions* 17, 5 (September 2010), 46-49. https://doi.org/10.1145/1836216.1836228

19. Edwin Chan, Teddy Seyed, Wolfgang Stuerzlinger, Xing-Dong Yang, and Frank Maurer. 2016. User Elicitation on Single-hand Microgestures. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 3403-3414. https://doi.org/10.1145/2858036.2858589

20. Euan Freeman, Stephen Brewster, and Vuokko Lantz. 2016. Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 2319-2331. https://doi.org/10.1145/2858036.2858308

21. Felicia Huppert. 2003. Designing for Older Users. In: P. John Clarkson, Roger Coleman, Simeon Keates, and Cherie Lebbon (Eds.), *Inclusive Design: Design for the whole population*. Springer, London. https://doi.org/10.1007/978-1-4471-0001-0_2

22. Hessam Jahani Fariman, Hasan J. Alyamani, Manolya Kavakli, and Len Hamey. 2016. Designing a user-defined gesture vocabulary for an in-vehicle climate control system. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction* (OzCHI '16). ACM, New York, NY, USA, 391-395. https://doi.org/10.1145/3010915.3010955

23. Hyunyoung Song, Francois Guimbretiere, Tovi Grossman, and George Fitzmaurice. 2010. MouseLight: bimanual interactions on digital paper using a pen and a spatially-aware mobile projector. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10). ACM, New York, NY, USA, 2451-2460.

24. I. Scott MacKenzie. 2003. Motor behaviour models for human-computer interaction. In J. M. Carroll (Ed.) *HCI models, theories, and frameworks: Toward a multidisciplinary science*, 27-54. San Francisco: Morgan Kaufmann.

25. Ilhan Aslan, Ida Buchwald, Philipp Koytek, and Elisabeth André. 2016. Pen + Mid-Air: An Exploration of Mid-Air Gestures to Complement Pen Input on Tablets. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA, Article 1, 10 pages. https://doi.org/10.1145/2971485.2971511

26. Ivan Golod, Felix Heidrich, Christian Möllering, and Martina Ziefle. 2013. Design principles of hand gesture interfaces for microinteractions. In *Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces* (DPPI '13). ACM, New York, NY, USA, 11-20. http://dx.doi.org/10.1145/2513506.2513508

27. J. L. Arnott, Z. Khairulla, A. Dickinson, A. Syme, N. Alm, R. Eisma, P. Gregor. 2004. E-mail Interfaces for Older People. In *Proc. IEEE Conference on Systems, Man & Cybernetics* (SMC 2004), 111-117.

28. Jacob O. Wobbrock, Meredith Ringel Morris, and Andrew D. Wilson. 2009. User-defined gestures for surface computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '09). ACM, New York, NY, USA, 1083-1092.

29. Jaime Ruiz and Daniel Vogel. 2015. Soft-Constraints to Reduce Legacy and Performance Bias to Elicit Whole-body Gestures with Low Arm Fatigue. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). ACM, New York, NY, USA, 3347-3350. https://doi.org/10.1145/2702123.2702583

30. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. https://doi.org/10.1145/2325616.2325625

31. Jennifer L. Davidson and Carlos Jensen. 2013. Participatory design with older adults: an analysis of creativity in the design of mobile healthcare applications. In *Proceedings of the 9th ACM Conference on Creativity & Cognition* (C&C '13). ACM, New York, NY, USA, 114-123.

32. Jennifer L. Davidson and Carlos Jensen. 2013. What health topics older adults want to track: a participatory design study. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility* (ASSETS '13). ACM, New York, NY, USA.

33. John Vines, Gary Pritchard, Peter Wright, Patrick Olivier, and Katie Brittain. 2015. An Age-Old Problem: Examining the Discourses of Ageing in HCI and

Strategies for Future Research. *ACM Trans. Comput.-Hum. Interact*. 22, 1, 2. https://doi.org/10.1145/2696867

34. John Vines, Mark Blythe, Stephen Lindsay, Paul Dunphy, Andrew Monk, and Patrick Olivier. 2012. Questionable concepts: critique as resource for designing with eighty somethings. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1169-1178.

35. Ka-Ping Yee. 2004. Two-handed interaction on a tablet display. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '04). ACM, New York, NY, USA, 1493-1496.

36. Karin Slegers, Martin P. J. Van Boxtel, and Jelle Jolles. 2012. Computer use in older adults: Determinants and the relationship with cognitive change over a 6 year episode. *Computers in Human Behavior*. 28, 1, 1-10.

37. Karyn Moffatt. 2013. Older-adult HCI: why should we care? *interactions.* 20, 4, 72-75. https://doi.org/10.1145/2486227.2486242

38. Kathrin Gerling, Ian Livingston, Lennart Nacke, and Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1873-1882. https://doi.org/10.1145/2207676.2208324

39. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346.

40. Mark Rice, Yian Ling Cheong, Jamie Ng, Puay Hoe Chua, and Yin-Leng Theng. 2012. Co-creating games through intergenerational design workshops. In *Proceedings of the Designing Interactive Systems Conference* (DIS '12). ACM, New York, NY, USA, 368-377. https://doi.org/10.1145/2317956.2318012

41. Meredith Ringel Morris, Andreea Danielescu, Steven Drucker, Danyel Fisher, Bongshin Lee, m. c. schraefel, and Jacob O. Wobbrock. 2014. Reducing legacy bias in gesture elicitation studies. *interactions*. 21, 3, 40-45. https://doi.org/10.1145/2591689

42. Michael W. Smith, Joseph Sharit, and Sara J. Czaja. 1999. Aging, Motor Control, and the Performance of Computer Mouse Tasks. Human Factors. 41, 3, 389-396.

43. Morten Hertzum and Kasper Hornbæk. 2010. How Age Affects Pointing With Mouse and Touchpad: A Comparison of Young, Adult, and Elderly Users. *International Journal of Human–Computer Interaction*. 26, 7, 703-734. https://doi.org/10.1080/10447318.2010.487198

44. Nic Hollinworth. 2009. Improving computer interaction for older adults. *SIGACCESS Access. Comput*. 93 (January 2009), 11-17. http://dx.doi.org/10.1145/1531930.1531932

45. Peter Gregor and Alan F Newell. 2001. Designing for dynamic diversity: making accessible interfaces for older people. In *Proceedings of the 2001 EC/NSF workshop on Universal accessibility of ubiquitous computing: providing for the elderly* (WUAUC'01). ACM, New York, NY, USA, 90-92. http://dx.doi.org/10.1145/564526.564550

46. Pew Research Center. 2014. Older Adults and Technology Use. In *Internet and Technology report*. Retrieved August 29, 2018 from http://www.pewinternet.org/2014/04/03/older-adults-and-technology-use/

47. Ravin Balakrishnan and Ken Hinckley. 2000. Symmetric bimanual interaction. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (CHI '00). ACM, New York, NY, USA, 33-40. http://dx.doi.org/10.1145/332040.332404

48. R. G. Marteniuk, C. L. MacKenzie & D. M. Baba. 1984. Bimanual movement control: Information processing and interaction effects. *The Quarterly Journal of Experimental Psychology Section A*. 36, 2, 335-365. https://doi.org/10.1080/14640748408402163

49. Ross McLachlan and Stephen Brewster. 2015. Bimanual Input for Tablet Devices with Pressure and Multi-Touch Gestures. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '15). ACM, New York, NY, USA, 547-556. https://doi.org/10.1145/2785830.2785878

50. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.

51. Silas Wan and H. T. Nguyen. 2008. Human computer interaction using hand gesture. In *Proceedings of the 2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, Vancouver, British Columbia, Canada, 2357-2360. https://doi.org/10.1109/IEMBS.2008.4649672

52. Stephen Lindsay, Daniel Jackson, Guy Schofield, and Patrick Olivier. 2012. Engaging older people using participatory design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1199-1208.

53. Steven C. Seow, Dennis Wixon, Ann Morrison, and Giulio Jacucci. 2010. Natural user interfaces: the prospect and challenge of touch and gestural computing. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '10). ACM, New York, NY, USA, 4453-4456. https://doi.org/10.1145/1753846.1754172

54. Sukeshini A. Grandhi, Gina Joue, and Irene Mittelberg. 2011. Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 821-824. https://doi.org/10.1145/1978942.1979061

55. Thammathip Piumsomboon, Adrian Clark, Mark Billinghurst, and Andy Cockburn. 2013. User-defined gestures for augmented reality. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '13). ACM, New York, NY, USA, 955-960. https://doi.org/10.1145/2468356.2468527

56. United Nations. 2015. Levels and trends in the number of older persons. In *World Population Ageing Report*. Retrieved 31 August, 2018 from http://www.un.org/en/development/desa/population/publications/pdf/ageing/WPA2015_Report.pdf

57. Volkert Buchmann, Stephen Violich, Mark Billinghurst, and Andy Cockburn. 2004. FingARtips: gesture based direct manipulation in Augmented Reality. In *Proceedings of the 2nd international conference on Computer graphics and interactive techniques in Australasia and South East Asia* (GRAPHITE '04), Stephen N. Spencer (Ed.). ACM, New York, NY, USA, 212-221. http://dx.doi.org/10.1145/988834.988871

58. W. Buxton and B. Myers. 1986. A study in two-handed input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '86), Marilyn Mantei and Peter Orbeton (Eds.). ACM, New York, NY, USA, 321-326.

59. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. *Journal of Hand Therapy*. 28, 1, 53-60.

8 *General Discussion and Conclusions*

8 General Discussion and Conclusions

This chapter summarises the main findings and discussions present in the previous chapters and suggests future research agenda relating to ageing and mid-air gesture interaction.

8.1 Summary of Findings

In *Investigating age-related differences in how novice users perform and perceive mid-air gestures as an input method for computer interaction* (**Chapter 3**), some of the main findings include:

- The results of the guessability study suggest that mid-air gestures based upon real-world interactions (e.g. clap, grab, point, make a fist, wave) might be easier for older adults to produce consistently, compared with those based upon touchscreen paradigms (e.g. swipe, air tap, finger rotation).
- The results of the task-based study showed that older adults were in general slower than younger adults at completing computer tasks using mid-air gestures, completing those tasks on average in 24.63 seconds versus 11.06 seconds for the younger participants. Also, in order to minimise the use of fine motor input and better accommodate the motor skills of older users, hand gestures should be given preference over finger gestures.
- Gestures such as swiping left and right in mid-air for browsing items, tilting palm up and down for scrolling, pointing-and-holding for selection, and rotating the index finger for controlling the volume, were found to be problematic for older

users in our task-based study. The fist gesture showed similar performance across the two age groups.

