

Voice Assistants for People with Cognitive Impairments due to Acquired Brain Injury

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Abstract

Acquired Brain Injury (ABI) can cause a wide range of cognitive and physical impairments, which can affect the person's ability to perform everyday tasks, and reduce their independence. The everyday functioning of people with ABI can be improved through rehabilitation, and through the use of external aids, which can be paper-based tools or electronic devices. Although research shows that the latter can be more effective, there are several barriers that can prevent their efficient. Voice Assistants offer the potential to provide support for people with ABI, overcoming some of this barriers through their hands-free and eyes-free interaction. However, there exist several challenges associated with the usability of speech-only interaction, and the use of VAs in that context has not been thoroughly examined.

This thesis presents a set of requirements capturing studies, aiming to examine how VAs can be used to benefit people with ABI, to identify the factors that can limit their usability in this context, and to explore ways to improve their usability through the design of their voice user interface. Study 1 investigated the common effects of ABI and how the users' background correlates to the use of external aids, and acquired initial information about the use of VAs among people with ABI. Study 2 further investigated the common cognitive effects of ABI, examined the common methods and objectives of ABI rehabilitation, and acquired the view of ABI experts on the application and design of technological aids.

Study 3 gathered additional information about the impact of the effects of ABI on the use of external aids, and acquired feedback by people with ABI on the concept of using VAs as cognitive aids. Study 4 examined how people with ABI use VAs, and how they compared them to other tools. The results were used to define a set of use-cases, describing how VAs can be used to support cognitive functioning, and facilitate the rehabilitation process.

Study 5 further examined how people with ABI interact with VAs, identifying the different factors that can hinder their usability in a variety of tasks. Finally, Study 6 evaluated different methods to design the voice user interface of a VA-based prompting system for people with ABI, presenting design guidelines to improve the presentation of conveyed information, to increase the effectiveness of conveyed prompts, to facilitate information input and reduce user errors, and techniques to provide help to the users and improve learnability.

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Declaration

The research presented in this thesis is entirely the author's own work. Research in this thesis has been included in the following papers, using only the parts of these papers that are directly attributable to the author:

- The research in chapters 3 and 4 was included in a doctoral consortium paper at ACM ASSETS 2018: Accessibility and acceptability of voice assistants for people with acquired brain injury. ACM SIGACCESS Accessibility and Computing, (123):1–1, 2020
- Study 3 (Chapter 4) was published in the Computing and Mental Health Symposium at CHI 2018: Designing a Prompting System to Facilitate the Rehabilitation of People with Acquired Brain Injury. Computing and Mental Health Symposium, CHI 2018.
- The research in chapters 4 and 5 (Studies 4 and 5) were included in a paper submitted to the ACM Transcations on Accessible Computing (TACCESS) journal in 2021, currently under revision.
- The research in chapters 3 and 6 (Studies 2 and 6) were included in a paper submitted to the JMIR Rehabilitation and Assistive Technologies journal in 2021, currently under review.

Chapter 1

Introduction

1.1 Motivation

Acquired Brain Injury (ABI) refers to any injury caused to the brain after birth. It can be caused by a head trauma from an accident or an assault (traumatic brain injury), by a stroke or an aneurysm, by brain infections such as encephalitis and meningitis, by brain tumours, and by a reduced flow of oxygen to the brain (e.g. due to cardiac or respiratory arrests).

An ABI can be classified by its severity from mild to very severe, and can have a wide range of physical and cognitive effects. The common physical effects include reduced mobility, affecting balance, co-ordination and the ability to walk [134], physical weakness or paralysis [176], spasticity, vision impairments [3], and pathological fatigue [13]. The cognitive effects of an ABI typically affect the way the person perceives, thinks, learns and remembers. The most commonly reported cognitive issue after an ABI is memory impairment [220], typically by causing an inability to transfer information from the short-term memory to the long-term memory (amnesia), by hindering the ability to retain information in the working memory, and by reducing the ability to remember to fulfil intended actions (prospective memory). Apart from memory impairments, an ABI often causes executive dysfunction, affecting skills essential to everyday functioning, such as planning and organisation, problem solving, self-awareness, motivation and initiation [198]. Additionally, an ABI can affect the ability to perceive and process information, can have behavioural and emotional effects, and can impair the ability to communicate. The above effects can often be long-lasting or permanent, and can have a high impact on the person's quality of life, limiting their ability to carry out everyday tasks and reducing their independence [123].

The duration and extend of recovery from a brain injury depends on the nature and severity of the brain damage. Neuropsychological rehabilitation can be a vital part of the recovery pro-

cess, usually administered through rehabilitation programmes that aim to increase the person's awareness, alleviate cognitive deficits, and help the development of compensatory skills [228], with the ultimate goal of increasing the person's independence and self-efficacy. ABI rehabilitation can be facilitated with the use of external aids, which can be either paper-based tools, or electronic devices. The former typically include diaries, notebooks, wall calendars and to-do lists, and can be used to compensate for memory deficits and help people function more independently [220].

Electronic aids used to enable, enhance or extend the cognitive function of people with ABI are commonly referred to as Assistive Technologies (AT) in the literature [157]. The most common type of AT is reminder systems, i.e. systems that provide timely prompts to aid remembering, or encourage activity [91, 116], utilising a variety of devices such as smartphones [202, 203], voice recorders [233] and PDAs [53]. Apart from providing prompts ATs are also used to facilitate task completion by providing appropriate guidance [158], to help with planning and organisation [72], to record autobiographical memories [17], and to facilitate communication [126, 149, 210].

Although ATs have been used widely in research, and have been found to be more efficient in supporting the functioning of people with ABI than their non-technological equivalents [91], research shows that they are not used as commonly ([61, 90]), due to several barriers that can impact their uptake and effective use. These include: cognitive accessibility, i.e. difficulties in using, or learning how to use technology efficiently and effectively due to cognitive deficits [194]; physical accessibility, due to vision loss or limited hand movement limiting the ability to use devices with a screen, touchscreen or buttons [92]; social factors [12] and poor integration in rehabilitation methods [116]. Recent approaches have examined ways to overcome these barriers, utilising unsolicited prompting [94], context awareness [142], and smart home environments [20].

Voice Assistants (VAs) are speech-activated virtual assistants (technologies like Amazon's Alexa, Apple's Siri, Google's Assistant and Microsoft's Cortana), which offer the potential to support people with ABI, providing functionality that allows the adoption of the above approaches to overcome some of the aforementioned barriers. Specifically, VAs offer hands-free and eyes-free interaction through their voice-user interface, providing an alternative way to carry out functions associated with smart mobile devices and computers, thus increasing physical accessibility to different services. Another important benefit of is that they can allow faster execution of certain tasks [181]. VAs can be used through smart speakers (speakers with embedded microphones and internet connectivity) or smartphones, and they can be embedded in modern cars and in some smart household devices.

Although the range of functions that are supported by VAs is very wide, research has shown

that they are used to perform a limited number of activities by the majority of users [6, 55]. The frequency of VA use has been shown to be associated with user satisfaction [55, 101, 184], which can be affected by several factors. One of the most commonly reported factors is poor speech recognition, which can impact user experience and cause frustration [1, 37]. Other factors include privacy and security concerns [1, 6, 37], inconsistency in hands-free interaction (in the case of smartphones), and increased workload when used to perform tasks that require several steps to complete [104].

Research examining the use of VAs has shown that they can be used to support people with disabilities [1, 158, 169], and elderly people [231]. The above indicate that there are several potential benefits that VAs could provide to people with ABI, such as easy access to a variety of services and quick task completion. However, there is very little work related to the use of Voice Assistants for this particular user group.

The research conducted in this thesis aimed to identify the different situations where the use of VAs can be appropriate and beneficial for people with Acquired Brain Injury, to examine the factors that can affect their usability for this particular group of users, and to explore ways that the impact of these factors can be reduced, through the design of their voice user interface. Specifically, it focused on investigating the common cognitive effects of ABI and how these can affect the use of technological aids, examining how people with ABI interact with VAs to identify problematic areas, and evaluating potential design solutions to improve their usability.

1.2 Thesis Statement

Although Voice Assistants can offer advantages over other external aids in supporting the everyday functioning of people with cognitive impairments due to Acquired Brain Injury, there exist several factors that can affect their usability, and their use with this particular user group has not been thoroughly examined. This thesis presents a set of requirements-capturing studies which examined the impact of the effects of a brain injury on the use of external cognitive aids, investigated how people with Acquired Brain Injury use and interact with Voice Assistants, and explored different methods to improve their usability through the design of their voice user interface. This thesis presents the different situations where the use of Voice Assistants is appropriate and beneficial for people with Acquired Brain Injury, the identified factors that can impact the technology's usability, and a set of design guidelines to increase their efficacy in supporting the functioning and rehabilitation process of brain injury survivors.

1.3 Research Questions

This thesis aims to answer the following research questions:

- **RQ1:** What are the use cases of Voice Assistants for users with cognitive impairments due to an Acquired Brain Injury?
- **RQ2:** What are the factors that affect the usability of Voice Assistants when used by people with ABI?
- **RQ3:** How can the usability of Voice Assistants be improved for people with ABI?

1.4 Thesis Structure

This Section summarises the contents of each Chapter. Table 1 shows the purpose of each Study, and the research questions that each Study contributed to answering.

Chapter 2 - Literature Review

This Chapter presents a review of the related literature on Acquired Brain Injury and Voice Assistants. The review begins by giving an overview of the context of ABI, presenting its common causes, and potential effects. Then, a brief description of the common areas of the brain and the associated functions typically affected by an ABI is given. The review then presents the context of neuropsychological rehabilitation, and presents research work related to the use of assistive technologies to support people with ABI and facilitate the rehabilitation process. Finally, the review introduces Voice Assistants, presents their potential benefits and reviews research work examining their use. This Chapter also introduces terminology related to ABI and its effects that will be used in the subsequent Chapters.

Chapter 3 - Effects of ABI and the Use of External Aids

This Chapter investigates the needs and purposes of technological aids for people with ABI, and examines how cognitive effects of ABI can affect the usability of these aids. It describes two requirements-capturing studies: an online survey which gathered information about the experience of ABI and the use of external aids, and a group interview with neuropsychologists, which acquired additional data about the common effects of ABI, looked into the common cognitive rehabilitation methods and examined the application and design of external aids. The Chapter

presents a set of broad use cases, and a set of design characteristics of assistive technologies for People with ABI. These lay the groundwork for examining the use and design of Voice Assistants to answer **RQ1** and **RQ2** in the following Chapters.

Chapter 4 - Examining the Use of Voice Assistants

This Chapter presents a set of focus groups with people with ABI to further examine the use of assistive technologies, and acquires feedback from people with ABI on the concept of using VAs as cognitive aids. It also presents a set of interviews with people with ABI who use VAs on a regular basis, acquiring information about how they use them and what are the features and aspects of interaction they find useful or challenging. The findings of these two studies are analysed to determine the different situations where the use of VAs to support people with ABI is appropriate and beneficial, thus addressing **RQ1**. The Chapter also presents identified factors that can impact the usability of VAs, informing the answer to **RQ2**.

Chapter 5 - Investigating the Usability of Voice Assistants

This Chapter presents a study with people with ABI who use a VA to carry out a wide range of tasks, further investigating their usability, the prevalence of the usability factors identified in Chapter 4, and explores how the design of VAs can alleviate the impact of these factors. The results of the study are analysed to clarify the manner and extent to which the identified factors limit the usability of VAs, thus answering **RQ2**.

Chapter 6 - Exploring the Design of a Voice Assistant-based Prompting System

This Chapter describes an expert review study to acquire feedback on the design of a prototype VA-based prompting system, for people with ABI. The study evaluates different approaches in designing a voice user interface, to overcome usability barriers induced by the factors identified in Chapter 5. The findings are analysed to create a set of design guidelines for improving the usability of a VA-based prompting system. These guidelines provide an answer to **RQ3**.

Chapter 7 - Conclusions

This final Chapter summarises the research work described in this thesis and how it provides the answers to the Research Questions presented in the Introduction. Then, it summarises the novel contributions of the thesis, describes limitations of the research work and discusses how they can be addressed in future work.

1.5 Overview of Studies

Study	Research Questions	Purpose
Study 1 - Online survey with people with ABI	RQ1 RQ2	Investigate the prevalence of common effects of ABI among users of external cognitive aids. Examine the use of different types of external aids and how that correlates to the users' background. Acquire general information about the use of VAs among people with ABI.
Study 2 - Group interview with neuropsychologists	RQ1 RQ2	Acquired experts' view on the prevalence and impact of common cognitive effects of ABI. Learn about the practicalities of NR methods. Gather the expert's feedback on the application and design of technological aids for people with ABI.
Study 3 - Focus groups with people with ABI	RQ1 RQ2	Gather information about the effects of ABI. Gather details about the use of external aids. Receive feedback on the concept of using VAs as cognitive aids.
Study 4 - Interviews with people with ABI who use VAs	RQ1 RQ2 RQ3	Determine how people with ABI use VAs. Examine how people with ABI compare VAs to other tools. Identify the aspects of VAs that people with ABI find particularly useful or problematic.
Study 5 - Study with people with ABI using a VA	RQ2 RQ3	Further examine how people with ABI interact with VAs. Investigate the prevalence of factors that affect usability in a variety of tasks. Examine whether certain types of tasks performed with VAs can be more demanding or problematic than others .
Study 6 - Evaluation of the design of a VA-based prompting system	RQ3	Evaluate different methods to design the voice user interface of a VA-based prompting system for people with ABI.

Table 1.1: Summary of the studies presented in this thesis and research questions the studies contributed to answering.