In *Text or Image? Investigating the Effects of Instruction Type on Mid-Air Gesture Making with Novice Older Adults* (**Chapter 4**), some of the main findings include:

- All three instruction types were highly accepted by older users, but the empirical findings showed a significant advantage of pictorial instructions (static and animated) over plain text-based instructions for guiding novice older adults in making mid-air gestures with regards to the combination of accuracy, completion time and user preference.
- Animated pictorials (i.e. a 3-frame animated gif depicting the gesture) led to fastest gesture making (1 second) with 100% accuracy across older users with no prior experience in gesturing in mid-air. Static pictorials also achieved 100% accuracy of gesture making but older users needed on average 1.2 seconds to perform mid-air gestures correctly. On the other hand, descriptive instructions (text-based) achieved an accuracy rate of gesture making of under 80% and older users needed on average 2.6 seconds to perform mid-air gestures correctly.
- As described in Chapter 4, both static and animated pictorials accompanied with gesture labels resulted in faster and more accurate gesture making in comparison with pure text-based instructions, therefore pictorial instructions should be given preference when designing gesture-based interfaces that support the learning of new mid-air gestures by novice older users.

In *Movement Characteristics and Effects of GUI Design on How Older Adults Swipe in Mid-Air* (**Chapter 5**), some of the main findings include:

- According to the data collected with older adults in Chapter 5, the Leap Motion's default parameters for a mid-air swipe gesture are not aligned with the natural swipe movement characteristics of older users. The minimum speed parameter of 1000 mm/s and the minimum length parameter of 150 mm may led to failed swipe attempts by older users and might affect the overall usability of swipe-based interactions for the older population.
- Interface design played a critical role on how older adults swiped in mid-air. Older users shaped their swiping movement according to the size of the menu they were trying to navigate within. The large carousel-style menu (2130x560 pixels) was the menu with highest swipe recognition rate (90%), whilst the smallest menu size (1390x330 pixels) achieved only 18% due to swipe lengths and speeds so low that the Leap Motion sensor was incapable of interpreting the motions as a recognisable swipe.
- The Leap Motion sensor may not necessarily take into consideration the psychomotor skills of older adults. Furthermore, Graphical User Interface (GUI) design choices (i.e. menu size) shaped how older users produced a gesture in mid-air but and can be a key factor for supporting older users with little familiarity in using this novel input method successfully.

In *Evaluating the Effects of Feedback Type on Older Adults' Performance in Mid-Air Pointing and Target Selection* (**Chapter 6**), some of the main findings include:

- Older adults aged 70 and older presented poorer performance in mid-air point-and-select tasks in comparison with older adults aged between 60 and 69 years old.

- In mid-air target acquisition by older users, bimodal Visual-and-Audio feedback lead to faster target selection (6.2 seconds on average) in comparison to unimodal Visual or Audio feedback (7.4 and 7.2 seconds respectively), but error rates remained the same across all feedback modalities.
- More importantly, target location on screen showed to be a more decisive factor for older adults' pointing and selection performance in mid-air than the feedback type due to how older adults positioned their hands in relation to the Leap Motion sensor.
- Although highly used in commercially available applications, mid-air pointing gestures were found to be poorly performed and fatiguing to older users, according to the findings of Chapter 6.

In *Investigating the Suitability and Effectiveness of Mid-Air Gestures Co-Design By and For Older Adults* (**Chapter 7**), some of the main findings include:

- In general, mid-air gestures co-designed by older adults for computer microinteractions, compared with off-the-shelf gestures and mouse interaction, achieved higher acceptance rates, faster task completion times and fewer errors.
- Co-designed mid-air gestures achieved higher memorability rates in comparison with off-the-shelf mid-air gestures, after a week of the first exposure.
- Co-designed mid-air gestures such as hand open (stop sign) for stopping a video, waving for opening a menu, and hand-to-left for locking the computer, achieved high preference over completing the same microinteractions with a mouse. On the other hand, older adults still preferred using the mouse for microinteractions such as scrolling and controlling the volume.

- In relation to cost-benefit analysis, participatory design methods may be an effective strategy for designing and improving mid-air gesture interactions that better support the needs and capabilities of older users.
- According to the findings of Chapter 8, mid-air gesture interaction showed to be an suitable and effective input method for supporting computer use by older adults, as long as it is intended to act as a facilitator for completing short microinteractions and not to completely replace mouse interaction.

Altogether with the discussions explored within the previous chapters, the empirical evidence provided in this doctoral thesis indicates that mid-air gesture interaction indeed offers many usability challenges for the older population (e.g. fatigue, learnability, memorability, technology acceptance). However, these problems can be minimised by using a more user-centred and inclusive approach. For instance, older adults' performance with off-the-shelf mid-air gestures in Chapter 7 is similar to older adults' performance in Chapter 3. The gesture sets used in both situations are similar and do not necessarily take into consideration the older population. Performance and user acceptance greatly improved once older users were included in the design process and the recommendations based on the findings of this doctoral research were put into practice.

8.2 Research Questions Revisited

This section aims to summarise main contributions by revisiting some of the research questions described in the introductory chapter of the thesis.

8.2.1 Questions regarding the cognitive aspects of mid-air gesture interaction and ageing

Are mid-air gestures easy to learn and to remember for novice older users with little familiarity with this novel input method? As reported in Chapter 7, older adults presented difficulties in recalling off-the-shelf mid-air gestures after an initial interaction. However, mid-air gestures co-designed by older adults generally achieved higher recall rates. A possible reason for this could be that co-designed mid-air gestures are generally more simple and may be more intuitive for older adults and their psychomotor models.

What are the design principles that may help older users in learning and remembering mid-air gestures more easily? According to the findings of Chapter 4, gesture-based interfaces that provide pictorial instructions (static or animated) may support novice older users in learning how to make correct mid-air gestures with higher accuracy and faster attempts in comparison with purely text-based descriptions of the same gestures.

8.2.2 Questions regarding motor aspects of mid-air gesture interaction and ageing

In what aspects does ageing affect the performance of mid-air gestures by older adults in comparison with younger users? And how can we design mid-air gestures that are physically appropriate for the older population? Older adults presented difficulties in making precise and steady movements when attempting to make pointing gestures. Furthermore, finger gestures such as finger pinch, index finger rotation, and air tapping, involved dexterity and were, in general, poorly performed by older users. Hand gestures that did not involve finger dexterity nor complex movements (e.g. clapping, hand waving, fist gesture, stop sign, hand open) showed to be more appropriate for the physical abilities of older adults

8.2.3 Questions regarding the sensory aspects of mid-air gesture interaction as well as empowering and supporting older users in using mid-air gestures correctly

What are the most efficient ways for providing older users with feedback on where and how to gesture correctly in relation to what is expected by the system? According to the findings of Chapter 6, a bimodal combination of visual and audio feedback achieved faster gesture making for selection amongst older adults aged 70 and over.

Does mid-air gesture interaction facilitate computer use for older users in comparison with traditional input methods? As a replacement, mid-air gesture interaction did not generally improve or facilitate computer use for older users, in comparison with traditional input method such as mouse and keyboard. However, mid-air gestures may be suitable as a secondary input choice if combined with other input methods.

In what context older users find mid-air gestures to be useful? Unlike younger adults who preferred mid-air gestures for direct manipulation (e.g. dragging objects by grabbing them in mid-air), older adults generally preferred simple “trigger” gestures that served as shortcuts – a substitute to actions that required multiple commands and clicking for instance (e.g. “hand wave” to open a menu).

How to better design age-friendly interfaces for mid-air gesture interaction? According to the findings of Chapter 7, applying participatory design methods for co-designing mid-air gestures with older adults showed to be an effective strategy to envisage age-friendly gesture sets that are intuitive and suitable for an older population. Co-designed gestures achieved higher usability ratings in comparison with off-the-shelf gestures when applied in a computer interaction context.

8.3 General Guidelines for Designing Age-Inclusive Mid-Air Gesture Interaction

The main findings of all studies presented in this research showed that age-inclusive mid-air gesture interaction requires considerations regarding the older population's physical, sensory and cognitive abilities on many levels. In order to summarise the research contributions, a list of main guidelines for developing age-inclusive gesture interfaces was generated based on common interaction problems identified during the research. The guidelines below aim to address age-related issues and solutions regarding gesture-based interfaces and older users.

Guideline 1: Minimise the use of finger gestures and heavy dexterity

Finger gestures - such as finger pinch, air tap, index finger rotation, and finger pointing - usually require heavy dexterity and fine precision. These motor abilities decline considerably during ageing, therefore should be avoided. Hands gestures should be given preference.

Guideline 2: Minimise the use of direct manipulation

Direct manipulation (i.e. continuous gestures) may require longer and steady movements that may not be as easy for older users. The use of mid-air gestures such as "grab and drag", "pinch and pull", or "pointing" should be minimised. Simple one-time action gestures should be given preference.

Guideline 3: Support gesture learning by using pictorial representations of new gestures

Some mid-air gestures may not be as straightforward to learn as others. Therefore, the inclusion of pictorial representations (static or animated, depending on the gesture) in a gesture-based interface may help novice older users in learning how to make new gesture commands for the first time. Purely text-based instructions should be avoided.

Guideline 4: Adapt sensing parameters

Older users may attempt to gesture in different ways than younger users (e.g. shorter and slower swiping, for example), therefore motion sensing parameters should be adapted to support these characteristics of the older population. Larger interface elements (e.g. menu size) may lead older users to making larger – and therefore more easily recognisable – gestures.

Guideline 5: Provide multimodal feedback

Novice older users may present difficulties in finding where and how to gesture, therefore appropriate feedback is fundamental. A bimodal combination of visual and audio feedback should be given preference for supporting older users in making correct gestures.