Chapter 2

Literature Review

2.1 Introduction

The first chapter introduced the research questions and explained why Voice Assistant technologies form an environment suitable for the development of applications for people with cognitive impairments due to Acquired Brain Injury (ABI). Before looking into the design of such applications and attempting to answer the research questions of this thesis, it is essential to comprehend the potential effects of ABI and how these affect everyday life, and to examine the existing methods and solutions for alleviating the impact of these effects. By presenting a review of the literature related to ABI and its effects, the use of external aids that support brain injury rehabilitation, and the relevant research on Voice Assistants, this chapter establishes the background to the research presented in this thesis. Moreover, it introduces the terminology that will be used in the subsequent chapters.

The first part of this chapter (Section 2.2) begins by introducing the different types of ABI. It continues with a brief overview of the main parts of the brain and their associated functions, which are more frequently affected by a brain injury. The rest of the section presents the most common effects of ABI, which are classified in two categories: the physical effects, referring to issues affecting muscle movement and sensory function, and the cognitive impairments, referring to functions related to cognition. By identifying the effects of ABI and the difficulties that they induce in everyday life, Section 2.2 highlights the situations where technology can be used to support people with ABI, and therefore it informs research question:

- **RQ1:** What are the use cases of Voice Assistants for users with cognitive impairments due to an Acquired Brain Injury?

The next section of the chapter (Section 2.3) gives an overview of the process and target out-

comes of the rehabilitation interventions that are frequently implemented after a brain injury. Through a review of related literature, it is shown that rehabilitation can be facilitated by external aids. It is also shown that there are several factors that can impact the effectiveness of these aids, highlighting that there is room for improved design. Information related to the process and objectives of ABI rehabilitation, as well as the ways that technology can be beneficial, inform RQ1. The same research question is further informed by identifying the shortcomings of existing technological solutions, therefore determining where Voice Assistants could be used as a better alternative. The obstacles affecting the efficacy of existing technological aids determine design issues in the development of new technologies, and therefore inform the second research question:

- **RQ2:** What are the factors that affect the usability of Voice Assistants when used by people with ABI?

The last part of this chapter (Section 2.4) briefly describes speech interfaces and virtual agents, and introduces Voice Assistants (VAs) in more detail. VAs are a novel technology that can be used to support people with ABI, and constitute the main focus of this thesis. Research investigating the usability of VAs is reviewed, and studies examining the use of VAs for people with disabilities and cognitive impairments are presented. This literature informs the third research question

- **RQ3:** How can the usability of Voice Assistants be improved for people with ABI?

Ultimately, by demonstrating the potential benefits of technology, but also by highlighting the challenges for current methods and tools, this chapter explains the motivation to examine the use and usability of Voice Assistants for people with ABI.

2.2 Acquired Brain Injury

The term Acquired Brain Injury (**ABI**) refers to any injury to the brain caused by an event that occurs after birth, in contrast to brain damage caused by a congenital disorder or a degenerative disease¹. This section gives an overview of the context of ABI and presents its common causes and potential effects.

Epidemiology statistics show that a very significant number of people experience ABI. In 2016-2017 in the United Kingdom, there were 348,453 hospital admissions with acquired brain

¹<https://www.headway.org.uk/about-brain-injury/individuals/types-of-brain-injury/> - Accessed: 11/5/2021

injury, which amounts to 531 admissions per 100,000 of the population. That number had increased by 10% since 2005-2006 [85]. ABI often results in disability and can have a high impact in economic terms and quality of life [123].

Types of ABI

There are many possible causes for an ABI. A Traumatic Brain Injury (TBI), which is one of the most common types, is the result of a trauma to the head caused by an accident (such as a fall, a motorcycle crash or a sports injury) or an assault [155]. Although TBI is a subcategory of ABI, it is often approached as a distinct public health concern due to its high incidence. In 2014, there were about 2.87 million TBI-related emergency department visits, hospitalisations and deaths in the U.S. and around 69 million individuals are estimated to be affected worldwide every year [47].

A *non-traumatic* ABI can be caused by a number of different incidents, the most common of which include the following:

- **Strokes and Aneurysms:** Strokes along with TBIs account for the majority of acquired brain injuries. In the UK there are approximately 152,000 strokes every year and in 2010 almost 17 million people experienced a stroke for the first time [7] across the world. A stroke can be either ischaemic, caused by a lack of blood flow, or haemorrhagic, caused by bleeding in, or around the brain and can result in the death of brain cells. A brain (or cerebral) aneurysm is a cerebrovascular disorder that occurs when an artery or blood vessel in the brain swells. If the aneurysm ruptures it can cause a subarachnoid haemorrhage (SAH), an extremely dangerous condition often resulting in death. One out of two people surviving a SAH suffer from permanent disability [185]. Stroke is a major cause for long-term disability [68].
- **Brain Infections:** A brain injury can also be caused by an illness affecting the brain. Two frequent conditions of this type are encephalitis [190], which can damage nerve cells causing long-term effects [147], and meningitis, an inflammation of the membranes surrounding the brain often leading to life-long deficits [76].
- **Brain Tumour:** Brain tumours, either malignant or benign, when growing and spreading can destroy healthy brain tissue and can cause significant morbidity [186], with negative impact on patients' quality of life [160]. The effects of a brain tumour depend on its size, location and how much it has spread.
- **Lack of Oxygen:** Conditions that affect the flow of oxygen to the brain such as cardiac arrests, respiratory arrests, carbon monoxide poisoning, choking and drowning can cause

irreparable brain damage [28].

Aside from its cause, an ABI can also be classified by its severity from mild, to moderate, severe or very severe. One way to indicate the severity of the injury is through the length of Post-Traumatic Amnesia (PTA) [136], a state occurring after a traumatic brain injury. During PTA the person is conscious but unable to memorise day-to-day events, and often confused and disoriented. Another method of diagnosing a brain injury's severity is through the use of the Glasgow Coma Scale (GCS) [204]. GCS assesses the patient's eye opening, motor and verbal responses. Additional severity assessment methods include brain imaging [193], cognition tests and neuropsychological assessment [43, 82, 180, 225]. The effects of an ABI can vary greatly from one person to another, and consequences depend on the severity and type of the injury, the person's pre-morbid state and the areas of the brain that have been affected.

Before considering how technology can be used to support people with ABI, it is important to have an understanding of the brain functions that are commonly affected and how they normally operate. The next section gives a brief overview of these functions and the brain areas associated with them, and introduces the terms related to the effects of ABI used later in the thesis.

2.2.1 Structure and functions of the Brain

The brain, together with the spinal cord, form the Central Nervous System (CNS) which, through the peripheral nervous system, is responsible for sending and receiving signals to and from the muscles, organs and receptors of the body, as well as for all of the cognitive functions necessary for functioning in everyday life.

Structure of the Brain

The cerebrum, which enables most of the complex mental activities, is the largest part of the brain (coloured areas in Figure 2.1) and consists of the left and the right hemisphere. Although the two hemispheres work together to execute most functions by transmitting messages to each other, each hemisphere is responsible for the movement and sensory input of the opposite side of the body².

As depicted in Figure 2.1, the brain can be divided in four main sections called lobes, each of which specialises in different functions.

- **Frontal lobe:** The frontal lobe is in the front of the brain, behind the forehead. It is mainly

²<https://www.ninds.nih.gov/Disorders/Patient-Caregiver-Education/Know-Your-Brain> - Accessed: 11/5/2021

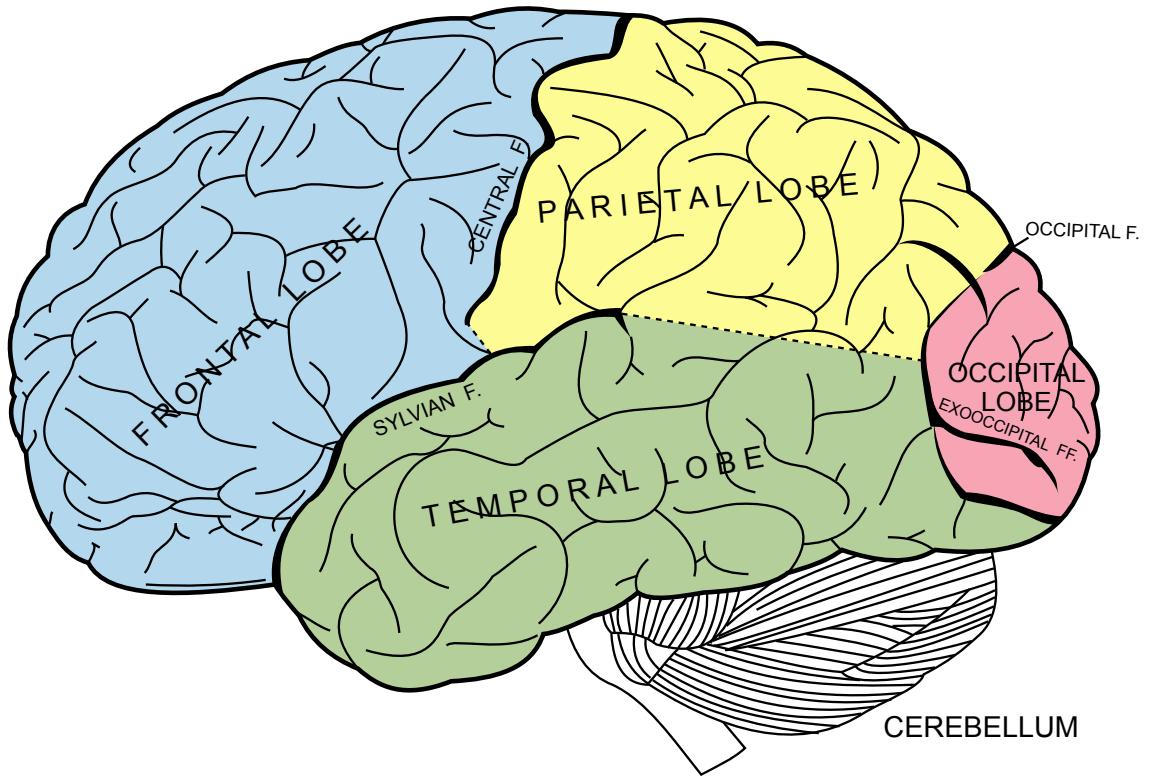


Figure 2.1: The four lobes of the brain [75].

responsible for functions referred to as the executive functions (described later in this section), but it is also involved in speech, motor and some memory related functions [175]. It consists of several smaller areas that specialise in different functions. These areas include: the primary motor cortex, which is responsible for muscle movement [96], the prefrontal cortex which plays an important role in complex cognitive behaviour, expression of personality, decision making, and executive functioning, and the supplementary and premotor cortex, which control the coordination and sequencing of movement of several muscles [172]. The frontal lobe is generally more susceptible to injury than other parts of the brain because of its position and large size. As a result, a frontal lobe lesion can cause serious deficits, which are described in Sections 2.2.2 and 2.2.3.

- **Parietal lobe:** The parietal lobe is located behind the frontal lobe and it is responsible for processing sensory information from the tongue, the skin, the ears and the eyes. It also plays an important role in the ability to understand spatial relationships [97]. Damage to the left parietal lobe can result in aphasia and agnosia, two possible effects of ABI described in Section 2.2.3.
- **Occipital lobe:** The occipital lobe is in the back end of the brain and is responsible for processing visual input, and in particular for functions like visuospatial processing, detection of colours and movement, and perception of depth [97]. Although it can be less susceptible to injury because of its position, damage to the occipital lobe can cause

significant changes to the visual perceptual system.

- **Temporal lobe:** The temporal lobe is involved in the organisation of sensory input, and it is highly associated with memory skills [97]. Damage to the temporal lobe can result in the impairment of various cognitive functions including auditory functioning, visual perception, language comprehension and long-term memory.

The cerebellum, which is under the temporal lobe and behind the brain stem (black and white area in Figure 2.1) is involved in the coordination of skilled motor activity, procedural memory, balance and visual perception [172]. It is relatively more protected against injury compared to other parts of the brain such as the frontal and temporal lobe, however cerebellar injury can result in movement related deficits.

As can be seen from the above, the brain has a very complex structure with different areas specialising in different functions. When one of these areas is damaged as a result of an ABI the performance of the corresponding actions can be affected (see sections 2.2.2 and 2.2.3). The CNS however retains some ability to recover and adapt to injury through neuroplasticity, i.e. the ability for neuronal circuits to change both on a structural and functional level [199]. Neuroplasticity can be facilitated by different treatment methods including Cognitive Rehabilitation (Section 2.3).

As discussed in the first chapter, one of the objectives of the research work described in this thesis is to investigate the potential role of technology (and in particular Voice Assistants) in alleviating the impact of deficits caused by ABI. Before examining the effects of ABI and how technology can be used to facilitate brain functions, it is essential to have an understanding of the most important, and more commonly affected, functions.

Memory

Memory is defined as the encoding, storage and retrieval of past experiences [8], and it is one of the most vital cognitive functions, considering that many important everyday activities depend on memory performance. In the literature, memory is generally classified based on the length of the recall period. This classification defines three main memory types: sensory memory, short-term (or working) memory, and long-term memory [8] (Figure 2.2). As described in the previous section, there are several areas of the brain involved in memory related functions, the most important of which are the hippocampus and amygdala in the temporal lobe, the prefrontal cortex in the frontal lobe and the cerebellum. For that reason, memory is one of the most frequently affected functions after a brain injury (Section 2.2.3). The different types of memory are presented below:

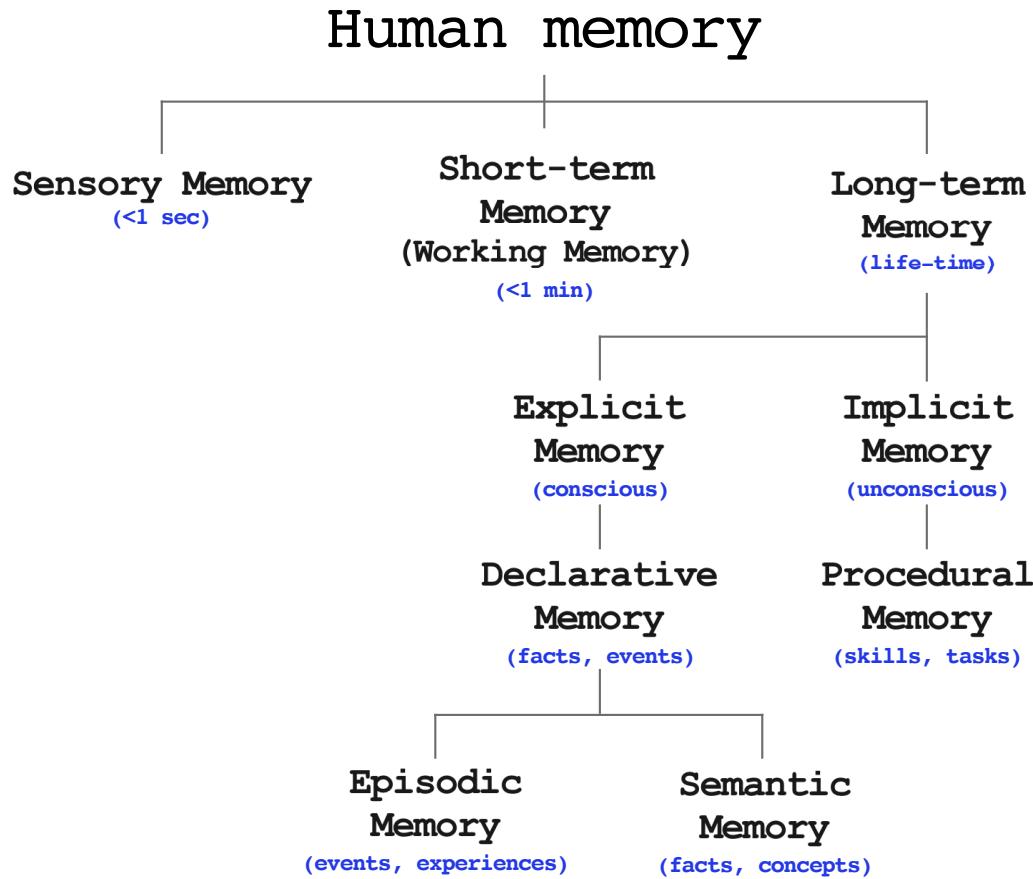


Figure 2.2: The different types of memory [139].

- **Sensory Memory** refers to impressions of information received by the five different senses: sight (iconic), hearing (echoic), taste, smell and touch (haptic). It is the shortest type of memory, with the information being stored for less than a second before being stored to the short-term memory.
- **Short-term/Working memory** is the ability to recall and perform mental operations on a limited amount of information. In literature, it is often used interchangeably with short-term memory, but usually short-term memory refers only to the storing of information and not its processing [10]. Working memory is essential for the functioning of long-term memory, and it is involved in many cognitive functions such as reasoning, problem-solving and learning. ABI can cause working-memory deficits, affecting executive function [133].
- **Long-term memory** refers to the storing of information for a long period of time. Short-term memories can become long-term memories through consolidation, and they are encoded semantically, based on meaning and association. Long-term memory is divided into implicit and explicit memories.

- **Explicit/Declarative memory** refers to memories that are consciously stored and retrieved, such as names and events, and it is often associative. It is divided into episodic and semantic memory. Episodic memory is autobiographical, where memories of experiences and events are represented in a sequence and can be reconstructed at any time, while semantic memory is a structured record of factual information, not associated with personal experiences or the context in which the memory is acquired.
- **Implicit/procedural memory** is the unconscious memory of skills, using objects and movement of the body, typically acquired through practice and repetition.

Retrospective and Prospective Memory

An alternative way to classify long-term memories that is particularly important when studying the effects of ABI, is based on the temporal aspect of remembering. This divides memory in retrospective and prospective.

Retrospective memory is where the information is recalled from one's past, such as past events or experiences, and it includes episodic, semantic and procedural memories [8]. As opposed to retrospective memory, **prospective memory** refers to remembering what we must do, in other words the processing of information that supports the realisation of future intentions. It is closely associated with the ability to carry out future actions and activities. Prospective memory can be broken down into the following stages: 1. The encoding of: the intended action (what to do), the intent (the decision to do something), and the retrieval context (when to retrieve and initiate the intent and action), 2. the retention interval, i.e. the delay between the encoding and the execution, 3. the performance interval, i.e. the period when the intended action should be retrieved, 4. the initiation and execution of the intended action, and 5. the evaluation of the outcome [58]. Prospective memory performance is often impaired after a brain injury (Section 2.2.3).

Executive Function

Executive functioning is an umbrella term that refers to several cognitive and behavioural skills at the highest level of human functioning associated with purposeful, goal-directed activity such as intellect, thought, self-control, and social interaction [74]. Although there are different ways to define and classify executive functions in the literature, typically these include cognitive abilities such as:

- Planning and organisation: the ability to think about the future and create plans of action. Highly associated with working memory performance;

- Flexible thinking: the ability to change perspectives both spatially and inter-personally, changing demands and priorities. Also referred to as cognitive flexibility [49];
- Self-regulation and inhibition: being able to regulate and control one's emotions, and to avoid impulsive and inappropriate behaviour;
- Self-awareness: the ability to monitor and evaluate one's performance in a certain task or behaviour.
- Reasoning and problem solving: The ability to reason, problem solve and recognise patterns or relations among items. Also referred to as fluid intelligence [49];
- Multitasking: being able to carry out multiple tasks with temporal overlap, or execute tasks in varying sequences. Although multitasking is not always considered as a separate executive function in literature, it is affected by the performance of other such functions [130].

Executive functions are associated with the frontal lobe which, as described above, is one of the commonly affected areas in a brain injury. Damage to the frontal lobe can cause impairment of executive functions known as executive dysfunction, which is described in Section 2.2.3.

2.2.2 Physical Effects of ABI

An ABI can have wide-ranging physical effects, the extent of which can vary depending on the severity of the injury. Some of these effects improve with time and with the help of rehabilitation [217], but their duration can sometimes be long term or even life-long.

A common physical effect of ABI is the reduction of the person's mobility. Impaired mobility can affect the person's balance and co-ordination, hindering their ability to walk and often requiring them to use a wheelchair or other mobility aids. Impaired locomotor ability can decrease walking speed [134] and can affect a broader range of simple activities such as getting in and out of bed, climbing stairs, picking up objects and bathing [79], thus reducing the person's independence. Additionally, people with impaired mobility as a result of an ABI are more likely to experience falls [205].

Another physical effect of ABI is physical weakness or paralysis. This can affect the entire body, a specific part of the body, or only one side of the body. The latter is known as *hemiplegia*, a condition that is particularly common after a stroke [176], where only one hemisphere of the brain is affected. Other types of partial paralyses that can be caused by ABI are *monoplegia*, when only one limb is affected, *quadriplegia*, when all four limbs and sometimes certain organs are paralysed, and *paraplegia*, when the person is paralysed from the waist down.

Spasticity can occur when the communication between the central nervous system and the muscles is disrupted. It can have a variety of movement-affecting symptoms, which include muscle stiffness, involuntary movement and spasms, muscle and joint deformities. Although spasticity can be caused by other conditions such as cerebral palsy or multiple sclerosis, it can also be the result of a TBI or a stroke [192]. The impact of some of the effects of spasticity can be alleviated through various rehabilitation techniques [112].

An ABI can also result in impaired vision, as a result of damage in the parts of the brain involved either in visual processing or visual perception (see section 2.2.1). Some of the common vision impairments following a brain injury are blurred vision, double vision and decreased peripheral vision, and they can have a wide-ranging impact on everyday activities like reading, driving and employment³. Cortical Visual Impairment (CVI), also referred to in the literature as Cerebral Visual Impairment, is a type of neurological vision impairment that refers to visual dysfunction resulting from injury to the visual centres of the brain. CVI can result in decreased visual acuity, impaired visual field function, and impairments in higher-order visual processing and attention [140].

Another common physical issue after a brain injury is pathological fatigue, which refers to excessive tiredness not caused by extensive physical or mental activity. Fatigue can be triggered by a variety of activities such as working at a computer, dealing with paperwork, being in busy environments or driving⁴. Furthermore, fatigue is not related to the severity of the injury, and can therefore be caused even by a mild brain injury [13].

The existence of the above issues can reduce the independence of people with ABI, who often have to rely on others to perform everyday activities. This highlights one of the main purposes of technological aids which, as described below, can aim to increase the person's self-reliance. These physical impairments can, however, induce several obstacles in using electronic devices. Specifically, issues like reduced mobility, physical weakness, paralysis and spasticity can hinder the ability of a person with ABI to efficiently use devices which require physical movement. Additionally, vision impairments can prevent users from using devices that rely on visual feedback. The above motivate the aim of this thesis to examine the use of Voice Assistants, which offer hands-free and eyes-free interaction that can bypass these obstacles. Furthermore, pathological fatigue is a factor that needs to be considered when designing technological aids for people with ABI, as it can become an obstacle when using solutions that require long, involved interactions.

³<https://msktc.org/tbi/factsheets/vision-problems-and-traumatic-brain-injury> - Accessed: 11/5/2021

⁴<https://www.headway.org.uk/about-brain-injury/individuals/effects-of-brain-injury/fatigue/> - Accessed: 11/5/2021

2.2.3 Cognitive Impairments

Apart from the physical effects described above, an ABI can have a wide range of cognitive effects, affecting the way the person perceives, thinks, learns and remembers. Like physical impairments, the nature and degree of a cognitive impairment caused by ABI usually depends on the area of the brain that has been affected, and the severity of the injury (Section 2.2.1).

Memory Problems

The most commonly reported issue after an ABI is memory impairment [220]. The common occurrence of memory problems is largely due to the fact that there are several brain areas that contribute to memory performance (Section 2.2.1).

One of the ways that ABI can affect memory is by causing amnesia, which is the lack of ability to either transfer information from the short-term memory to the long-term memory, or to retrieve stored information before a specific date. The first condition is known as anterograde amnesia. It can be caused by damage to the temporal lobe and particularly the hippocampus, however it is still unclear exactly which areas of the brain are associated with this condition [4]. People with anterograde amnesia are often able to remember things up to the time of the brain injury, but are unable to store declarative memories of events happening after it, therefore having difficulties with everyday tasks such as meeting new people, adapting to life changes, and learning new things. The second condition, i.e. the inability to remember events before the injury is known as retrograde amnesia, and it usually occurs after damage to the brain regions associated with declarative memory, like the temporal lobe and prefrontal cortex. Although the two types of amnesia usually appear concurrently (global amnesia), they can occasionally exist as isolated conditions [60]. Another issue affecting long-term memory performance is topographic amnesia, which hinders the ability of finding one's way around familiar environments or learning to navigate in new environments, and can exist regardless of the occurrence of perceptual disorders such as the ones described later in this section [131].

Many of the difficulties in executive functioning that people with a brain injury often experience (described below) are related to the impairment of working memory, as a result of damage to the frontal lobe of the brain [133]. A working memory deficit can hinder one's ability to retain vital information during the performance of cognitive functions such as problem-solving and language comprehension [10].

Prospective memory is often affected by an ABI. As described in section 2.2.1, successful prospective memory functioning relies on the effective fulfilment of intended actions after a delay. Prospective memory is not considered a discrete memory system, but depends upon the

integrated operation of several cognitive functions including memory, attention and executive functions. People with ABI often experience poor prospective memory performance, which prevents them from successfully completing many activities in everyday life and work environments. This, in turn, can have negative effects on people's social life, affecting their interaction with others and can result in them being perceived as unreliable persons [22]. Moreover, impaired prospective memory can hinder the ability to complete critical tasks, such as turning off the oven or taking medication, with potentially disastrous consequences, reducing the person's independence [77]. Successful prospective memory performance not only requires recalling the action that must be taken, but also doing so at the right time (during the performance interval). This is related to the context in which the encoding of the intended action took place, and the retrieval context. Prospective memory functioning can be facilitated with different compensating methods and with the help of external cognitive aids, described in Section 2.3.

Executive Dysfunction

The previous section described Executive Functioning as an umbrella term for several cognitive and behavioural skills. Executive dysfunction is the impairment of those skills, which is a result of damage of the frontal lobe, and it is common among ABI survivors [198]. Executive dysfunction can have a serious impact on many aspects of the person's everyday life. A study by Mazaux *et al.* [129] found that 1 out of 5 TBI patients suffered disability for at least one social ability; these skills included being able to drive, plan for the week, use public transport and write letters, and often resulted in loss of social autonomy.

A frequent effect of executive dysfunction is difficulty with motivation and initiation, which prevents the person from starting a task. This can often be mistaken for laziness, and it can be related with the inability to plan ahead and come up with the different steps required to complete a task or the inability to initiate an intended action. Executive dysfunction can also cause attention and concentration difficulties, making it harder to learn new things, and complete tasks. Another issue associated with executive dysfunction is lack of self-awareness. People who experience lack of self-awareness as a result of a brain injury often fail to realise the extent of their cognitive deficits, such as poor prospective memory performance [177], sometimes refusing assistance, and taking up tasks that they are unable to carry out. This can result in frustration, disappointment and further withdrawal.