Guideline 6: Choose mid-air gesture sets based on real world gestures instead of gestures used on touchscreen devices

Some older users may not be familiar with touchscreen devices. Mid-air gestures based on real world gestures such as hand wave, thumbs up, and stop sign, may be easier for older users to learn, perform and remember in comparison with mid-air gestures based on touchscreen interactions (e.g. swipe, tap, pinch to zoom).

Guideline 7: Provide alternative to purely gesture-based commands

Older users consist of a diverse group that may present different levels of familiarity with different input devices. Providing multimodal input methods such as the combination of mid-air gesture commands with touchpad or mouse may support older users in completing computer tasks in a more effective way than providing a single input method.

8.4 Theoretical Contributions and Practical Implications

Mid-air gesture interaction had not previously been studied systematically with regard to its usability for older adults (aged 60 and older). Therefore, the body of research reported in this thesis was predominantly explorative in its core. The majority of literature related to the usability of gesture-based interfaces is currently supported by touchscreen interfaces [3, 12] and empirical data either from young or skilled users [4, 9, 15, 16] so, consequently, the lack of empirical evidence from older users, prior to this thesis, was not sufficient to put this user population into perspective.

The major contribution of the research is related to the advances toward a better understanding on how older adults perceive and interact with interfaces based on mid-air gesture interactions. These results are summarised in greater detail in Section 8.1. Unlike the generally disseminated idea of gesture interaction being natural and intuitive for most users [5, 6, 15], the main evidence emerging from the different empirical investigations that integrate this thesis is the overall comprehension that older adults indeed encounter many interaction challenges that were never properly evaluated or elucidated in the literature regarding mid-air gesture interaction and motion-based systems. These challenges were first identified in Chapter 3 and clearly contrast the results from younger participants in the same study, which are aligned to the findings of similar studies in the literature [9, 15].

Some typical challenges such as the physical effort related to direct manipulation and constant arm movements were addressed in the past on a conceptual level [5, 9, 11], but were never studied in-depth in order to find practical user interface solutions to minimise these problems. Other interaction challenges such as the lack of visible user interface affordances related to finding "where" and "how" to make gesture commands (i.e. addressing the interaction space) were discussed in the literature but lacked the inclusion of older adults in previous empirical studies [4, 16]. Therefore, it remained unclear how the user group was affected by this fundamental issue. Although the challenge of addressing the interaction space can be faced by any user regardless of age, novice older users are more likely to be affected by this problem according to the results presented in Chapter 3 and Chapter 6. The thesis also proposes age-inclusive user interface methods for minimising the "where" (Chapter 6) and "how to gesture" problems (Chapter 4).

From a methodological perspective, the thesis presents a combination of theory-driven and data-driven approaches. There was little understanding of how age affects mid-air gesture interactions, and answering the main research questions of this thesis solely by using HCI literature on touchscreen gestures [3, 12, 16] or general literature on ageing and motor psychology [1, 2, 10] would be insufficient and inadequate. Therefore, an applied perspective that focused on real use and empirical evidence was combined with the theories in the field. The data-driven contributions of the thesis lie on the combination of objective and subjective measurements present in the empirical studies within the chapters.

In addition to applying usability testing methods [7] in Chapters 3 to 7, the thesis expanded the use of gesture elicitation methods [8] by not only eliciting but also validating the suitability of the elicited gestures on functional tasks (Chapter 3). Furthermore, the thesis expanded the use of participatory and co-design methods [10, 13] for designing age-inclusive gestures with older adults by not only co-designing gestures but also comparing the efficiency of these gestures on an experimental level with off-the-shelf gestures that may not take into consideration the older population (Chapter 7). Lastly, the functional prototype based on the findings of Chapter 3 to 6 and built in Chapter 7 allowed the evaluation of co-designed gestures on both objective and subjective measures in the same way that helped validating the design recommendations proposed in the thesis on a practical level.

Related to design recommendations, general guidelines on how to design suitable interfaces for older adults have been suggested in the past [2, 3, 11, 14], but mostly on a rather abstract level. For instance, the recommendations proposed by [11] and [14] suggest to eliminate unnecessary complexity, accommodate a wide range of literacy skills and reduce physical efforts. Whilst this approach may apply to a range of gesture-based interfaces and may claim universal adequacy, they provide little practical guidance to designers and software developers in the field of mid-air gesture interaction or gesture-based interfaces.

Other design recommendations, including for example the use of simple gestures for reducing upper limb fatigue [9, 11] and the use of multimodal feedback for guiding

novice users [1, 4, 16] were also proposed in the past and may indeed help to design better gesture-based interfaces. However, these recommendations lack contextualised use.
For example, the idea of using simple gestures for reducing fatigue is associated with the type and duration of the interaction, as well as the gesture set available for the users. Prior guidelines do not propose specific gesture sets for reducing fatigue nor clarify what gestures should be avoided. Similarly, the idea of using multimodal feedback for guiding novice users serve as a basis for designing better gesture-based interfaces, but it provides little consideration on the different interaction contexts that might need specific feedback modalities. In addition to that, these guidelines were mostly based on the input of younger users and lack age-inclusiveness.

Therefore, unlike prior work in the field, each study of the thesis proposes practical and contextualised age-inclusive recommendations for designing mid-air gesture input based on empirical evidence from older adults and related to the interaction context explored within each chapter. These recommendations do not only identify key interaction points to consider, but also provide specific methods for minimising interaction challenges and enhancing the usability of gesture-based interfaces.

8.5 Summary of Contributions

The thesis makes the following contributions to the field of ageing and mid-air gesture interaction:

- It evaluates age-related differences on how older users (aged 60+) differ from younger users when interacting with mid-air gestures for the first time by comparing their performance and user preference on different gesture commands for computer tasks.

- It identifies key interaction challenges faced by older adults that affect how they interact with mid-air gestures due to age-related changes.
- It expands the use of gesture elicitation methods by eliciting gestures with older adults and testing their suitability in a task-based context.
- It investigates different user interface methods for enhancing age-inclusive gesture learning and correct gesture execution for novice users.
- It evaluates different feedback modalities for guiding older users in mid-air point-and-select tasks.
- It provides data-driven parameters for improving the Leap Motion sensor's recognition rate of swipe gestures made by older adults.
- It recommends gesture sets that are either better performed or preferred by older users.
- It expands the use of co-design methods by co-designing age-friendly mid-air gestures for older users by comparing their suitability with off-the-shelf gestures on an experimental level.
- It provides a contextualised set of guidelines for designing user interfaces and age-inclusive mid-air gesture interactions.

8.6 Limitations and Future Work

The focus of this research was the practical implications of mid-air gesture interaction in the context of computer use and older users. Different interaction contexts such as gaming and personal entertainment, public space interfaces, wall-sized displays, virtual and augmented reality, and the use of full-body interaction may offer challenges and insights on how older adults engage with these physically embodied input methods that may be not necessarily covered in this thesis. Also, the findings of this research are associated with the gesture sets used within its series of user studies and should be generalised with caution since different gestures may involve interaction aspects that could differ from the guidelines explored by this work. Furthermore, since familiarity plays a fundamental role in computer interaction and all of the 64 older adults that participated throughout this research reported past computer-mediated exposure, the inclusion of older adults with little to no familiarity with interactive devices as well as individuals with physical impairments would probably raise additional questions and face greater difficulties which were not addressed so far.

Regarding future directions for work, the main findings of this research on ageing and mid-air gesture interaction suggest that gesture literacy, execution and acceptance are affected by age and psychomotor functions. Therefore, the exploration of adaptive gesture-based interfaces that not only predict the particularities of users based on their gesturing characteristics (e.g. gesture kinematics, learning curve, interaction pace) but also adapt its gesturing parameters in order to better accommodate the individualities of each user may be a relevant and promising area for HCI research.

References

[1] A. Chaparro et al. 1999. The impact of age on computer input device use: Psychophysical and physiological measures. *International Journal of Industrial Ergonomics*. 24, 503--513.

[2] C. J. Ketcham et al. 2002. Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *Journal of Gerontology*. 57, 1, 54-64.

[3] C. Stößel, L. Blessing. 2010. Tap, Swipe & Pinch: Designing suitable multi-touch gestures for older users. In *Proceedings the 11th International Design Conference* (DESIGN 10). The Design Society, 463-472.

[4] E. Freeman et al. 2016. Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 2319-2331.

[5] J. Bobeth et al. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44.

[6] J. Hurtienne et al. 2010. Physical gestures for abstract concepts: Inclusive design with primary metaphors. *Interacting with Computers*. 22, 6 (November 2010), 475-484.

[7] J. M. C. Bastien. 2010. Usability testing: a review of some methodological and technical aspects of the method. *International Journal of Medical Informatics*. 79, 4, April 2010, 18-23.

[8] J. O. Wobbrock et al. 2005. Maximizing the guessability of symbolic input. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '05). ACM, New York, NY, USA, 1869-1872.

[9] J. Ruiz, D. Vogel. 2015. Soft-Constraints to Reduce Legacy and Performance Bias to Elicit Whole-body Gestures with Low Arm Fatigue. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). ACM, New York, NY, USA, 3347-3350.

[10] J. Vines et al. 2015. An Age-Old Problem: Examining the Discourses of Ageing in HCI and Strategies for Future Research. *ACM Trans. Comput.-Hum. Interact*. 22, 1.

[11] K. Gerling et al. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1873-1882.

[12] L. Findlater et al. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346.

[13] L. M. Muriana, H. H. Hornung. 2017. Including Older Adults into the Design Process: Challenges and Lessons Learned. In *Proceedings of the XVI Brazilian Symposium on Human Factors in Computing Systems* (IHC 2017). ACM, New York, NY, USA.

[14] M. A. Farage et al. 2012. Design Principles to Accommodate Older Adults. *Global Journal of Health Science*. 4, 2, March 2012.

[15] S. A. Grandhi et al. 2011. Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 821-824.

[16] S. S. Billinghurst, K. L. Vu. 2015. Touch screen gestures for web browsing tasks. *Computers in Human Behavior*. 53 (December 2015), 71-81.