Dysexecutive syndrome, also frontal lobe syndrome, is another term found in the literature that is analogous to executive dysfunction, which refers to the impairment of a set of cognitive, behavioural and emotional functions [9].

As with memory problems, there is a set of strategies and tools used in rehabilitation that have

been shown reduce the effects of executive dysfunction, and improve everyday functioning in people with ABI. Some of these are discussed in Section 2.3.

Information Processing

The cognitive function of processing information can be affected after a brain injury in different ways: by reducing the amount of information that the person is able to process, by reducing the speed at which the information is decoded and interpreted, and by impeding the ability to organise one's thinking process [222]. This often makes people unable to function in busy environments, or feel overwhelmed when participating in group discussions. Although impaired information-processing ability should be taken into consideration as a distinct characteristic of people with ABI in the context of Human-Computer Interaction, from a neuropsychological perspective it can be related to (or resulting from) other cognitive effects, such as executive dysfunction and mental fatigue [95, 128].

Behavioural and Emotional Effects

An acquired brain injury can sometimes result in various behavioural changes. These can be related to previous behavioural characteristics, or they can be completely inconsistent with the person's pre-injury character.

Two frequently observed behavioural issues are disinhibition and impulsive behaviour. These can result in socially inappropriate behaviour, such as using crude language or being rude and offensive towards others, often without realising or without considering possible consequences. This can affect the person's social relationships and their participation in social activities [111]. Another prevalent behavioural problem after a brain injury is increased irritability. People who experience this issue can be impatient and intolerant to interruptions, resulting in verbal or physical aggression [174].

The effect of the behavioural issues described above can be exacerbated by lack of self awareness, resulting in the person's inability to justify other people's response to his/her own inappropriate behaviour [87].

Emotional problems, like depression and anxiety, are also common among people with ABI. Determining these effects is often difficult, and can be complicated by the overlap of other cognitive effects of the injury [162]. A study that examined data from over one thousand stroke patients found that over 20% had depression and 29% were suffering from anxiety, with the severity of the stroke not being a predictor of either condition [26]. These conditions can have a big impact on people's daily lives and can obstruct their rehabilitation. Depression can be a

direct result of damage to the brain regions affecting emotions, but it can also occur due to the sense of loss following the injury, and can be associated with the person's insight into the effects of the injury [87].

Another psychological issue that can be seen in people with ABI is post-traumatic stress disorder (PTSD), which is a psychological reaction to a traumatic event that caused the injury, or the early stages of the recovery, and can be more common in people who suffered a TBI and who retain memories of the circumstances of the injury [218].

The occurrence of behavioural and emotional effects of ABI can complicate the recovery process, and together with the cognitive impairments are addressed in neuropsychological rehabilitation following the holistic model (section 2.3.1).

Perception Impairments

Additionally, ABI can affect other senses such as hearing, smell or touch⁵. One sensory related condition that can occur after a brain injury is agnosia, which refers to the inability to process sensory information [3]. Although only a single modality is usually affected, there are different types of agnosia that can follow a brain injury, the most common of which include: visuo-spatial agnosia (which affects the visual recognition of objects or the spatial relationships between them), prosopagnosia (inability to recognise familiar faces), topographical agnosia (inability to recognise familiar surroundings) and anosognosia (lack of ability to recognise one's own condition). Agnosia can have an impact in carrying out everyday activities such as reading, writing, cooking, participating in social events or navigation [208]. Visual (or spatial) neglect is another vision-related condition that can be caused by an ABI, which results in lack of attention to stimuli in one part of the field of vision [211], most commonly the left side.

Communication Problems

Problems with communication are common after an ABI and can be a result of the physical effects (movement of muscles used in speech), the cognitive effects (ability to think, learn and remember), and the emotional and behavioural effects described above. Several of the cognitive deficits mentioned earlier in this section can impair the person's ability to communicate effectively and participate in social activities, in different ways. For example, attention and concentration difficulties can make it difficult to stay focused on a conversation, and memory issues can make it hard to remember people's names or faces.

⁵<https://www.headway.org.uk/about-brain-injury/individuals/effects-of-brain-injury/physical-effects/sensory> - Accessed: 11/5/2021

Injury to the brain regions associated with language can result in the language impairment called aphasia, which can have the following effects: impaired ability to understand language (receptive aphasia), difficulty reading and recognising words or letters, problems with writing, and impaired ability to produce speech. Although it can be one of the most devastating cognitive impairments caused by an ABI, recovery from aphasia can be possible through speech-language therapy and medication [18].

Finally, ABI can impair the physical ability to speak, causing reduced control and clarity of speech (dysarthria), or causing difficulty saying what one is consciously thinking about saying (apraxia or dyspraxia of speech) [86].

Cognitive Impairments and Voice Assistants

The cognitive issues described above highlight some of the potential purposes of Voice Assistants. Specifically, VAs can be used to support memory functioning of people with ABI, or support the execution of everyday activities hindered by executive dysfunction. Additionally, they could be used to facilitate the application of rehabilitation strategies to mitigate problematic behaviour, to improve communication, or to provide emotional support (see Sections 2.3.2 and 2.4.2).

Furthermore, when designing solutions aids for people with ABI, it is essential to be aware of the existence of the above issues as they can impact the way users interact with technology. The exact manner and extent in which they can affect the use of Voice Assistants will be examined in later Chapters.

2.2.4 Summary

This section provided an overview of the different types and causes of brain injury, introduced the main regions of the brain and the functions that these regions are associated with, and presented how these functions can be impaired after an ABI. Furthermore, this section introduced terms related to ABI and its effects that are being used throughout the thesis.

ABI can have a wide range of physical, cognitive and psychological effects, which can limit the person's independence and make it difficult, or sometimes impossible, to carry out everyday tasks. As will be described in the next section, technology can be used to compensate for many of these effects, and to improve people's everyday functioning. However, the effects of ABI are many and diverse, and can vary greatly from one person to the other. This makes the task of designing technologies for people with ABI especially challenging, and before it is attempted, it is essential to carefully consider the characteristics and impairments of the target users.

By examining the common effects of ABI and the difficulties that people with ABI face in their daily life as a result, we can identify the situations where the use of technology could be beneficial as an external aid. Therefore, this section informs research question:

- **RQ1:** Which are the use cases of Voice Assistants for users with cognitive impairments due to an Acquired Brain Injury?

Furthermore, the knowledge of how the commonly affected cognitive functions (e.g. memory) normally operate, and how they can be impacted by an ABI, can be used to inform the design of assistive technologies.

It is apparent that several of the effects of ABI described, such as impaired motor skills, loss of vision, memory problems and executive dysfunction, can hinder people's ability to use common technologies like computers and smartphones efficiently (this is further discussed in section 2.3). This supports the motivation behind this thesis to examine the use of Voice Assistants, an emerging speech-activated smart technology, as a technological aid in the context of ABI rehabilitation. Section 2.4 discusses why Voice Assistants can offer a promising alternative to more mainstream devices with the potential to overcome some of the usability challenges that ABI effects can induce.

2.3 Rehabilitation and External Aids

Before looking into the use and design of technologies to assist people with a brain injury, it is important to understand the ABI rehabilitation process and its purpose, and to examine the benefits as well as shortcomings of the methods used.

Rehabilitation after an ABI can be a slow and complicated process, depending on the nature and severity of the injury. It involves assessing the brain damage and determining the extent of physical and cognitive deficits, setting a rehabilitation plan and desired outcomes, informing the person affected and their families about the injury and the recovery process, and providing psychological support.

Usually rehabilitation after brain injury begins once the person is medically stable and has been discharged from the hospital, and it can occur in different settings, depending on the time since the injury, the person's condition, and expected outcomes. These settings can be: Inpatient rehabilitation, which refers to intensive and structured rehabilitation programmes usually provided by specialists in neurological rehabilitation centres; outpatient rehabilitation, which involves regularly visiting a rehabilitation centre or hospital to receive treatment while living at home; and community rehabilitation, which may take place at a person's home or in a centre

located within a community setting rather than a hospital setting, where people develop their independent living skills [67]. ABI rehabilitation also involves a variety of professionals from different disciplines such as clinical neuropsychologists, occupational therapists, speech and language therapists and physiotherapists.

ABI rehabilitation can be facilitated by the use of external aids, which can be either paper-based or technological tools. These can be used to compensate for cognitive deficits, or to support the rehabilitation process. However, there can be several factors that might affect their efficient use. This section gives an overview of the process and objectives of brain injury rehabilitation, and presents research related to this thesis that examines the use of technology in that context. It also presents the challenges around the utilisation of technological solutions for people with ABI, which largely determine the motivation behind the research objectives of this thesis.

2.3.1 Neuropsychological Rehabilitation

Wilson and colleagues describe Neuropsychological Rehabilitation (NR) as the type of rehabilitation concerned with "enabling people with cognitive, emotional or behavioural deficits to achieve their maximum potential in the domains of psychological, social, leisure, vocational or everyday functioning" [228]. From that description, it is apparent that NR is a multidisciplinary process, with multiple objectives and different areas of importance, which include: cognitive functioning, emotion, social interaction, behaviour and learning.

Although there have been many different models for NR, neuropsychologists now follow a holistic approach, which considers the cognitive effects of ABI to be interlinked with the emotional, social and functional effects [14, 51]. Most holistic rehabilitation programmes are concerned with increasing the person's awareness, alleviating cognitive deficits, developing compensatory skills, and providing vocational counselling [228].

Usually the first stage of NR is that of assessment, which involves collecting, organising and interpreting information about the person and their situation, in a systematic way. Assessment is carried out with the help of a series of standardised neuropsychological tests, and it is also concerned with predicting the person's behaviour and situation in the future [200]. The next step after the assessment is to create a rehabilitation plan, through the process of goal setting, where professionals discuss rehabilitation goals with the patients and their families, and decide how these goals will be achieved [227]. Ideally there should be a combination of short-term and long-term goals, which should be realistic yet challenging, and specific enough to be monitored and evaluated [69, 105].

One of the main goals of NR is to increase independence and self-efficacy [186], which can

be reduced after an ABI. People with cognitive impairments often have to rely on support from others to perform everyday activities. This can exacerbate the emotional stress for the person with ABI, but can also lead to psychological strain for those providing the support [25, 122]. Besides the psychological reasons, self-efficacy is also important for commitment to rehabilitation goals, as people are more likely to work towards a goal if they believe they can achieve it. This also works in reverse with short-term goals, which can increase the person's sense of self-efficacy when accomplished, and increase their motivation to work on their rehabilitation plan [228]. However, people with cognitive impairments can have difficulties in monitoring their progress, and remembering their rehabilitation goals and their rationales. Support can be given to them through their care-givers, or with the use of external aids, as will be described later in this section.

The evidence on the efficacy of Neuropsychological Rehabilitation interventions on people with ABI is indisputable, showing that NR can improve cognitive performance and everyday functioning [89, 109, 144, 147, 186]. However, evaluating the outcome and efficacy of an intervention in NR (whether that involves a technological tool or not) can be challenging [19]. One of the important issues is how to determine the element that will be measured. This depends on the rehabilitation goals that have been set: If the treatment being evaluated aims to improve a particular cognitive function, it is useful to have an assessment of that cognitive function as an outcome measure. However, according to Wilson *et al.*, since the ultimate objective of NR is to help people carry out valued activities and improve their functioning in everyday life, the outcome of rehabilitation should be measured at this level whenever possible [228]. This can be achieved using direct measures of real-life behaviour, rather than relying exclusively on standardised tests, whose relationship with real-life functioning is unclear [183, 225].

The goals of NR described above can be used to determine some of the potential purposes of technological aids (and therefore Voice Assistants) for people with ABI, such as increasing self-efficacy and improving commitment to rehabilitation goals. Moreover, comprehending the process of NR is essential when investigating the design of technologies such as VAs which can be used alongside rehabilitation, or to facilitate the rehabilitation process.

External Aids

Rehabilitation for people with ABI can be facilitated with the use of external aids. These can be either paper-based tools, or electronic aids, which are usually referred to as Assistive Technologies (AT). People with ABI might use external aids as part of a rehabilitation strategy, or on their own accord because they find them beneficial.

One of the common ways that paper-based tools are being used by people with ABI is as

memory aids. Although the extent to which they can restore memory is unclear, paper-based memory aids have been found to be effective in compensating for memory deficits and in helping people function more independently [220]. In a study by Evans *et al.* investigating the factors that predict use of memory aids, the most commonly reported paper-based tools were wall calendars, notebooks, lists, appointment diaries, hand-written notes and personal organisers [61]. The number of aids that participants reported using depended on their age, the time since their injury, the number of aids they used before their injury and their attention capacity.

Dairies and notebooks are also among the most common aids used in research studies investigating neuropsychological rehabilitation methods, with several benefits being reported. A study by Fleming *et al.* [66] which examined the outcome of an intervention that included regular diary entries, reported improvement in prospective memory performance. Another study reported that participants using a memory notebook not only showed better prospective memory performance, but they were also able to perform more meaningful and functional tasks independently [135]. The additional benefits of memory aids are also demonstrated in other studies, where in addition to helping with successful remembering, memory aids improved self awareness, orientation to time and overall everyday functioning [77, 182, 188].

Although the usefulness of paper-based tools is evident in ABI rehabilitation, there are several challenges induced by the participants' deficits that can affect the efficient and continued use of the aids. These include poor self awareness, frustration, cognitive impairments and physical limitations [27]. To overcome these challenges, researchers have highlighted the need for extensive training, and tailoring the tools based on the characteristics of the individual, to increase the probability of a beneficial outcome [66, 135, 191].

In the aforementioned study by Evans and colleagues [61], technological aids were much less common among participants than their paper-based equivalents (it should be noted that the study was published in 2003). The authors speculate that this was because "high-tech" aids can be too complex to learn for people with severe cognitive impairments, or because they were not being recommended by rehabilitation professionals. However, most of the reported technological tools were described to be more efficient than the more popular paper-based ones. A more recent (2017) follow-up study by Jamieson *et al.* found technological memory aids to be significantly more common than in the first study, however, they were still much less popular than paper-based ones [90], and a systematic review examining the efficacy of cognitive aids on the performance of everyday tasks requiring memory found that technological memory aids can be more beneficial than "non-tech" methods [91].

These findings show that there is promise in Assistive Technologies for people with ABI. Although there are clear benefits from the use of paper-based tools in brain injury rehabilitation, there are certain factors that can hinder their use and limit their efficiency. Although technolog-

ical tools can be more effective, in order to examine the design of Voice Assistants it is essential to identify the factors that prevent people with ABI from using them as widely. The next section focuses on the use of AT for people with cognitive impairments due to ABI, and presents related research that examines their efficacy and design.

2.3.2 Assistive Technologies

There is a plethora of research examining the use of technological aids for people with cognitive impairments aiming to support cognition and to increase the user's independence and everyday functioning. LoPresti *et al.* define technological interventions for people with acquired impairments or developmental disorders as *Assistive Technology for Cognition* (ATC) [116]. O'Neill and Gillespie describe ATC as "technologies that enable, enhance or extend cognitive function" [157]. Since this thesis focuses on technological solutions for people with cognitive impairments due to Acquired Brain Injury, from this point on the term Assistive Technologies (AT) will be used to refer to all ATC used in that particular context.

Several studies have investigated the efficacy of AT for people with cognitive impairments. The results of the systematic review by LoPresti *et al.* indicate that, by enabling a person with cognitive impairments to engage in more therapeutic activities, ATs can improve the outcome of traditional rehabilitation methods [116]. According to the authors, another way that ATs can be beneficial is by providing alternative ways to carry out activities through enhancing the impaired functions, and therefore introducing new rehabilitation methods.

A review of 25 studies by DeJoode *et al.* measured the changes in cognitive performance and the level of participation in everyday life, to determine the efficacy of portable electronic aids for people with cognitive impairments [40]. The devices used in the studies were PDAs, pagers, voice recorders and mobile phones, and they were used to support prospective memory, independent functioning and social participation. The authors report that the studies showed positive results for most aids, with the ones examining the use of a pager demonstrating the bigger benefits. They also report that the use of AT is generally met with optimism by potential users and rehabilitation professionals. Similar findings are reported in the systematic search by Jamieson *et al.* which investigates the impact of AT used as memory aids (the majority of which were found to be prompting devices), concluding that they can improve people's performance on everyday tasks that require memory [91]. According to the authors, the results of their analysis provide "very convincing evidence for the efficacy of prospective memory prompting devices [...] compared to a non-technological or usual practice control condition".

Regarding the prevalence of AT in people with ABI, the survey by Jamieson and colleagues [90] found a significant increase compared to an older study [61], with mobile phones, alarms

and timers being the more popular devices. Other aids were pagers, electronic personal organisers, dictaphones and electronic watches. Higher use of electronic memory aids was associated with younger age, higher use of technological memory aids before the injury, and higher use of other non-tech memory aids or strategies. The most common use cases for AT was to facilitate prospective memory functioning. Other uses cases included help with organisation and orientation.

Reminder Systems

Probably the most common use of AT found in the literature is in systems providing timely prompts or cues to aid remembering or encourage activity [91, 116]. One of the most widely reported examples is Neuropage, a simple paging system that sends reminders to carry out an action, like taking medication or attending a doctor's appointment [88]. In a study by Wilson *et al.* which evaluated the efficacy of Neuropage with 15 people with ABI and memory difficulties, the mean percentage of everyday tasks completed successfully increased from around 37% to around 85% across all participants. For some, the improved performance also continued after the intervention, indicating a long-term effect from the use of the device [226]. A larger study with 143 participants who had memory, planning, organisation or attention difficulties found that people were performing significantly better at carrying out everyday tasks independently after using the Neuropage [223]. The long-lasting impact of Neuropage was replicated in this study, with many participants retaining the improved performance even seven weeks after returning the device. Effective use of Neuropage has also been demonstrated in numerous other studies, in the rehabilitation of people with ABI from cerebrovascular incidents [63], people with encephalitis [59], and children and adolescents [222]. A study by Martin-Saez *et al.* examining how the application of the Neuropage system evolved in a 10-year period (2000-2010) found that in some cases the pager device had been replaced by a smartphone during rehabilitation, which was used to successfully convey the same prompting messages [127].

Smartphones, as well as mobile phones in general, have also been used in several other cases as prompting devices to aid people with ABI [202, 203]. Fish *et al.* investigated the use of a mobile phone to improve the outcome of a goal management training for 20 people with ABI [64]. The participants were asked to perform a prospective memory related task (make a phone call) at specific times, four times a day for several days. On some days, a text message saying just "STOP" was sent to participants' mobile phones, with the purpose of making the stop and think about their goals and intentions. The task performance was significantly increased on the days that the prompt was received. The same goal management training was also facilitated by cues received on a smartphone in a study by Tornås *et al.*, which demonstrated long-term improvement of everyday executive functioning in people with executive dysfunction due to ABI [206].

Another study by Stapleton *et al.* examined the use of smartphone reminders in individuals with TBI [194]. For some participants, the phone usage greatly improved the achievement of target behaviour, with the effect remaining even after the phone was removed. However, the use of the device was not beneficial for participants with severe memory impairments. Groussard and colleagues applied participatory design to implement SAMI (Services Assistance Mobile and Intelligent), a smartphone application that supported people with cognitive impairments in planning, health monitoring and money management [78]. The results showed improvement in life satisfaction. Smartphones have also been used together with existing calendar software to provide prompting for people with ABI. McDonald *et al.* compared the use of Google Calendar to a paper-based diary [132]. Participants were required to create and edit events using Google's software on a computer, and link it to their phones to receive the reminders. The results showed that the electronic aid was more effective in supporting prospective intentions.

Another type of device that has been used for reminding is the voice recorder. Yasuda *et al.* used a voice recorder to aid people with impaired prospective memory in carrying out various daily tasks such as diary writing [233]. Prompts were given in the form of pre-recorded voice messages, and were found to be highly effective in increasing task completion. A similar device called Voice Organizer was shown to be beneficial in helping people with ABI to complete prospective memory demanding tasks [207, 219]. Van Hulle and Hux combined the use of a voice recorder with a wristwatch alarm, to increase the independence of people with memory deficits due to TBI in remembering to take their medications [209]. The use of wearable devices for prompting have also been examined in other studies (e.g. [50, 93]).

Another reminder AT providing audiovisual cues was the TAP (Television Assisted Prompting) system, which displayed reminders at scheduled times on the users' home television. TAP allowed the completion of more tasks and led to increased confidence [108].

The use of PDAs (Personal Digital Assistants) has also been investigated in related research. Dowds *et al.* examined the use of PDA devices as scheduling and reminding aids with 36 persons with TBI and memory impairments [53]. They found that participants completed significantly more memory tasks when using the PDAs compared to when using a paper-based schedule book, or no aid at all. The authors argue that the difference was due to the reminder cues provided by the PDAs. Similar results in improving prospective memory performance were reported by Waldron *et al* [212].

Task Guidance

Technology has also been used to facilitate people with ABI to carry out specific tasks. A study by O'Neill and colleagues used the Guide system to help amputees with cognitive impairments

put on their prosthetic limb [158]. Guide was a sequencing system that provided verbal instructional prompts and responded to simple verbal feedback. Video analysis was used to determine the participants' performance, and it was found that the use of Guide led to fewer errors and less omissions in the donning process. The authors speculated that the success of the intervention was partly due to the verbal interface, which was familiar for the users. A similar solution was Pocket Coach, which aimed to facilitate task completion by displaying a sequence of visual cues on a PDA [70], improving the users' occupational performance and participation in everyday life tasks.

Kinerehab is another good example of task guidance AT [32], albeit somewhat outside the scope of this thesis, as its purpose was to facilitate physical rehabilitation. The system used the Kinect technology to detect joint position and determine the user's movement. It also included an interactive audiovisual interface to direct users through the exercises. Kinerehab was shown to significantly increase the users' motivation and performance during rehabilitation activities.

Planning and Organisation

Besides helping with reminders and guiding users through the completion of different tasks, ATs have also been helpful in providing a framework for scheduling and planning daily activities. In 1989, Giles and Shore used Psion Organiser, an electronic device which allowed diary entries and memo notes, with a woman who had experienced a subarachnoid haemorrhage and had a significant memory deficit [72]. The use of the organiser greatly improved the participant's ability to carry out everyday activities. Another early example of this type of AT is the Planning and Execution Assistant and Trainer (PEAT), a multi-functional hand held device which used AI software to automatically generate a daily plan and monitor its execution using visual and auditory cues [110]. A more recent study incorporated sensory feedback to PEAT to automatically detect the activity the user was performing, and provided more effective cues [145].

Rehabilitation and Care Taking

AT has been also used to facilitate different rehabilitation methods and processes. Hart et al examined the efficacy of a portable voice organiser in helping people with TBI recall their rehabilitation goals and plans they had discussed with their clinical case managers [81]. They found that the goals that had been recorded with the organiser were recalled more successfully, and participants were better at associating them with their therapy objectives. Improvement in recalling rehabilitation goals with the help of technology was also achieved in a study by Culley and Evans, in which SMS text messages were sent to participants three times per day for 14 days [39].

Another application of AT is to aid care givers in providing support to people with ABI. One such example of AT was ICue, a software allowing caregivers to organise the activities of the person with cognitive impairments into a daily schedule [115]. After the schedule had been inserted into the system, ICue would provide instructions on how to complete each task, through a PDA device or a web interface. Similarly, the MAPS (Memory Aiding Prompting System) system allowed caregivers to design prompts with images and audio, which would then be conveyed to the user through a handheld device (PDA) at specific times [30]. MAPS also featured data logging which allowed the evaluation of the prompts and the effectiveness of the system. Solo was another cognitive aid designed to support people with cognitive impairments and their givers in organising and scheduling daily activities [114].

Recording Memories

A noteworthy example of AT is SenseCam, which was originally developed by Microsoft as a personal 'Black Box' for recording accidents⁶. SenseCam is an early case of wearable computing that can be worn around the neck, and it features a wide angle lens and different sensors such as accelerometers and temperature sensors. It automatically takes a photograph every time one of the internal sensors is triggered, creating a photo diary with several hundred photos per day.

Berry and colleagues used SenseCam in a case study with a person with anterograde and retrograde memory impairment, to create a pictorial diary with all the events the participant experienced during the day [17]. When compared to a paper-based diary, the pictorial diary generated by the photos captured by SenseCam led to the successful recalling of 31% more autobiographical events, which were retained in the long-term. Another study by Loveday and Conway demonstrated similar results [118]. SenseCam was also effective when used in a cognitive behavioural therapy intervention for a person with anxiety disorder and memory difficulties due to ABI [24]. The retrieval of events triggering anxiety were significantly higher with the SenseCam than with other methods. Svanberg and Evans found that, by recalling autobiographical memories through the use of SenseCam, subjective ratings of identity were improved in a person with severe memory impairment [201]. The authors discussed that being aware of the memory impairment and receiving adequate support may be required for the effective use of this type of AT.

Similar devices inspired by the SenseCam which have been used in analogous ways are the Autographer and the Vicon Revue [48, 107].

⁶<https://www.microsoft.com/en-us/research/project/sensecam/> - Accessed: 11/5/2021

Facilitating communication

As seen in Section 2.2.3, ABI can affect a person's ability to communicate in several ways. ATs have been successfully used to support people with communication difficulties, in different situations.

CHAT (Conversation Helped by Automatic Talk) was a prototype system originally designed to help people unable to speak due to physical impairments such as paralysis or spasticity [5, 149]. Users of CHAT could press a key while speaking with others people, to fill in gaps with automatically generated phrases and small sentences. A more recent technology aiming to support this particular user group is Voiceitt⁷, a speech recognition application for mobile devices that uses machine learning to learn how to understand users with severe speech impairments, and automatically transcribe their words into text that other people can read.

Two common speech impairments caused by ABI are aphasia and apraxia of speech (section 2.2.3). Piper *et al.* examined the design multimodal digital pens to support speech-language therapy for people experiencing these conditions [166]. GeST was a computer gesture therapy tool designed for people with severe aphasia [126, 178]. The studies showed that practice with GeST for a period of six weeks could significantly improve gesture production. Virtual Reality (VR) has also been used to aid therapy for people with aphasia. A VR platform named EVA Park allowed interaction between users in virtual locations, aiming to promote well-being and communication abilities of people with aphasia [124, 125]. Although the data measuring the outcome of therapy interventions using the platform were not conclusive, the researchers showed that such solutions can help overcome recruitment and feasibility related obstacles that arise when conducting studies with people with aphasia. Varley and colleagues explored the effect of a self-administered software for apraxia of speech with stroke survivors, and found significant improvement in production of speech [210].

Alleviating Emotional Effects

Section 2.2.3 also described some of the psychological problem that often arise after an ABI, one of which is PTSD. A promising technology-based approach to address this is through virtual reality exposure treatment. VR allows a person with PTSD to practice being in controllable virtual environment that resembles traumatic situations, and practice the required cognitive skills to function in an adequate level [102, 215].