Full List of References

Chapter 1

1. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258. http://dx.doi.org/10.1145/2783446.2783599

2. Ben Shneiderman. 1980. Software Psychology: Human Factors in Computer and Information Systems. Winthrop, USA.

3. Donald A. Norman and Stephen W. Draper. 1986. User-Centered System Design: New Perspectives on Human-Computer Interaction. L. Erlbaum Assoc. Inc., USA.

4. Donald A. Norman. 2010. Natural User Interfaces Are Not Natural. *interactions*. 17, 3, 6-10. https://doi.org/10.1145/1744161.1744163

5. Jakob Nielsen. 1994. Usability Engineering. Kaufmann Publishers, USA.

6. Paul Dourish. 2001. Where the Action is: The Foundations of Embodied Interaction. MIT Press, Cambridge, MA, USA.

7. Sukeshini A. Grandhi, Gina Joue, and Irene Mittelberg. 2011. Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 821-824. https://doi.org/10.1145/1978942.1979061

8. Thomas T. Hewett, Ronald Baecker, Stuart Card, Tom Carey, Jean Gasen, Marilyn Mantei, Gary Perlman, Gary Strong, and William Verplank. 1992. ACM SIGCHI Curricula for Human-Computer Interaction. *Technical Report*. ACM, New York, NY, USA.

9. United Nations. 2015. Sustainable Development Goals. In *Department of Economic and Social Affairs' knowledge platform*. Retrieved September 2018 from: https://sustainabledevelopment.un.org/

10. University of Reading's Graduate School. 2016. Writing a Thesis as a Collection of Papers. In *Guide for Examiners of Research Degrees*. Retrieved September 2018 from: http://www.reading.ac.uk/web/files/graduateschool/gradschwritingthesisascollectionofpapers.pdf

11. World Health Organization (WHO). Ageing and Life Course. In *Global Health and Ageing*. Retrieved September 2018 from: http://www.who.int/ageing/en/

Chapter 2

1. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266.

2. B. Laursen, B.R. Jensen, and A. Ratkevicius. Performance and muscle activity during computer mouse tasks in young and elderly adults. *European Journal Applied Physiology* 84 (2001), 329-336.

3. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78.

4. European Union statistics. 2018. Population Structure and Ageing. In *Eurostat Statistics Publication*. Retrieved September 2018.

5. Esben Warming Pedersen and Kasper Hornbæk. 2012. An Experimental Comparison of Touch Interaction on Vertical and Horizontal Surfaces. In *Proceedings of NordiCHI '12*. ACM, New York, NY, USA, 370-379.

6. Genaro Motti, Lilian and Vigouroux, Nadine and Gorce, Philippe *Interaction techniques for older adults using touchscreen devices : a literature review.* (2013) In: 25eme conference francophone sur l'Interaction Homme-Machine (IHM 2013), 13 November 2013 - 15 November 2013 (Bordeaux, France).

7. Hiroyuki Umemuro. 2004. Lowering elderly Japanese users' resistance towards computers by using touchscreen technology. *Univers. Access Inf. Soc*. 3, 3-4 (October 2004), 276-288. http://dx.doi.org/10.1007/s10209-004-0098-6

8. H. Wandke, M. Sengpiel, and M. Sönksen. 2012. Myths About Older People's Use of Information and Communication Technology. *Gerontology*. 58, 6, 564-570.

9. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. https://doi.org/10.1145/2325616.2325625

10. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346.

11. Kathrin Gerling, Ian Livingston, Lennart Nacke, and Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1873-1882. https://doi.org/10.1145/2207676.2208324

12. Michael W. Smith, Joseph Sharit, and Sara J. Czaja. 1999. Aging, Motor Control, and the Performance of Computer Mouse Tasks. Human Factors. 41, 3, 389-396.

13. Peter Gregor and Alan F Newell. 2001. Designing for dynamic diversity: making accessible interfaces for older people. In *Proceedings of the 2001 EC/NSF workshop on Universal accessibility of ubiquitous computing: providing for the elderly* (WUAUC'01). ACM, New York, NY, USA, 90-92. http://dx.doi.org/10.1145/564526.564550

14. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.

15. United Nations. 2017. World Population Ageing report. In *Department of Economic and Social Affairs, Population Division*. Retrieved September 2018.

Chapter 3

Blackler, A., and Popovic, V. (2015). Towards Intuitive Interaction Theory. *Interacting with Computers*, 27(3), 203-209.

Blackler, A., Popovic, V. and Mahar, D. (2003). The nature of intuitive use of products: an experimental approach. *Design Stud.*, 24, 491–506.

Bobeth, J., Schmehl, S., Kruijff, E., Deutsch, S., Tscheligi, M. (2012). Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proc. of EuroiTV '12*, 35-44.

Braun, V., Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3, 77-101.

Brooke, J. (1996). SUS: a “quick and dirty” usability scale. In: Jordan, P. W., Thomas, B., Weerdmeester, B. A., McClelland, I. L. Eds.: *Usability Evaluation in Industry*, pp. 189-194. London: Taylor & Francis.

Buxton, W., Fiume, E., Hill, R., Lee, A., Woo, C. (1983). Continuous hand-gesture driven input. *Graphics Interface '83*, 191-195.

Cabreira, A. T., Hwang, F. (2015). An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258.

Cabreira, A. T., Hwang, F. (2016). How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA.

Chaparro A., Rogers M., Fernandez J., Bohan M., Choi S.D., Stumpfhauser L. (2000). Range of motion of the wrist: implications for designing computer input devices for the elderly. *Disabil Rehabil.* 2000 Sep 10-20;22(13-14):633-7.

Charness, N. and W.R. Boot, W.R. (2009). Aging and information technology use: potential and barriers, *Current Directions in Psychological Science* 18 (5), 253–258.

Coughlin, J.F., Pope, J.E., & Leedle, B.R. Jr. (2006). Old age, new technology, and future innovations in disease management and home health care. *Home Health Care Management & Practice*, 18, 196–207.

Czaja, S.J., and Lee, C.C. (2007). The impact of aging on access to technology. *Universal Access in the Information Society,* 5, 341-349.

Delamare, W., Janssoone, T., Coutrix, C., Nigay, L. (2016). Designing 3D Gesture Guidance:

Visual Feedback and Feedforward Design Options. In Proc. AVI '16. ACM.

Dourish, P. (2004). Where the Action Is: The Foundations of Embodied Interaction. MIT Press.

Emery, V.K., et al. (2003). Toward achieving universal usability for older adults through multimodal feedback. In *Proc. the 2003 ACM Conference on Universal Usability* (CUU03), 46–53.

Findlater, L., Froehlich, J.E., Fattal, K., Wobbrock, J.O., and Dastyar, T. (2013). Age-related differences in performancewith touchscreens compared to traditional mouse input. In *Proc. of CHI '13,* 343–346. ACM.

Findlater, L., Lee, B., and Wobbrock, J. (2012). Beyond QWERTY: augmenting touch screen keyboards with multi-touch gestures for non-alphanumeric input. In *Proc. CHI 2012*, 2679-2682. ACM.

Fisk A.D., Rogers A.R., Charness N, Czaja S.J., & Sharit J. (2009). Designing for Older Adults – Principles and Creative Human Factors Approaches. Boca Raton: CRC Press.

Gerling K., Livingston, I., Nacke L., and Mandryk, R. (2012). Full-body motion-based game interaction for older adults. In *Proc. CHI 2012*, 1873-1882. ACM.

Grandhi, S. A., Joue, G., Mittelberg, I. (2011). Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proc. CHI 2011*, 821-824. ACM.

Hartson, R. (2003). Cognitive, physical, sensory, and functional affordances in interaction design. *Behaviour & Information Technology*, 22:5, 315-338.

Hincapié-Ramos, J. D., Guo, X., Moghadasian, P., and Irani, P. (2014) Consumed endurance: A metric to quantify arm fatigue of mid-air interactions. In *Proc. CHI 2014,* 1063–1072. ACM.

Huppert, F.A. (2003). Designing for Older Users. In: PJ Clarkson, R Coleman, S Keates & C Lebbon (Eds) *Inclusive Design: Design for the whole population*. Springer Verlag, London.

Hurtienne, J. (2009). Image Schemas and Design for Intuitive Use. Technischen Universität Berlin, Berlin.

Hutchins E.L., Hollan, J.D. and Norman D.A. (1986) Direct manipulation interfaces. In: Norman & Draper (eds) *User centered system design: new perspectives on human-computer interaction*. Lawrence Earlbaum Associates, Hillsdale, NJ.

Hwang, F., Hollinworth, N., and Williams, N. (2013). Effects of target expansion on selection performance in older computer users. *ACM Trans. Access. Comput.* 5, 1, Article 1.

Johnson, M. (1987). The Body in the Mind. The Bodily Basis of meaning, Imagination, and reason. The University of Chicago Press.

Kalisch, T., Tegenthoff, M., and Dinse, H.R. (2008). Improvement of sensorimotor functions in old age by passive sensory stimulation. *Clin. Intervent. Aging* 2008; 3:673–90.

Kaptelinin, V., Nardi, B. (2012). Affordances in HCI: toward a mediated action perspective. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 967-976.

Kim, H., Takahashi, I., Yamamoto, H., Maekawa, S., Naemura, T. (2014). Mario: Mid-air augmented reality interaction with objects. *Entertainment Computing* 5, 4, 233 – 241.

Ketcham, C. J., Seidler, R. D., Van Gemmert, A. W.A., Stelmach, G. E. (2002). The Journals of Gerontology: Series B 57, 1, 54-64.

Komerska, R., Ware, C. (2003) Haptic task constraints for 3D interaction. In *Proceedings of IEEE HAPTICS 2003*, 270–277. IEEE.

Köpsel, A., and Bubalo, N. (2015). Benefiting from legacy bias. *interactions* 22, 5, 44-47.

Koutsabasis, P., Domouzis, C. (2016). Mid-Air Browsing and Selection in Image Collections. *International Working Conference on Advanced Visual Interfaces* (AVI) 2016. ACM.

Kratz, S., Rohs, M., Guse, D., Müller, J., Bailly, G. and Nischt, M. (2012). PalmSpace: continuous around-device gestures vs. multitouch for 3D rotation tasks on mobile devices. In *Proc. AVI '12*, 181-188.