Other common emotional effects of ABI mentioned in section 2.2.3 were anxiety and aggression. A key to addressing these issues can be to increase awareness of the person's emotional

⁷<https://voiceitt.com/> - Accessed: 11/5/2021

status, which can be done through providing biofeedback on heart rate variability [44, 98]. A study by Kim *et al.* examined the extent to which heart-rate variability biofeedback can help people with ABI improve their emotional regulation and problem-solving ability [100]. The authors argue that the person's cognitive impairments can affect that the measurement of physiological behaviours can have on their executive function. In another study evaluating the efficacy of a biofeedback-based intervention it was shown that can help reduce aggressive behaviour [156].

Barriers

The numerous examples of technological aids for people with ABI described above demonstrate that AT can compensate for cognitive impairments and help brain injury survivors in several situations. Additionally, many of the aforementioned research studies have shown that AT can be more effective than non-technological methods and tools. However, it was also shown that, despite their frequent and effective use in research studies, ATs are not as common as one would expect in rehabilitation practice and everyday life. Moreover, some of the above research studies reported obstacles in the use and design of AT which can prevent their efficient use. The most important and prevalent factors that can affect the uptake and effectiveness of AT are examined below.

One of the apparent factors that can affect the efficiency of AT is the user's cognitive deficits. In the previously mentioned study by Stapleton *et al.* examining smartphone reminders for people with TBI, participants with severe memory impairments did not benefit from receiving the prompts [194]. This was most likely due to users forgetting to use them at the appropriate time, or being unable to relate the received cues with their intended purpose. As Wilson put it: "external cues are of little use for people with TBI who may be unable to remember what the cue is for" [221]. Cognitive accessibility was also one of the themes that emerged in Jamieson and colleagues' study investigating the issues influencing the use of smartphone reminder apps for people with ABI [92]. This can also affect the learning or training required for the cognitively impaired user to use the AT efficiently, making tools with steep learning curves inappropriate for people with learning and memory difficulties, low tolerance for frustration and lack of motivation [92]. Similarly, a study by DeJoode and colleagues looking at the use of calendar software found that people with ABI became upset more easily, needed more effort and became tired quicker than healthy users, which led to lower success in task completion [42]. Another theme illustrating a barrier stemming from a cognitive effect of ABI in the study by Jamieson *et al.*, was not using the AT due to limited self awareness [92]. This occurs when users lack insight into their cognitive difficulties and believing they don't need the external aids to function properly.

Besides cognitive difficulties, physical impairments such as vision loss or limited hand movement can reduce accessibility to electronic devices. In Jamieson and colleagues' co-design study

for smartphone reminder apps, people with ABI expressed their dissatisfaction with interfaces containing a lot of visual information, small fonts or low colour contrast [92].

Another factor that can prevent people with ABI from using AT is social acceptance or pressure. Being seen in public with a cognitive prosthetic might make users feel embarrassed, or believing that others would perceive them as someone unintelligent or in need of help [12, 92].

Finally, the uptake of AT is also affected by the fact that they are not well integrated in rehabilitation methods, and therapists or care takers are not adequately trained to use them or suggest them to their clients [61, 90, 91, 116]. Although this is an important issue, it is not directly related to the design of AT, and will therefore not be taken into consideration in this research.

Novel Approaches

Research studies have explored ways to increase the efficacy of assistive technology by overcoming the above-mentioned barriers. One approach regarding prompting systems is directed towards minimising reliance on user's initiative. Jamieson *et al.* defined prompts that alert the user prior to any input as Unsolicited Prompts (UPs) [94]. In their study the authors used prompts that periodically asked the user if they needed to set reminders into a smartphone app, resulting in an improvement of reminder setting performance.

The success of UPs relies on providing appropriate prompts at the right time. The correct timing and content of the prompts can be automatically predicted either by analysing the users' behaviour, or by sensing their environment. Autominder was a prompting system that used artificial intelligence to automatically determine the timing of prompts, based on a model of the user's daily schedule [167]. The system was integrated in a mobile robot aimed to provide assistance to elderly people. A similar approach was taken in a study that used an intelligent, context-aware prompting system to support elder people in taking their medication, resulting in significantly improved adherence [84]. Context awareness was also utilised in a system called COACH (Cognitive Orthosis for Assisting aCtivities in the Home), which aimed to assist people with cognitive deficits complete activities of daily living [142]. COACH used AI to recognise the user's location and social environment to give suitable audio and video prompts.

Smart environments provide ideal settings for context-awareness and behaviour-sensing. These environments usually combine different devices that can communicate with each other, offering various ways to monitor the user's behaviour and provide prompts. A study by Boman *et al.* examined the use of a smart-home memory aid system, consisting of several sensors placed inside the participant's house [20]. The system could record the user's activities through data collected from the sensors, and determine whether a spoken reminder should be given. The results showed improvement in the completion of targeted activities. The Aware Home was another research

project aiming to increase independence of people with cognitive difficulties, through the use of multiple sensors which collected data to determine the person's activities [2].

2.3.3 Summary

Neuropsychological rehabilitation aims to help people with ABI cope with their cognitive impairments. The process and outcome of rehabilitation can be improved through the use of external aids, which can be either paper-based tools or assistive technologies (ATs). Research has shown that both types of aids can be beneficial, but ATs are often more effective. However, according to studies, ATs are not used as frequently by people with ABI, and there are several barriers that can negatively impact their use.

This section presented different applications of external aids and demonstrated how ATs can compensate for the different cognitive effects of ABI. The most common form of ATs is the reminder system, which have been shown to increase prospective memory performance. ATs have also been designed and applied to successfully support task completion, planning and organisation, as well as facilitate the communication between the person with ABI and their carer giver. The studies that examined the use of ATs have identified several factors that can prevent their uptake or reduce their efficiency. These are usually related to cognitive and physical limitations, the user's social context and lack of training or guidance. Different approaches have been taken to bypass some of the obstacles created by these factors and to create more efficient ATs, aiming to optimise the content and timing of the support being provided, minimising the reliance on the user's initiative.

By identifying the various ways that ATs can be beneficial to people with cognitive impairments due to ABI, as well as the situations where its use is acceptable and appropriate, this section also identifies some of the areas where the use of Voice Assistants would be suitable, and therefore informs the first research question of the thesis:

- **RQ1:** Which are the use cases of Voice Assistants for users with cognitive impairments due to an Acquired Brain Injury?

RQ1 is also informed by the description of factors hindering the efficacy of AT, as this identifies situations where there is room for better design or use of alternative tools such as Voice Assistants. Moreover, the section identified some of the issues that can affect the usability of different types of technology in people with ABI. Several of these factors could also have an impact on the usability of VAs, and will therefore have to be examined in later Chapters. By identifying these issues, this section lays the groundwork for answering the second research question:

- **RQ2:** Which are the factors that affect the usability of Voice Assistants when used by people with cognitive impairments due to ABI?

Before trying to determine the use cases of Voice Assistants and examine their usability in people with ABI, it is essential to understand the differences and similarities between VAs and other technologies which are commonly used as ATs. The next section describes the technology of Voice Assistants and their potential benefits over other tools, and presents the motivation for examining their use to support people with cognitive impairments due to ABI.

2.4 Voice Assistants

2.4.1 Voice User Interfaces

Voice-user interfaces (VUIs) enable users to control a software system or an electronic device through speech, using their voice to input information into the system, and receive feedback from that system or device, usually as audio or as a combination of audio and other modalities. Although VUIs have been a subject of research in the field of artificial intelligence for decades, recent advancements in speech recognition and speech synthesis have allowed them to become an essential part of most modern computing systems. Popular operating systems for personal computers, such as Windows and MacOS, include speech recognition that provides an alternative input method for users to navigate through the system and input information. They also include text to speech technology that can convey written text to the users in the form of audio. Similarly, VUIs have been incorporated into modern mobile devices like smartphones and tablets with analogous input and output functionality. VUIs are also present in many modern cars, allowing the users to issue voice commands to manipulate different controls (e.g. music or GPS). Finally, VUIs can also be found in some state-of-the-art household devices, like televisions, and even ovens and washing machines.

One of the main benefits that VUIs offer is hands-free and eyes-free interaction, enabling people to use the system while their hands and eyes are occupied with a different task (multi-tasking) [121]. This is largely due to the fact that VUIs reduce the visual demand of a system and can be less distracting compared to other modalities [143, 165]. Low distraction and visual demand are especially important when performing a task like driving which demands the user's full focus and attention and where errors can have serious consequences. However, the extent to which the interaction with a VUI is not distracting the user from the main task largely depends on its design and implementation [52].

Another important benefit of VUIs is that they can allow faster execution of certain tasks.

For example, a study examining the speed of text entry using a keyboard and a VUI found that the latter allowed users to input text almost 3 times faster on a smartphone [181]. Similarly, a study found that the use of voice commands enabled users to perform tasks faster than with a touchscreen, while using a flight simulator [141]. However, the completion time depended on the nature and complexity of the tasks, and while the VUI was generally faster, some complex tasks were completed more quickly using the touch screen.

It can therefore be argued that VUIs have several advantages which can benefit people with ABI. Specifically, reducing distraction and visual demand of a system can be important for people with impaired attention and concentration. Also, faster task completion can reduce required effort and frustration, which can be crucial for users with cognitive impairments. Finally, eyes and hands-free interaction can increase accessibility for people with ABI who have impaired motor movement or vision difficulties.

Spoken Dialogue Systems

Early forms of VUIs could support a limited number of voice commands, with the user input usually consisting of small, specific sentences or single words (e.g. choosing from a list of options by saying the corresponding number). Advancements in machine learning led to a revolution in natural language processing, which allowed VUIs to evolve into systems that simulate dialogues exchanged between humans. Such systems are known as Spoken Dialogue Systems (SDS), which have been defined as "computer systems with which humans interact on a turn-by-turn basis and in which spoken natural language plays an important part in the communication" [71]. McTear [138] describes SDS as systems that enable "casual and naive users to interact with complex computer applications in a natural way using speech" and distinguishes three main types:

1. *Finite state-based* systems, in which the user is taken through a dialogue that consists of a sequence of predetermined steps or states. The system maintains the control of the dialogue, delivering prompts at each step of the dialogue, and recognising or rejecting the user's response based on whether it includes specific words and phrases.
2. *Frame-based* systems, which analyse the user's responses to specific questions to fill slots in a template (e.g. extracting the date, time from the user's response to "when do you want to travel?"). Frame-based systems can work like finite state-based ones when the users' responses contain only one piece of information at a time, but can recognise and process responses containing multiple pieces of information.
3. *Agent-based* systems, which use artificial intelligence to permit complex communication in order to support the completion of a task. These systems are capable of taking the

preceding context into account and evolving the dialogue dynamically as a sequence of related steps that build on each other.

The above classification of SDS is important to take into consideration when building or analysing a speech-operated system, with regards to its architecture and implementation. From an interaction design perspective, all SDS with interfaces based on natural language belong in Conversational User Interfaces (CUIs). Although very different from a Graphical User Interface (GUI), the interaction with a CUI is not always done through voice, but can also be text-based, consisting of simple visual elements borrowed from instant messaging or short message service interfaces (SMS), or it can combine voice and visual feedback to convey information to the user [146]. Some aspects of the User Experience (UX) design of a CUI can be different depending on the modalities used. However, most of the characteristics and principles are common across modalities, and should all be considered when examining the design of a conversational voice interface [137].

2.4.2 Digital Assistants

CUIs are being utilised to interact with many different types of technology, and they are one of the main characteristics of -and the typical way to interact with- Digital Assistants (DAs). DAs are autonomous software agents, which use a knowledge base, AI algorithms, natural language processing and a CUI to provide a variety of services to their users.

Digital Assistants have been used to provide support to people for many years, and in a variety of ways. One of the early examples was ELIZA, which was designed to simulate the conversation between a person and their psychotherapist [213], and which played an important role in the evolution of CUIs and the use of chatbots in the context of therapy and emotional support. A modern example of a chatbot-based DA to provide mental health support is Woebot⁸. Woebot uses a variety of methods including brief daily conversations, mood tracking, videos and word games to help people manage their mental health. A recent study reported that students who chatted with the bot for a few weeks showed significantly lower stress levels compared to those who were pointed to a self-help book [65]. Other examples of chatbots used in a similar context include Therachat⁹, which can be used by therapists to keep their clients engaged in the therapy process, and Wysa¹⁰, a chatbot that uses techniques from cognitive-behavioural therapy and meditation to help users build emotional resilience.

Although their conversational capabilities are essential, an important factor that makes DAs

⁸<https://woebohealth.com/> - Accessed: 11/5/2021

⁹<https://www.therachat.io/> - Accessed: 11/5/2021

¹⁰<https://www.wysa.io/> - Accessed: 11/5/2021

suitable for providing psychological support is that they can allow users to discuss about personal issues more comfortably, bypassing interpersonal anxiety and related emotions such as shame, guilt and embarrassment, which could arise in a face-to-face interaction. A study that used a fully automatic 3D avatar of a virtual psychologist (Figure 2.3) found that people were more likely to discuss sensitive information with the avatar than with a human interviewer [46]. Similar findings were reported in a study using a virtual interviewer resembling a therapist to discuss with people with PTSD [197].

In conclusion, CUIs have enabled Digital Assistants to provide mental health support by facilitating the process of therapy, and by encouraging users to discuss personal issues due to the lack of interpersonal communication. These benefits of DAs could also be utilised in a similar way to support the rehabilitation of people with ABI. However, some of the common barriers that can hinder the usability and effectiveness of ATs (discussed in section 2.3.2) would also appear in the use of DAs, if the interaction is done through mainstream technologies such as smartphones and personal computers. The recent advancements in speech recognition and speech synthesis have allowed the development of Voice Assistants (VAs), a technology that offers both the functionalities of DAs and the benefits of a SDS (e.g. increased accessibility, allowing multitasking and faster execution of simple tasks), with the potential to provide more efficient support to people with ABI bypassing some of the common barriers of ATs.

2.4.3 Voice Assistants

Voice Assistants (VAs) are speech-activated Digital Assistants that feature an agent-based SDS and can be used to perform a variety of tasks, ranging from simple actions like setting alarms or describing the weather, to more complex tasks like buying groceries or booking flight tickets. VAs can also be found in literature as Intelligent Personal Assistants, Voice-Activated Personal Assistants or Virtual Personal Assistants.

VAs are defined by providing an alternative way to carry out functions associated with smart mobile devices, such as performing online queries, sending messages, controlling mobile applications etc. There are, however, several functions that are unique to VAs, and which can only be enabled through their voice-operated VUI, like simulating brief human-like conversations or playing speech based games. Moreover, VAs have their own platforms for developing original speech-based applications or for creating VUI interfaces to interact with existing applications or systems. The most prominent examples of modern VAs are Amazon's Alexa¹¹, Apple's Siri¹²,

¹¹<https://developer.amazon.com/en-GB/alexa>

¹²<https://www.apple.com/siri/>

Google's Assistant¹³ and Microsoft's Cortana¹⁴. These assistants are commonly used through devices called smart speakers¹⁵¹⁶, a specific type of speaker with embedded microphones and internet connectivity, typically used in a home setting to carry out a variety of tasks. Additionally, they can be found in smartphones that run the manufacturer's corresponding operating system, as well as in other electronic devices such as tablets, electronic notebooks and personal computers. Specially designed versions of Voice Assistants like Android Auto¹⁷ and CarPlay¹⁸ are integrated in modern cars through applications that mirror the functionality of smart speakers and allow control of certain car functions.

The range of functions that are supported by VAs is very wide, and it is constantly expanding. Besides being aware of their capabilities, in order to examine how VAs can benefit people with ABI it is also important to comprehend the tasks that people commonly use them for, as well as the factors that determine whether users would choose to carry out a certain task through a VA. A recent study including interviews with regular users of VAs and an analysis of log files of smart speaker devices, found that the most common task that VAs were being used for was to play music [6]. The second most common was to search for information online, followed by controlling Internet of Things (IoT) devices in the house, such as smart lights. These three types of tasks constituted the majority of the use cases of VAs. Other, much less common tasks included setting alarms and timers, asking about the weather, asking for jokes or exploring the device's capabilities often in playful ways. Similarly, a survey investigating the use of VAs identified simple tasks such as queries, weather updates or playing music to be the most common use cases [55]. The study highlights that many of the more complex functions that VAs are capable of performing are either hardly used, or completely unexplored. Since one of the aims of this research is to determine how VAs can be used to support people with ABI, it is important to examine why users find them preferable for certain tasks but not for others. Moreover, the way VAs are being used can differ depending on several characteristics of the users, such as their background, previous experience with VUIs or their age [117, 151]. It is therefore crucial to carefully study and consider the characteristics of people with ABI before looking into how VAs should be designed for their benefit.

User Experience and Design of Voice Assistants

User satisfaction is an important factor in determining whether people choose to use VAs, as there is a direct link between satisfaction and frequency of use [55, 184]. However, it is unclear

¹³<https://assistant.google.com/>

¹⁴<https://www.microsoft.com/en-us/cortana>

¹⁵https://store.google.com/gb/category/connected_home?

¹⁶<https://www.amazon.co.uk/b?ie=UTF8node=14100223031>

¹⁷https://www.android.com/intl/en_uk/auto/

¹⁸<https://www.apple.com/uk/ios/carplay/> - Accessed: 11/5/2021

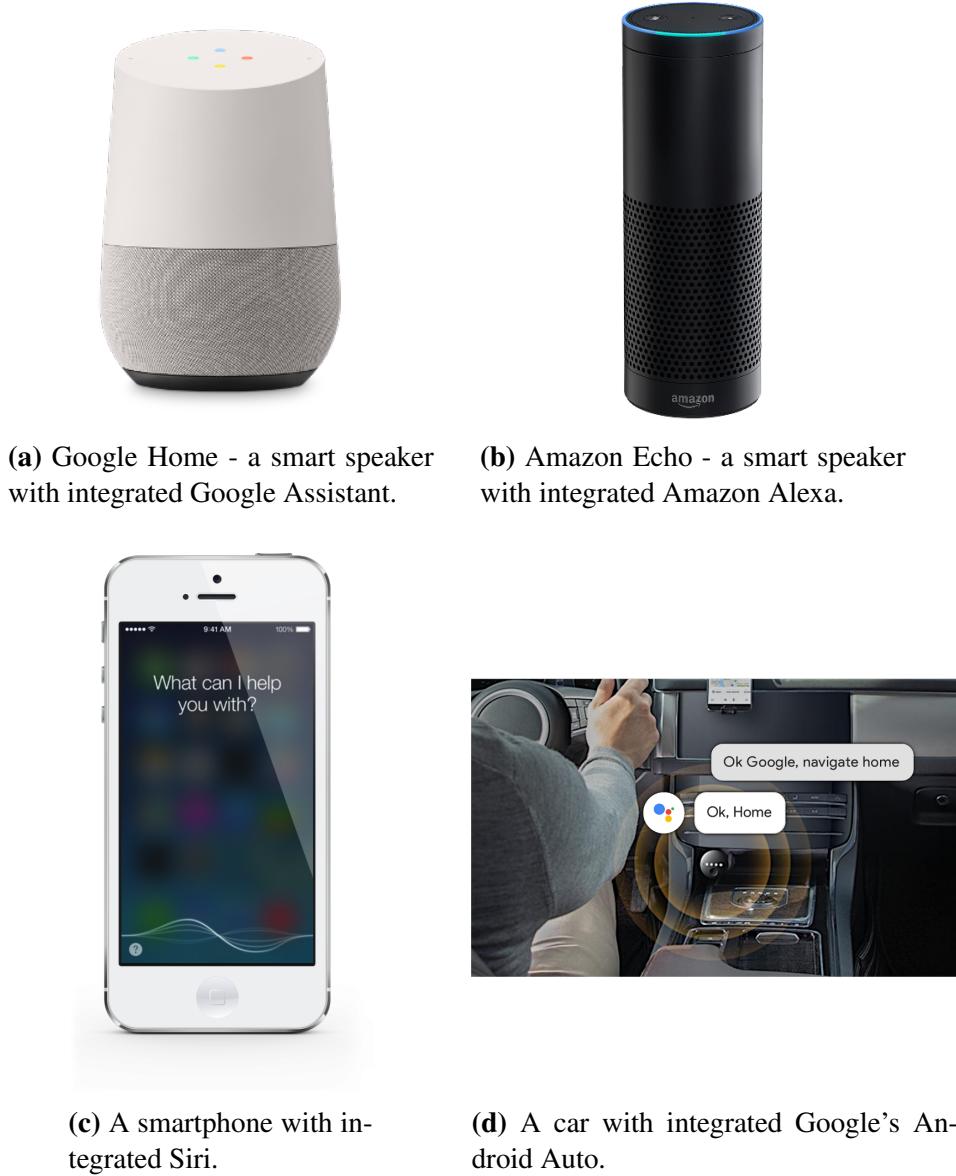


Figure 2.3: Examples of popular VAs embedded in smart speakers, smartphones and cars.

how satisfaction is determined when interacting with a VA. In a study by Lopatovska *et al.* [113] users of Alexa reported being satisfied with the VA even when it did not produce sought information. The authors concluded that the interaction experience can be more important than the interaction output. However, the notion of user satisfaction can vary depending on the context, and while in some scenarios it is determined by task completion, in other scenarios it can be determined by the amount of effort spent [101], or the time required to complete a task [56].

Another, distinguishing aspect of VAs which can affect how people use them and experience the interaction is their human-like nature. VAs are commonly designed to appear like virtual personas, with a specific identity and personality traits. According to Google's design guidelines for the Google Assistant, "defining a clear system persona is vital to ensuring a consistent

user experience¹⁹. Similarly, Amazon provide specific characteristics that determine the personality of Alexa which should be applied to maintain consistency and clarity of use²⁰. The perceived human-like nature of VAs can also affect the user's satisfaction. A study analysing customer reviews for the Amazon Echo (a smart speaker with integrated Alexa VA) found that the personification of Alexa was associated with increased levels of satisfaction, regardless of the frequency of technical issues or how the device was used [171]. Additionally, this "virtual persona" design approach can be useful for establishing trust with the VA and largely affects the users' initial impression of the Assistants, perceiving them as friendly and likeable. Such a positive initial impression can ultimately impact the frequency of use [29], and can determine how users perceive their intelligence and capabilities [54]. However, when interviewing regular users of a VA, Luger and Sellen found that the personified VUI often established a false perception and created a gap between the users' expectations and the device's capabilities [119]. Moreover, a study examining the use of VAs in people with intellectual disabilities found that the users' mental model of the VA being a person was a source of implications, as it resulted in users having to speak in long polite sentences which sometimes caused issues with language recognition [11].

Although it has several advantages and is praised by the manufacturing companies of VAs, the importance of their behavioural realism has been questioned by researchers [168]. Clark and colleagues [35] found that, when interacting with conversational agents, people do not care about developing a relationship with them, and often see them as tools rather than dynamic social entities. The authors also report that, even though it includes elements of social talk, the interaction with VAs rarely transcends the constraint of a single question or response, and therefore conclude that VUIs should aim for task completion and not a simulation of human conversation. Similar findings were reported in a study examining the design of social robots for people with ABI, concluding that even though the agent can be perceived as a person, its role in this context is mostly functional [163].

In conclusion, VAs can be used to perform a variety of tasks, offering several advantages due to their conversational, speech-based interface that can benefit people with ABI. However, the common use cases of VAs cover only a fraction of their capabilities. Moreover, the frequency of use is associated with the user's satisfaction, which can depend on several attributes such as the user's background or the context of use. Finally, although the personality aspect of the VAs' interface can have some benefits, it can lead to usability issues. This indicates that the primary focus of the design of VAs should be to facilitate task completion and minimise required effort, two features that can be particularly important for users with cognitive impairments. Before

¹⁹<https://designguidelines.withgoogle.com/conversation/conversation-design/what-is-conversation-design.html>what-is-conversation-design-system-user-personas - Accessed: 11/5/2021

²⁰<https://developer.amazon.com/en-US/alexa/branding/alexa-guidelines/communication-guidelines/brand-voice> - Accessed: 11/5/2021

determining the use cases of VAs for people with ABI, and how they should be designed to better support their everyday functioning, it is essential to further examine the factors that affect their user experience.

One of the most commonly reported issues affecting the UX of VAs is poor speech recognition. This can occur either due to errors in the conversion of the user's voice input to text, or due to the system's inability to correctly parse the user's utterance and associate it with the intended action. Such issues can result in users having to spend more effort thinking how to phrase their input, or prevent the use of VAs in noisy environments [37]. Speech recognition errors can occur more often in users with uncommon accents, or when pronouncing location names and words from another language [173]. Regardless of how they occur, however, they can result in users losing their confidence in VAs, and becoming frustrated [1]. However, a study by Myers *et al.* [150] investigating the design of a VA showed that, although speech recognition issues are very common, they are not the biggest threat to the UX of a VUI, and that there are several strategies (e.g. hyperarticulation) that users employ to overcome them. Although the ability of VAs to understand natural language is consistently improving, it is important to consider poor speech-recognition as an existing obstacle. Careful design can support users in changing their strategy of interacting with the VA when not being understood, something that can be particularly useful for those who do not have the cognitive capacity to do so on their own [117]. More specific ways to approach error handling are discussed later in this section.

Another common issue reported in studies examining the use of VAs is concerns regarding their privacy and security [1, 6, 37]. These concerns are usually related to users feeling a lack of transparency in how their personal data (e.g. personal contacts or job related information) is being handled, or fearing a data breach that might expose their information to a third party. Privacy concerns are also associated with the danger of strangers overhearing personal information, when VAs are used in public [1]. Social embarrassment is another issue related to using VAs in public spaces such as busses, offices or in business meetings, where interacting with a VA would be against the social norms [37], or where onlookers may perceive the user to be talking to themselves [1]. The above concerns can prevent people from using VAs in certain contexts, and lead them to prefer using VAs in private locations [57]. This can be reinforced by issues related to portability and requirement of internet connectivity [173]. Although there are mitigation strategies that can be applied to alleviate these concerns, it is important to consider that a big part of the interaction with VAs will be carried out in the home setting.

The two issues described above (speech recognition and privacy concerns) need to be taken into consideration as obstacles when looking into the use of VAs for people with ABI, but they mostly depend on the technological capabilities of VAs and the approach of their manufacturing companies. Studies, however, have also identified several other issues that can affect the UX of VAs which are more associated to the design of their speech interface. Cowan *et al.* [37]

found that users of Siri became frustrated when the interaction with the VA was not completely hands free, e.g. when they had to input additional information using the touch screen of their phone. They also reported users being frustrated due to the VA's poor integration with third party applications. Additionally, a study that compared using a phone manually to using it through Siri found that the latter could be more time consuming, and some complex tasks required more steps to complete with the VA [104]. Complex tasks like making a calendar appointment or composing an email can also be associated with user frustration due to the VA's timeout, i.e. the specific time period allocated to complete a voice command [1]. Finally, users can occasionally find the feedback from VAs to be too verbose, unnecessary, irrelevant or insufficient [1].