Lee, S., et al. (2013). Towards more natural digital content manipulation via user freehand gestural interaction in a living room. In *Proc. UbiComp '13*, 617-626. ACM.

Maes, P., and Schneiderman, B. (1997). Direct manipulation vs. Interface agents: a debate. *Interactions* 4, 42–61.

McGrenere, J., Ho, W. (2000). Affordances: Clarifying and evolving a concept. In *Proceedings of the Graphics Interface 2000*, Canadian Human-Computer Communications Society: Toronto, 179 – 186.

Moffatt, K. A. and McGrenere, J. (2009). Exploring methods to improve pen-based menu selection for younger and older adults. *ACM Trans. Access. Comput.* 2, 1, Article 3. 1–32.

Moffatt, K. (2013). Older-adult HCI: why should we care? *interactions* 20, 4, 72-75.

Morris, M. R., Danielescu, A., Drucker, S., Fisher, D., Lee, B., and Wobbrock, J. O. (2014). Reducing legacy bias in gesture elicitation studies. *Interactions*, 21(3), 40-45.

Nacenta, M.A., Kamber, Y., Qiang, Y. and Kristensson, P.O. (2013). Memorability of pre-designed and userdefined gesture sets. *Proc. CHI 2013*. ACM.

Nielsen, M., Störring, M., Moeslund, T.B. and Granum, E. (2003). A procedure for developing intuitive and ergonomic gesture interfaces for HCI. *Int'l Gesture Workshop 2003*, LNCS vol. 2915. Heidelberg: SpringerVerlag, 409-420.

Norman, D. A. (1988). The psychology of everyday things. New York: Basic Books.

Norman, D. A., Nielsen, J. (2010). Gestural interfaces: a step backward in usability. *interactions* 17, 5, 46-49.

Norman, D.A., Wadia, B. (2013). Opportunities and Challenges For Touch and Gesture-Based Systems. In *2013 Society for Information Display conference*, Vancouver, Canada (May, 23).

Oakley, I., McGee, M., Brewster, S., Gray, P. (2000) Putting the feel in ‘look and feel’. In *Proceedings of ACM CHI 2000*, 415–422. ACM.

O’Hara, K., et al. (2014). Touchless Interaction Surgery. *Communications of the ACM*, 57, 1, 70-77.

Piper, A. M., Campbell, R., Hollan, J. D. (2010). Exploring the accessibility and appeal of surface computing for older adult health care support. *Proc. CHI 2010*, 907–916. ACM.

Pullin, G., Newell, A. (2007). Focussing on Extra-Ordinary Users. In: Stephanidis C. (eds) *Universal Acess in Human Computer Interaction*. Coping with Diversity. UAHCI 2007. Lecture Notes in Computer Science, vol 4554. Springer, Berlin, Heidelberg.

Rahman, M., Gustafson, S., Irani, P. and Subramanian, S. (2009). Tilt techniques: investigating the dexterity of wrist-based input. In *Proc. CHI '09*. 1943-1952. ACM.

Rice, M., et al. (2011). Evaluating gesture-based games with older adults on a large screen display. In *Proc. of the 2011 ACM SIGGRAPH Symposium on Video Games* (Sandbox '11), 17-24.

Rice, M., et al. (2013). The dynamics of younger and older adult's paired behavior when playing an interactive silhouette game. In *Proc. CHI 2013*, 1081-1090. ACM.

Rodriguez, I. B., Marquardt, N. (2017). Gesture Elicitation Study on How to Opt-in & Opt-out from Interactions with Public Displays. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (ISS '17). ACM, New York, NY, USA, 32-41.

Rogers, Y. (2004) New theoretical approaches for HCI. *ARIST: Annual Review of Information Science and Technology*, 38, 87-143.

Ruiz, J., Li, Y., and Lank, E. (2011). User-Defined Motion Gestures for Mobile Interaction. *Proc. CHI 2011*, 197-206. ACM.

Ruiz, J., Vogel, D. (2015). Soft-Constraints to Reduce Legacy and Performance Bias to Elicit Whole-body Gestures with Low Arm Fatigue. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15), 3347-3350. ACM.

Saffer, D. (2008). Designing Gestural Interfaces: Touchscreens and Interactive Devices. O’Reilly Media.

Selwyn, N. (2004). The information aged: A qualitative study of older adults’ use of information and communications technology, *Journal of Aging Studies* 18 (4) (2004) 369–384.

Shneiderman, B. (1982). The future of interactive systems and the emergence of direct manipulation. *Behavior and Information Technology,* I, 237-256.

Shneiderman, B. (1983). Direct manipulation: A step beyond programming languages. *IEEE Computer*, 16(8), 57-69.

Shneiderman, B. (2010). Designing the user interface: Strategies for effective human-computer interaction (5nd ed.). Reading, MA: Addison-Wesley.

Smyth, T. N., Kirkpatrick, A. E. (2006). A new approach to haptic augmentation of the GUI. *In Proc. ICMI ’06*. ACM.

Stößel, C. (2009). Familiarity as a factor in designing finger gestures for elderly users. In *Proc. MobileHCI '09,* Article 78.

Stößel, C., Wandke, H. and Blessing, L. (2010). Gestural interfaces for elderly users: Help or hindrance? *Gesture in Embodied Communication and Human-Computer Interaction*, Springer, 269-280.

Te'eni, D. (1990). Direct manipulation as a source of cognitive feedback: a human-computer experiment with a judgment task. *International Journal of Man-Machine Studies*, 33, 453-466.

Vatavu, R. (2012). User-defined gestures for free-hand TV control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12), 45-48. ACM.

Venkatesh, V., Bala, H. (2008). Technology acceptance model 3 and a research agenda on interventions. *Decision Sciences* 39 (2), 273–315.

Vitense, H., Jacko, J.A., and Emery, V.K. (2003). Multimodal feedback: an assessment of performance and mental workload. *Ergonomics* 46 (1–3), 68–87.

Vosinakis, S., Koutsabasis, P., Makris, D., Sagia, E. (2016). A Kinesthetic Approach to Digital Heritage using Leap Motion: The Cycladic Sculpture Application. *8th International Conference on Games and Virtual Worlds for Serious Applications* (VS-GAMES). IEEE.

Vuibert, V., et al. (2015). Evaluation of Docking Task Performance Using Mid-air Interaction Techniques. In *Proc. SUI '15,* 44-52. ACM.

Walker, N., Philbin, D. A., and Fisk, A. D. (1997). Age-related differences in movement control: Adjusting submovement structure to optimize performance. *J. Gerontology: Psychol. Sci.* 52B, 1, 40–52.

Walter, R., Bailly, G., Müller, J. (2013). StrikeAPose: Revealing Mid-Air Gestures on Public Displays. In *Proc. CHI 2013,* 841-850. ACM.

Wigdor, D., and Wixon, D. (2011). Brave NUI World: Designing Natural User Interfaces for Touch and Gesture. Morgan Kaufmann.

Wobbrock, J. O., Aung, H. H., Rothrock, B., and Myers, B. A. (2005). Maximizing the guessability of symbolic input. In *Proc. CHI'05 extended abstracts*, 1869-1872. ACM.

Wobbrock, J.O., Morris, M.R., Wilson, A.D. (2009). User-defined gestures for surface computing. In *Proc. of CHI 2009,* 1083-1092. ACM.

Wu, H., Jianmin Wang, J. 2016. A visual attention-based method to address the midas touch problem existing in gesture-based interaction. *Vis. Comput.* 32, 1 (January 2016), 123-136.

Ziefle, M., Schroeder, U., Strenk, J., Michel, T. (2007). How young and older users master the use of hyperlinks in small screen devices. In *Proc. SIGCHI Conference on Human Factors in Computing Systems 2007*, 307-316. ACM.

Ziefle, M., Bay, S. (2005). How older adults meet complexity: Aging effects on the usability of different mobile phones. *Behaviour & Information Technology*, Vol. 24-5. Taylor & Francis.

Chapter 4

1. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15), 257-258. http://dx.doi.org/10.1145/2783446.2783599

2. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16), 122-128. https://doi.org/10.1145/2971485.2996757

3. Blake Ives. 1982. Graphical user interfaces for business information systems. *MIS Quarterly*. 6, 4: 15-47.

4. C. Egido and J. Patterson. 1988. Pictures and category labels as navigational aids for catalog browsing. In *Proceedings of the Conference on Human Factors in Computing Systems* (CHI 88). 127-132.

5. Charles J. Kacmar. 1991. An experimental comparison of text and icon menu item formats. In J. M. Carey, Ed. *Human Factors in Information Systems: An Organization Perspective*. Ablex Publishing, Norwood, New Jersey, USA, 27-41.

6. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In Proceedings of the 11th *International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78. http://dx.doi.org/10.1145/1613858.1613950

7. Daniel Avrahami, Scott E. Hudson, Thomas P. Moran, Brian D. Williams. 2001. Guided gesture support in the paper PDA. In *Proceedings of the 14th annual ACM symposium on User interface software and technology* (UIST '01), 197-198. http://dx.doi.org/10.1145/502348.502385

8. David Gittins. 1986. Icon-based human-computer interfaces. *International Journal of Man-Machine Studies*. 24, 6: 519-543. https://doi.org/10.1016/S0020-7373(86)80007-4

9. Donald A. Norman and Jakob Nielsen. 2010. Gestural interfaces: a step backward in usability. *interactions* 17, 5 (September 2010), 46-49. https://doi.org/10.1145/1836216.1836228

10. Douglas Frye and Elliot Soloway. 1986. Interface design: a neglected issue in educational software. In *Proceedings of the SIGCHI/GI Conference on Human Factors in Computing Systems and Graphics Interface* (CHI '87), 93-97. http://dx.doi.org/10.1145/29933.30865

11. G. Kurtenbach, T. P. Moran, W. Buxton. 1994. Contextual animation of gestural commands. In *Proc. Eurographics Computer Graphics Forum*. 13, 5: 305-314.

12. G. Rohr and E. Keppel. 1984. Iconic interfaces: where to use and how to construct? In H. W. Hendrick and O. Brown, Eds. *Human Factors in Organizational Design and Management*. Elsevier, New York, 269-275.

13. Ian H. Witten and Saul Greenberg. 1985. User interfaces for office systems. In P. Zorkoczy (Ed.), *Oxford Surveys in Information Technolog*y. 2: 69-104. Oxford University Press.

14. Izak Benbasat and Peter Todd. 1993. An experimental investigation of interface design alternatives: icon vs. text and direct manipulation vs. menus. *International Journal of Man-Machine Studies*. 38, 3: 369-402. http://dx.doi.org/10.1006/imms.1993.1017

15. J. L. Arnott, Z. Khairulla, A. Dickinson, A. Syme, N. Alm, R. Eisma, P. Gregor. 2004. E-mail Interfaces for Older People. In *Proc IEEE Conference on Systems, Man & Cybernetics* (SMC 2004), 111-117.

16. John Whiteside, Sandra Jones, Paula S. Levy, Dennis Wixon. 1985. User performance with command, menu, and iconic interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '85), 185-191. http://dx.doi.org/10.1145/317456.317490

17. Kathrin Gerling, Ian Livingston, Lennart Nacke, Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 1873-1882. http://dx.doi.org/10.1145/2207676.2208324

18. Kenneth Lodding. 1983. Iconic Interfacing. *IEEE Computer Graphics and Applications*. 3, 2: 11-20. http://dx.doi.org/10.1109/MCG.1983.262982

19. Martin Mihajlov, Effie Lai-Chong Law, and Mark Springett. 2016. The Effect of Dyadic Interactions on Learning Rotate Gesture for Technology-Naïve Older Adults. In *Proceedings of the International Symposium on Interactive Technology and Ageing Populations* (ITAP '16), 99-108. https://doi.org/10.1145/2996267.2996277

20. Nicolas Griffon et al. 2014. Design and Usability Study of an Iconic User Interface to Ease Information Retrieval of Medical Guidelines. *Journal of the American Medical Informatics Association: JAMIA* 21.e2 (2014), 270–277.

21. Olivier Bau and Wendy E. Mackay. 2008. OctoPocus: a dynamic guide for learning gesture-based command sets. In *Proceedings of the 21st annual ACM symposium on User interface software and technology* (UIST '08), 37-46. https://doi.org/10.1145/1449715.1449724

22. Sri Kurniawan and Panayiotis Zaphiris. 2005. Research-derived web design guidelines for older people. In *Proceedings of the 7th international ACM SIGACCESS conference on Computers and accessibility* (ASSETS '05), 129-135. https://doi.org/10.1145/1090785.1090810

23. Susan T. Dumais and William P. Jones. 1985. A comparison of symbolic and spatial filing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '85), 127-130. http://dx.doi.org/10.1145/317456.317479

24. Wei Lu, Zheng Tong, Jinghui Chu. 2016. Dynamic Hand Gesture Recognition With Leap Motion Controller. *IEEE Signal Processing Letters*. 23, 9: 1188-1192.

25. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. *Journal of Hand Therapy*. 28, 1, 53-60.

Chapter 5

1. 3D Carousel Using TweenMax.js & jQuery. Available at: https://codepen.io/johnblazek/pen/nceyw
2. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266. https://doi.org/10.1007/s10209-010-0208-6
3. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15), 257-258. http://dx.doi.org/10.1145/2783446.2783599
4. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16), 122-128. https://doi.org/10.1145/2971485.2996757
5. Caroline J. Ketcham and George E. Stelmach. 2001. Age-Related Declines in Motor Control. In Birren, J. E. & Schaie, K.W. (Eds.), *Handbook of the Psychology of Aging*. Academic Press.
6. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78. http://dx.doi.org/10.1145/1613858.1613950
7. Darren Guinness, G. Michael Poor, and Alvin Jude. 2014. Gestures with speech for hand-impaired persons. In *Proceedings of the 16th international ACM SIGACCESS*

conference on Computers & accessibility (ASSETS '14). ACM, New York, NY, USA, 259-260. http://dx.doi.org/10.1145/2661334.2661398

8. Donald A. Norman and Jakob Nielsen. 2010. Gestural interfaces: a step backward in usability. *interactions* 17, 5 (September 2010), 46-49. https://doi.org/10.1145/1836216.1836228
9. Gözel Shakeri, John H. Williamson, and Stephen Brewster. 2017. Novel Multimodal Feedback Techniques for In-Car Mid-Air Gesture Interaction. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (AutomotiveUI '17). ACM, New York, NY, USA, 84-93. https://doi.org/10.1145/3122986.3123011
10. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. https://doi.org/10.1145/2325616.2325625
11. Kathrin Gerling, Ian Livingston, Lennart Nacke, Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 1873-1882. http://dx.doi.org/10.1145/2207676.2208324
12. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346. DOI: https://doi.org/10.1145/2470654.2470703
13. Robert Walter, Gilles Bailly, Nina Valkanova, and Jörg Müller. 2014. Cuenesics: using mid-air gestures to select items on interactive public displays. In *Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services* (MobileHCI '14). ACM, New York, NY, USA, 299-308. https://doi.org/10.1145/2628363.2628368
14. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.
15. Swipe Gesture – Leap Motion Documentation. Available at: https://developer-archive.leapmotion.com/documentation/v2/python/api/Leap.SwipeGesture.html?proglang=python
16. Wei Lu, Zheng Tong, Jinghui Chu. 2016. Dynamic Hand Gesture Recognition With Leap Motion Controller. *IEEE Signal Processing Letters*. 23, 9: 1188-1192.
17. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. *Journal of Hand Therapy*. 28, 1, 53-60.

Chapter 6

1. Alex Butler, Shahram Izadi, and Steve Hodges. 2008. SideSight: multi-"touch" interaction around small devices. In *Proceedings of the 21st annual ACM symposium on*

User interface software and technology (UIST '08). ACM, New York, NY, USA, 201-204. DOI: https://doi.org/10.1145/1449715.1449746

2. Andy Cockburn and Stephen Brewster. 2005. Multimodal feedback for the acquisition of small targets. *Ergonomics*. 48, 9, 1129-1150.

3. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266. DOI: https://doi.org/10.1007/s10209-010-0208-6

4. Anne Köpsel, Päivi Majaranta, Poika Isokoski, Anke Huckauf. 2016. Effects of auditory, haptic and visual feedback on performing gestures by gaze or by hand. *Behaviour & Information Technology*. 35, 12: 1044-1062.

5. Aqueasha Martin-Hammond, Foad Hamidi, Tejas Bhalerao, Abdullah Ali, Catherine Hornback, Casey Means, and Amy Hurst. 2017. The Participatory Design of an Adaptive Interface to Support Users with Changing Pointing Ability. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility* (ASSETS '17). ACM, New York, NY, USA, 343-344. DOI: https://doi.org/10.1145/3132525.3134810

6. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258. DOI: http://dx.doi.org/10.1145/2783446.2783599

7. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA. DOI: https://doi.org/10.1145/2971485.2996757

8. Caroline J. Ketcham and George E. Stelmach. 2001. Age-Related Declines in Motor Control. In Birren, J.E. & Schaie, K.W. (Eds.), *Handbook of the Psychology of Aging*. Academic Press.

9. Caroline J. Ketcham, Rachael D. Seidler, Arend W.A. Van Gemmert, and George E. Stelmach. 2002. Age-Related Kinematic Differences as Influenced by Task Difficulty, Target Size, and Movement. *The Journals of Gerontology: Series B*. 57, 1, 54-64.

10. Chris Harrison and Scott E. Hudson. 2009. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology* (UIST '09). ACM, New York, NY, USA, 121-124. DOI: https://doi.org/10.1145/1622176.1622199

11. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09). DOI: http://dx.doi.org/10.1145/1613858.1613950

12. Christian Winkler, Ken Pfeuffer, Enrico Rukzio. 2012. Investigating mid-air pointing interaction for projector phones. In Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces (ITS '12), 85-94. DOI: https://doi.org/10.1145/2396636.2396650

13. Daniel Vogel and Ravin Balakrishnan. 2005. Distant freehand pointing and clicking on very large, high resolution displays. In Proceedings of the 18th annual ACM symposium on User interface software and technology (UIST '05), 33-42. DOI: http://dx.doi.org/10.1145/1095034.1095041

14. Euan Freeman, Stephen Brewster, and Vuokko Lantz. 2014. Tactile Feedback for Above-Device Gesture Interfaces: Adding Touch to Touchless Interactions. In *Proceedings of the 16th International Conference on Multimodal Interaction* (ICMI '14). ACM, New York, NY, USA, 419-426. DOI: https://doi.org/10.1145/2663204.2663280

15. Euan Freeman, Stephen Brewster, and Vuokko Lantz. 2016. Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 2319-2331. DOI: https://doi.org/10.1145/2858036.2858308

16. Faizan Haque, Mathieu Nancel, Daniel Vogel. 2015. Myopoint: Pointing and Clicking Using Forearm Mounted Electromyography and Inertial Motion Sensors. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15), 3653-3656.

17. Faustina Hwang, Simeon Keates, Patrick Langdon, and P. John Clarkson. 2003. Multiple haptic targets for motion-impaired computer users. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '03). ACM, New York, NY, USA, 41-48. DOI: http://dx.doi.org/10.1145/642611.642620

18. Felicia Huppert. 2003. Designing for Older Users. In: P. John Clarkson, Roger Coleman, Simeon Keates, and Cherie Lebbon (Eds.), *Inclusive Design: Design for the whole population*. Springer, London. DOI: https://doi.org/10.1007/978-1-4471-0001-0_2

19. Holly S. Vitense, Julie A. Jacko, and V. Kathlene Emery. 2002. Multimodal feedback: establishing a performance baseline for improved access by individuals with visual impairments. In *Proceedings of the fifth international ACM conference on Assistive technologies* (Assets '02). ACM, New York, NY, USA, 49-56. DOI: http://dx.doi.org/10.1145/638249.638260

20. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. DOI: https://doi.org/10.1145/2325616.2325625

21. Jörg Müller, Matthias Geier, Christina Dicke, and Sascha Spors. 2014. The boomRoom: mid-air direct interaction with virtual sound sources. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '14). ACM, New York, NY, USA, 247-256. DOI: https://doi.org/10.1145/2556288.2557000

22. Ju-Hwan Lee, Ellen Poliakoff, and Charles Spence. 2009. The Effect of Multimodal Feedback Presented via a Touch Screen on the Performance of Older Adults. In *Proceedings of the 4th International Conference on Haptic and Audio Interaction Design* (HAID '09). Springer, Berlin, Heidelberg, 128-135. DOI: https://doi.org/10.1007/978-3-642-04076-4_14

23. Julie Jacko, V. Kathlene Emery, Paula J. Edwards, Mahima Ashok, Leon Barnard, Thitima Kongnakorn, Kevin P. Moloney, and François Sainfort. 2004. The effects of multimodal feedback on older adults' task performance given varying levels of computer experience. *Behaviour & Information Technology*. 23, 4, 247-264. DOI: https://doi.org/10.1080/01449290310001659213

24. Kathrin Gerling, Ian Livingston, Lennart Nacke, and Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 1873-1882. DOI: http://dx.doi.org/10.1145/2207676.2208324

25. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346. DOI: https://doi.org/10.1145/2470654.2470703

26. Mathieu Nancel, Emmanuel Pietriga, Olivier Chapuis, Michel Beaudouin-Lafon. 2015. Mid-Air Pointing on Ultra-Walls. ACM Trans. Comput.-Hum. Interact. 22, 5. DOI: https://doi.org/10.1145/2766448

27. Mathieu Nancel, Julie Wagner, Emmanuel Pietriga, Olivier Chapuis, Wendy Mackay. 2011. Mid-air pan-and-zoom on wall-sized displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11), 177-186. DOI: https://doi.org/10.1145/1978942.1978969

28. Motoyuki Akamastu, I. Scott MacKenzie, Thierry Hasbrouc. 1995. A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. Ergonomics, 38, 816-827.

29. Peng Song, Wooi Boon Goh, William Hutama, Chi-Wing Fu, and Xiaopei Liu. 2012. A handle bar metaphor for virtual object manipulation with mid-air interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1297-1306. DOI: http://dx.doi.org/10.1145/2207676.2208585

30. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.

31. Sean Gustafson, Christian Holz, and Patrick Baudisch. 2011. Imaginary phone: learning imaginary interfaces by transferring spatial memory from a familiar device. In Proceedings of the 24th annual ACM symposium on User interface software and

technology (UIST '11). ACM, New York, NY, USA, 283-292. DOI: https://doi.org/10.1145/2047196.2047233

32. Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (UIST '13). ACM, New York, NY, USA, 505-514. DOI: https://doi.org/10.1145/2501988.2502018

33. Vanessa Vuibert, Wolfgang Stuerzlinger, and Jeremy R. Cooperstock. 2015. Evaluation of Docking Task Performance Using Mid-air Interaction Techniques. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction* (SUI '15). ACM, New York, NY, USA, 44-52. DOI: https://doi.org/10.1145/2788940.2788950

34. Vicki L. Hanson and Susan Crayne. 2005. Personalization of Web browsing: adaptations to meet the needs of older adults. *Universal Access in the Information Society*. 4, 1, 46-58. DOI: https://doi.org/10.1007/s10209-005-0110-9

35. Wijnand Ijsselsteijn, Henk Herman Nap, Yvonne de Kort, and Karolien Poels. 2007. Digital game design for elderly users. In *Proceedings of the 2007 Conference on Future Play* (Future Play '07). ACM, New York, NY, USA, 17-22. DOI: http://dx.doi.org/10.1145/1328202.1328206

36. Wei Lu, Zheng Tong, Jinghui Chu. 2016. Dynamic Hand Gesture Recognition With Leap Motion Controller. IEEE Signal Processing Letters. 23, 9: 1188-1192.

37. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. Journal of Hand Therapy. 28, 1, 53-60.

Chapter 7

1. Alan Newell, John Arnott, Alex Carmichael, and Maggie Morgan. 2007. Methodologies for Involving Older Adults in the Design Process. In: Stephanidis C. (eds) *Universal Acess in Human Computer Interaction* (UAHCI 2007). Lecture Notes in Computer Science, vol 4554. Springer, Berlin.

2. Amanda Lazar, Raymundo Cornejo, Caroline Edasis, and Anne Marie Piper. 2016. Designing for the Third Hand: Empowering Older Adults with Cognitive Impairment through Creating and Sharing. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (DIS '16). ACM, New York, NY, USA, 1047-1058.

3. André Kunert, Alexander Kulik, Anke Huckauf, and Bernd Fröhlich. 2007. A comparison of tracking- and controller-based input for complex bimanual interaction in virtual environments. In *Proceedings of the 13th Eurographics*

conference on Virtual Environments (EGVE'07), Bernd Fröhlich, Roland Blach, and Robert van Liere (Eds.). Eurographics Association, Aire-la-Ville, Switzerland, Switzerland, 43-52. http://dx.doi.org/10.2312/EGVE/IPT_EGVE2007/043-052

4. Anna Dickinson, Roos Eisma, and Peter Gregor. 2011. The barriers that older novices encounter to computer use. *Universal Access in the Information Society*. 10, 3, 261-266.

5. Anna Macaranas, Alissa N. Antle and Bernhard E. Riecke. 2015. What is Intuitive Interaction? Balancing Users' Performance and Satisfaction with Natural User Interfaces. *Interacting with Computers*. 27, 3, 357-370.

6. Anne Köpsel and Nikola Bubalo. 2015. Benefiting from legacy bias. *interactions*. 22, 5, 44-47. https://doi.org/10.1145/2803169

7. Anne Marie Piper and Amanda Lazar. 2018. Co-design in health: what can we learn from art therapy? *interactions*. 25, 3, 70-73.

8. Anne Marie Piper, Ross Campbell, and James D. Hollan. 2010. Exploring the accessibility and appeal of surface computing for older adult health care support. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10). ACM, New York, NY, USA, 907-916. https://doi.org/10.1145/1753326.1753461

9. Antti Oulasvirta, Sakari Tamminen, Virpi Roto, and Jaana Kuorelahti. 2005. Interaction in 4-second bursts: the fragmented nature of attentional resources in mobile HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '05)*. ACM, New York, NY, USA, 919-928. https://doi.org/10.1145/1054972.1055101

10. Arthur Theil Cabreira and Faustina Hwang. 2015. An analysis of mid-air gestures used across three platforms. In *Proceedings of the 2015 British HCI Conference* (British HCI '15). ACM, New York, NY, USA, 257-258. http://dx.doi.org/10.1145/2783446.2783599

11. Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA, Article 122, 6 pages. https://doi.org/10.1145/2971485.2996757

12. Caroline J. Ketcham and George E. Stelmach. 2001. Age-Related Declines in Motor Control. In Birren, J.E. & Schaie, K.W. (Eds.), *Handbook of the Psychology of Aging*. Academic Press.

13. Christian Kray, Daniel Nesbitt, John Dawson, and Michael Rohs. 2010. User-defined gestures for connecting mobile phones, public displays, and tabletops. In *Proceedings of the 12th international conference on Human computer*

interaction with mobile devices and services (MobileHCI '10). ACM, New York, NY, USA, 239-248. https://doi.org/10.1145/1851600.1851640

14. Christian Stößel. 2009. Familiarity as a factor in designing finger gestures for elderly users. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '09), Article 78.

15. Dan Saffer. 2008. Designing Gestural Interfaces: Touchscreens and Interactive Devices. O'Reilly Media, Inc.

16. Dan Saffer. 2013. Microinteractions: Designing with Details. O'Reilly Media, Inc.

17. Daniel L. Ashbrook. 2010. Enabling Mobile Microinteractions. *Ph.D. Dissertation*. Georgia Institute of Technology, Atlanta, GA, USA.

18. Donald A. Norman and Jakob Nielsen. 2010. Gestural interfaces: a step backward in usability. *interactions* 17, 5 (September 2010), 46-49. https://doi.org/10.1145/1836216.1836228

19. Edwin Chan, Teddy Seyed, Wolfgang Stuerzlinger, Xing-Dong Yang, and Frank Maurer. 2016. User Elicitation on Single-hand Microgestures. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 3403-3414. https://doi.org/10.1145/2858036.2858589

20. Euan Freeman, Stephen Brewster, and Vuokko Lantz. 2016. Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 2319-2331. https://doi.org/10.1145/2858036.2858308

21. Felicia Huppert. 2003. Designing for Older Users. In: P. John Clarkson, Roger Coleman, Simeon Keates, and Cherie Lebbon (Eds.), *Inclusive Design: Design for the whole population*. Springer, London. https://doi.org/10.1007/978-1-4471-0001-0_2

22. Hessam Jahani Fariman, Hasan J. Alyamani, Manolya Kavakli, and Len Hamey. 2016. Designing a user-defined gesture vocabulary for an in-vehicle climate control system. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction* (OzCHI '16). ACM, New York, NY, USA, 391-395. https://doi.org/10.1145/3010915.3010955

23. Hyunyoung Song, Francois Guimbretiere, Tovi Grossman, and George Fitzmaurice. 2010. MouseLight: bimanual interactions on digital paper using a pen and a spatially-aware mobile projector. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10). ACM, New York, NY, USA, 2451-2460.

24. I. Scott MacKenzie. 2003. Motor behaviour models for human-computer interaction. In J. M. Carroll (Ed.) *HCI models, theories, and frameworks: Toward a multidisciplinary science,* 27-54. San Francisco: Morgan Kaufmann.

25. Ilhan Aslan, Ida Buchwald, Philipp Koytek, and Elisabeth André. 2016. Pen + Mid-Air: An Exploration of Mid-Air Gestures to Complement Pen Input on Tablets. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, New York, NY, USA, Article 1, 10 pages. https://doi.org/10.1145/2971485.2971511

26. Ivan Golod, Felix Heidrich, Christian Möllering, and Martina Ziefle. 2013. Design principles of hand gesture interfaces for microinteractions. In *Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces* (DPPI '13). ACM, New York, NY, USA, 11-20. http://dx.doi.org/10.1145/2513506.2513508

27. J. L. Arnott, Z. Khairulla, A. Dickinson, A. Syme, N. Alm, R. Eisma, P. Gregor. 2004. E-mail Interfaces for Older People. In *Proc. IEEE Conference on Systems, Man & Cybernetics* (SMC 2004), 111-117.

28. Jacob O. Wobbrock, Meredith Ringel Morris, and Andrew D. Wilson. 2009. User-defined gestures for surface computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '09). ACM, New York, NY, USA, 1083-1092.

29. Jaime Ruiz and Daniel Vogel. 2015. Soft-Constraints to Reduce Legacy and Performance Bias to Elicit Whole-body Gestures with Low Arm Fatigue. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). ACM, New York, NY, USA, 3347-3350. https://doi.org/10.1145/2702123.2702583

30. Jan Bobeth, Susanne Schmehl, Ernst Kruijff, Stephanie Deutsch, and Manfred Tscheligi. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44. https://doi.org/10.1145/2325616.2325625

31. Jennifer L. Davidson and Carlos Jensen. 2013. Participatory design with older adults: an analysis of creativity in the design of mobile healthcare applications. In *Proceedings of the 9th ACM Conference on Creativity & Cognition* (C&C '13). ACM, New York, NY, USA, 114-123.

32. Jennifer L. Davidson and Carlos Jensen. 2013. What health topics older adults want to track: a participatory design study. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility* (ASSETS '13). ACM, New York, NY, USA.

33. John Vines, Gary Pritchard, Peter Wright, Patrick Olivier, and Katie Brittain. 2015. An Age-Old Problem: Examining the Discourses of Ageing in HCI and

Strategies for Future Research. *ACM Trans. Comput.-Hum. Interact*. 22, 1, 2. https://doi.org/10.1145/2696867

34. John Vines, Mark Blythe, Stephen Lindsay, Paul Dunphy, Andrew Monk, and Patrick Olivier. 2012. Questionable concepts: critique as resource for designing with eighty somethings. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1169-1178.

35. Ka-Ping Yee. 2004. Two-handed interaction on a tablet display. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '04). ACM, New York, NY, USA, 1493-1496.

36. Karin Slegers, Martin P. J. Van Boxtel, and Jelle Jolles. 2012. Computer use in older adults: Determinants and the relationship with cognitive change over a 6 year episode. *Computers in Human Behavior*. 28, 1, 1-10.

37. Karyn Moffatt. 2013. Older-adult HCI: why should we care? *interactions*. 20, 4, 72-75. https://doi.org/10.1145/2486227.2486242

38. Kathrin Gerling, Ian Livingston, Lennart Nacke, and Regan Mandryk. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1873-1882. https://doi.org/10.1145/2207676.2208324

39. Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346.

40. Mark Rice, Yian Ling Cheong, Jamie Ng, Puay Hoe Chua, and Yin-Leng Theng. 2012. Co-creating games through intergenerational design workshops. In *Proceedings of the Designing Interactive Systems Conference* (DIS '12). ACM, New York, NY, USA, 368-377. https://doi.org/10.1145/2317956.2318012

41. Meredith Ringel Morris, Andreea Danielescu, Steven Drucker, Danyel Fisher, Bongshin Lee, m. c. schraefel, and Jacob O. Wobbrock. 2014. Reducing legacy bias in gesture elicitation studies. *interactions*. 21, 3, 40-45. https://doi.org/10.1145/2591689

42. Michael W. Smith, Joseph Sharit, and Sara J. Czaja. 1999. Aging, Motor Control, and the Performance of Computer Mouse Tasks. Human Factors. 41, 3, 389-396.

43. Morten Hertzum and Kasper Hornbæk. 2010. How Age Affects Pointing With Mouse and Touchpad: A Comparison of Young, Adult, and Elderly Users. *International Journal of Human–Computer Interaction*. 26, 7, 703-734. https://doi.org/10.1080/10447318.2010.487198

44. Nic Hollinworth. 2009. Improving computer interaction for older adults. *SIGACCESS Access. Comput.* 93 (January 2009), 11-17. http://dx.doi.org/10.1145/1531930.1531932

45. Peter Gregor and Alan F Newell. 2001. Designing for dynamic diversity: making accessible interfaces for older people. In *Proceedings of the 2001 EC/NSF workshop on Universal accessibility of ubiquitous computing: providing for the elderly* (WUAUC'01). ACM, New York, NY, USA, 90-92. http://dx.doi.org/10.1145/564526.564550

46. Pew Research Center. 2014. Older Adults and Technology Use. In *Internet and Technology report*. Retrieved August 29, 2018 from http://www.pewinternet.org/2014/04/03/older-adults-and-technology-use/

47. Ravin Balakrishnan and Ken Hinckley. 2000. Symmetric bimanual interaction. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (CHI '00). ACM, New York, NY, USA, 33-40. http://dx.doi.org/10.1145/332040.332404

48. R. G. Marteniuk, C. L. MacKenzie & D. M. Baba. 1984. Bimanual movement control: Information processing and interaction effects. *The Quarterly Journal of Experimental Psychology Section A*. 36, 2, 335-365. https://doi.org/10.1080/14640748408402163

49. Ross McLachlan and Stephen Brewster. 2015. Bimanual Input for Tablet Devices with Pressure and Multi-Touch Gestures. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '15). ACM, New York, NY, USA, 547-556. https://doi.org/10.1145/2785830.2785878

50. Sara J. Czaja and Chin Chin Lee. 2007. Information technology and older adults. In J. A. Jacko & A. Sears (Eds.), *The Human Computer-Interaction Handbook* (2nd ed., 777-792. Lawrence Erlbaum Associates, New York.

51. Silas Wan and H. T. Nguyen. 2008. Human computer interaction using hand gesture. In *Proceedings of the 2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, Vancouver, British Columbia, Canada, 2357-2360. https://doi.org/10.1109/IEMBS.2008.4649672

52. Stephen Lindsay, Daniel Jackson, Guy Schofield, and Patrick Olivier. 2012. Engaging older people using participatory design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1199-1208.

53. Steven C. Seow, Dennis Wixon, Ann Morrison, and Giulio Jacucci. 2010. Natural user interfaces: the prospect and challenge of touch and gestural computing. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '10). ACM, New York, NY, USA, 4453-4456. https://doi.org/10.1145/1753846.1754172

54. Sukeshini A. Grandhi, Gina Joue, and Irene Mittelberg. 2011. Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 821-824. https://doi.org/10.1145/1978942.1979061
55. Thammathip Piumsomboon, Adrian Clark, Mark Billinghurst, and Andy Cockburn. 2013. User-defined gestures for augmented reality. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '13). ACM, New York, NY, USA, 955-960. https://doi.org/10.1145/2468356.2468527
56. United Nations. 2015. Levels and trends in the number of older persons. In *World Population Ageing Report*. Retrieved 31 August, 2018 from http://www.un.org/en/development/desa/population/publications/pdf/ageing/WPA2015_Report.pdf
57. Volkert Buchmann, Stephen Violich, Mark Billinghurst, and Andy Cockburn. 2004. FingARtips: gesture based direct manipulation in Augmented Reality. In *Proceedings of the 2nd international conference on Computer graphics and interactive techniques in Australasia and South East Asia* (GRAPHITE '04), Stephen N. Spencer (Ed.). ACM, New York, NY, USA, 212-221. http://dx.doi.org/10.1145/988834.988871
58. W. Buxton and B. Myers. 1986. A study in two-handed input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '86), Marilyn Mantei and Peter Orbeton (Eds.). ACM, New York, NY, USA, 321-326.
59. Ying Chih Wang, Richard W. Bohannon, Jay Kapellusch, Arun Garg, Richard C. Gershon. 2015. Dexterity as measured with the 9-Hole Peg Test (9-HPT) across the age span. *Journal of Hand Therapy*. 28, 1, 53-60.

Chapter 8

[1] A. Chaparro et al. 1999. The impact of age on computer input device use: Psychophysical and physiological measures. *International Journal of Industrial Ergonomics*. 24, 503--513.
[2] C. J. Ketcham et al. 2002. Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *Journal of Gerontology*. 57, 1, 54-64.
[3] C. Stößel, L. Blessing. 2010. Tap, Swipe & Pinch: Designing suitable multi-touch gestures for older users. In *Proceedings the 11th International Design Conference* (DESIGN 10). The Design Society, 463-472.
[4] E. Freeman et al. 2016. Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 2319-2331.

[5] J. Bobeth et al. 2012. Evaluating performance and acceptance of older adults using freehand gestures for TV menu control. In *Proceedings of the 10th European Conference on Interactive TV and Video* (EuroITV '12). ACM, New York, NY, USA, 35-44.

[6] J. Hurtienne et al. 2010. Physical gestures for abstract concepts: Inclusive design with primary metaphors. *Interacting with Computers*. 22, 6 (November 2010), 475-484.

[7] J. M. C. Bastien. 2010. Usability testing: a review of some methodological and technical aspects of the method. *International Journal of Medical Informatics*. 79, 4, April 2010, 18-23.

[8] J. O. Wobbrock et al. 2005. Maximizing the guessability of symbolic input. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '05). ACM, New York, NY, USA, 1869-1872.

[9] J. Ruiz, D. Vogel. 2015. Soft-Constraints to Reduce Legacy and Performance Bias to Elicit Whole-body Gestures with Low Arm Fatigue. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). ACM, New York, NY, USA, 3347-3350.

[10] J. Vines et al. 2015. An Age-Old Problem: Examining the Discourses of Ageing in HCI and Strategies for Future Research. *ACM Trans. Comput.-Hum. Interact*. 22, 1.

[11] K. Gerling et al. 2012. Full-body motion-based game interaction for older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 1873-1882.

[12] L. Findlater et al. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 343-346.

[13] L. M. Muriana, H. H. Hornung. 2017. Including Older Adults into the Design Process: Challenges and Lessons Learned. In *Proceedings of the XVI Brazilian Symposium on Human Factors in Computing Systems* (IHC 2017). ACM, New York, NY, USA.

[14] M. A. Farage et al. 2012. Design Principles to Accommodate Older Adults. *Global Journal of Health Science*. 4, 2, March 2012.

[15] S. A. Grandhi et al. 2011. Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 821-824.

[16] S. S. Billinghurst, K. L. Vu. 2015. Touch screen gestures for web browsing tasks. *Computers in Human Behavior*. 53 (December 2015), 71-81.