All the above issues can negatively impact the user's experience when interacting with a VA, but could disproportionately affect people with ABI who have cognitive impairments, or those with impaired vision or other physical disabilities that wouldn't allow them the option to seek alternative interaction methods. In order to efficiently use VAs to support people with ABI, it is necessary to address these issues through interaction design. Schmidt and Brauner [184] identified three features of a voice user interface that can improve the user experience of VAs:

- Personalisation: The importance of taking the user's context and background into consideration has been discussed earlier in this section. As the effects of ABI can be very different from one user to the other, personalisation would require to consider the individual's level of cognitive functioning and deficits, and provide options to adjust the system accordingly.
- Adaptivity: An essential aspect of an adaptive system is error handling, i.e. to provide appropriate feedback or alternative solutions when the interaction fails. An initial approach would be to inform the user of the cause of the error, as users of VAs are often unable to understand what is wrong with their queries when they don't work [33]. Adaptivity could also be accomplished through automatic adjustment of the VUI, depending on the context of use and situationally induced impairments [120]. An example of an adaptive SDS is the MIMIC system [34], which dynamically extracted information from user utterances to adapt response generation strategies, leading to better user satisfaction and dialogue quality and efficiency. Similarly, the CHAT system used an intelligent recommender method to optimise the content of responses when it could not produce any results for the user's query, improving user experience and task completion rate [214].
- Proactivity: A proactive VUI would be required to have the initiative in the conversation, i.e. leading the dialogue by asking questions in order to get responses from the user. This can lead to reduced frustration and task completion [99], and it can be particularly important for people with executive dysfunction and memory impairments.

Finally, although VUIs could require less training to be used efficiently, understanding a VA's functionality and capabilities can be challenging [232], and its human-like appearance can be misleading [119]. Supporting users in learning how to benefit from the system through appropriate tutorials and "what can I say?" functions can significantly improve their efficiency and overall interaction experience [36].

Voice Assistants for People with Acquired Brain Injury

Although there are several potential benefits that VAs could provide to people with ABI, such as easy access to a variety of services and quick task completion, there is very little work related to the use of Voice Assistants for this particular user group. To examine how the factors affecting the UX of VAs discussed above would affect people with ABI, it is necessary to conduct further research work in this area. However, the use of VAs for people with ABI can also be informed by applications of the technology in other user groups that share some characteristics, such as people with disabilities, people with dementia or elderly users.

Abdolrahmani *et al.* interviewed people who are blind and use VAs regularly [1], and found that they can benefit by gaining access to technologies and services that would be otherwise inaccessible to them, or by saving time through completing tasks significantly faster than with a computer or a smartphone. Most of these tasks were common to those found in studies examining the use of VAs in healthy users, including time-management functions like setting alarms and reminders, seeking information like the weather, accessing other applications, controlling smart devices and playing media. Pradhan and colleagues [169], through an analysis of reviews for the Amazon Echo by people with disabilities and interviews with visually-impaired users of home-based VAs, recognised an "immense potential of VAs to provide inclusive, accessible interaction for people with a range of disabilities". However, besides some of the usability issues of VAs that are common among non-disabled users, the study also identified several difficulties in use that were specific to users with disabilities. These included: limited control over speech output settings for users with hearing loss, visual accessibility problems with the physical design of the smart speaker device, challenges in the discoverability of voice commands, and difficulties in using the VA to control smart devices related to the accessibility of purchase and setup. The study also included reviews by people with memory loss, who reported difficulties in remembering voice commands. The authors argue that this problem could be addressed through adaptive interaction e.g. by learning the user's usage patterns to efficiently prompt actions.

As mentioned in Section 2.2.3, ABI can cause speech impairments, which could make the -already common- speech recognition issues of VAs even more prevalent for some brain injury survivors. Although there is significant progress in the development of technologies that can improve speech recognition for people with severe speech impairments (see Section 2.3.2), a

direct interaction with most current mainstream VAs might not be feasible for these users. However, study findings indicate that through user-centred design and training, the use of VAs can be appropriate for people with moderate or mild speech impairments [45, 83], and in some cases they can even be utilised to help people manage their impairment, e.g. by supplementing speech therapy [169].

The three features of VUIs identified by Schmidt and Braunger presented earlier (personalisation, adaptivity and proactivity) are also identified in studies examining the use of VUIs for people with cognitive impairments. Specifically, when designing a speech-activated routine management system for people with dementia, Caroll *et al.* concluded that customisation and adaptability of the system are essential to align with changes over time in the user's cognitive function and to support completion of tasks with varying difficulty [31]. Moreover, they argued that proactive assistance can make prompting more efficient by asking users at specific intervals if they have completed a task, and keeping track of their routine. Similarly, the Guide system described in section 2.3.1, which was used to effectively support amputees with a brain injury to put on their prosthetic limb, featured a VUI that prompted users and asked questions in a context-sensitive manner [158]. Although the responses accepted by the system were limited to a few specific words, the authors argued that the system's interaction with the users simulated analogous conversations with their carers, and included a problem-solving mechanism to adjust the dialogue in case of negative responses.

The motivation for examining the use of VAs for people with ABI can also be supported by the successful application of the technology in elderly people, who share some common characteristics with people with ABI (e.g. reduced cognitive functioning and lower information processing speed) [148]. For instance, a study that investigated the use of Siri with older users reported several benefits and an overall positive attitude and high acceptance of speech-only interaction in everyday life [231]. Furthermore, a study comparing the use of a keyboard to a smartphone-embedded VA for everyday tasks, found that senior users with less technical knowledge or who were experiencing hand dexterity issues preferred the speech-based method [234]. Another common characteristic between elderly people and people with ABI is, to a certain extent, reduced memory performance. The practice of reminiscence has several benefits in older people's mental health and emotional well-being, and can also be used to support people with ABI who have long-term memory impairments. This practice can be facilitated through the use of conversational agents, by removing the need for co-located human presence [154]. Besides long-term memory, as previously discussed, short-term memory can be significantly impaired after a brain injury. This makes memory demand a particularly important aspect of the design of VAs for people with ABI, especially in speech-only interfaces where supporting recall through visual feedback is not an option. Wolters *et al.* [230] examined memory demand across different models of speech-interface design and found that users with lower working memory can benefit

when the system presents them more options to choose from, on every step of the interaction. The authors also highlight the need for accurate assessment of the actual cognitive demand of each task that the VA provides.

The literature reviewed in this section informs the research questions of this thesis regarding the use and design of VAs for people with cognitive impairments due to ABI. However, as pointed out by recent systematic reviews, the related work examining the use of Voice Assistants in similar contexts is limited [103, 189]. Therefore, further research work needs to be carried out to acquire evidence regarding their usability.

2.4.4 Summary

Voice User Interfaces present an alternative, hands-free and eyes-free way to interact with technology, offering several benefits to people with ABI, such as increased accessibility to different services and faster completion for certain tasks. The recent advancements in natural-language processing have led to the evolution of agent-based Spoken Dialogue Systems and Conversational User Interfaces (CUIs), which provide interaction that simulates human-like conversation. CUIs can be utilised to interact with digital assistants, autonomous agents often presented as virtual personas which can provide a variety of services and efficiently support people in contexts like remote therapy and rehabilitation.

Voice Assistants (VAs) are an emerging technology that combines the benefits of VUIs and digital assistants. They can be operated through a wide range of devices such as smartphones, personal computers, and smart speakers to perform a wide range of functions. However, only a small portion of these functions are used by the majority of users, who prefer not to use VAs for more complex tasks, indicating the existence of usability-related issues. By presenting the functionality and capabilities of VAs, and determining the way they are generally being used, this section informed research question:

- **RQ1:** What are the use cases of Voice Assistants for users with cognitive impairments due to an Acquired Brain Injury?

Regarding the factors that affect the usability of VAs, certain conclusions can be drawn from the literature reviewed in this section: 1) User satisfaction is associated both with task completion and the interaction experience, but generally depends on the nature of the task and the context of use; 2) The human-like nature of VAs can improve the consistency of the interaction experience and the users' trust towards the system, but can be misleading about the system's capabilities or redundant since the role of VAs is mostly functional; 3) There are several issues related to the interaction with VAs that are common among healthy users and users with cognitive or physical

disabilities, the most common of which include: problems with speech recognition, privacy concerns, inconsistency in hands-free interaction, problematic integration with 3rd party apps and systems, inefficient or irrelevant output, and input timeouts. Although the above factors are not specific to people with ABI, they provide a framework for examining the usability of VAs in this particular context, and therefore inform research question:

- **RQ2:** What are the factors that affect the usability of Voice Assistants when used by people with ABI?

This section also presented methods that can be used to overcome some of the usability issues and to improve the UX of VAs: personalisation, adaptivity, and proactivity. Similarly with RQ2, these methods are drawn from literature that is not focused on users with ABI, but they can provide a starting point in the research that is required to answer research question:

- **RQ3:** How can the usability of Voice Assistants be improved for people with ABI?

2.5 Conclusions

This chapter presented the different types of ABI and their effects, as well as how these effects can impact the everyday functioning and the use of technology in people with cognitive impairments due to ABI. It also presented how the result of ABI effects can be alleviated through Neuropsychological Rehabilitation, and how external aids can facilitate that process. These aids can be either paper-based or technological tools, with research showing the latter to be more effective. There are certain barriers, however, that can impact their use, some of which can be addressed by utilising newer technological approaches with features such as context awareness and personalisation, to provide more efficient support. One such technology is the Voice Assistant, which combines the accessibility and speed of Voice User Interfaces and the benefits of Digital Assistants to provide a wide range of services through a variety of devices.

Research question **RQ1** was addressed with regard to where and how VAs can be useful for people with ABI, by presenting the effects of a brain injury and how they are likely to affect use of technology. **RQ1** was also informed by determining the capabilities of VAs and how they are commonly being used. Although more investigation is needed to specify the use cases of VAs for people with ABI in detail, some broad purposes of use can be presumed. Specifically, Voice Assistants could be used to: 1) Increase accessibility to different services for people with ABI who also have visual and physical impairments; 2) Support memory and organisation through prompting and the use of functions like calendars and reminders; and 3) Facilitate the processes

of rehabilitation and care taking, acting as medium between the user and their therapist/carer, or as a monitoring tool.

The effects of ABI and the barriers that prevent efficient use of assistive technologies also informed **RQ2**, in combination with the reported findings regarding the factors that affect the UX of VAs. In particular, cognitive deficits that affect memory, attention, speech and concentration can exacerbate the common issues with the VAs' natural language understanding and input time limitation (timeout). Difficulties in integration with 3rd party applications and systems can increase mental demand, and be more prominent in users with impaired cognitive functioning. One of the factors that can prevent the use of AT discussed in Section 2.3.2 was fear of social embarrassment; this can be reinforced by the acceptance and privacy issues associated with using a VA in public. Another barrier mentioned in Section 2.3.2 was the lack of technology integration and training in rehabilitation. This is likely to be true for VAs as well, due to the recentness of the technology and as indicated by the limited research examining their use in this context [103].

Finally, this chapter informed **RQ3** by presenting the different solutions and approaches of assistive technologies, and by reviewing studies examining the use and design of VAs to identify certain methods to improve their usability. These methods include: 1) personalisation, which can be utilised to address the diverse range of effects of ABI and the variance in people's cognitive capacity; 2) adaptivity, which can be achieved by employing the conversational capabilities and context awareness of VAs to provide more efficient support; 3) proactivity, which can improve prompt effectiveness and better support people with memory difficulties and lack of initiation.

The use cases of VAs, factors that affect their user experience and methods to improve their usability discussed here, comprise an initial framework which will be used to further investigate the use and design of this technology for people with cognitive impairments due to ABI. Additional examination of why people choose whether to use a VA or not for specific tasks is essential to comprehend their UX and to consider their application. Moreover, further investigation is required to determine if the way that people use VAs described in literature also applies to people with ABI, or if there are other use cases and usability issues specific to this particular user group. Chapters 3, 4 and 5 attempt to answer these issues through a set of exploratory studies.

Chapter 3

Effects of ABI and the Use of External Aids

3.1 Introduction

Chapter 2 presented the common effects of Acquired Brain Injury (ABI) and the use of external aids to support cognition. It was demonstrated that ABI can impact everyday functioning in many different ways, and limit a person's independence and participation in social activities. It was also shown that external aids, and especially technology-based tools, can compensate for several of the common cognitive deficits following a brain injury. However, the reviewed literature in Section 2.3 identified a number of barriers that can impact the uptake and usability of such aids, indicating that there is room to improve the design of existing tools and to investigate the application of new technologies.

One such technology is that of Voice Assistants (VAs) which, as discussed in section 2.4, can increase accessibility to different services and generally require less training to be used efficiently. Every novel technology introduces new challenges regarding its design and application, and VAs are no exception. Studies have identified different issues that can affect the usability of speech interfaces, and that people avoid using VAs for complex tasks (see Sections 2.4.3 and 2.4.4). To design better interaction between technology and its users, a user-centred approach is essential in HCI research, requiring the identification of user needs, characteristics and limitations [170]. This is particularly important when designing technologies for users with disabilities, and especially when it comes to a user group with such a wide range of impairments, as people with ABI.

The first objective of this thesis (**RQ1**) is to identify the situations where the use of Voice Assistants can be beneficial for people with ABI. This Chapter builds upon the information presented in Chapter 2, to further inform the answer to this research question, by:

1. Identifying the situations where there is a need for technological aids and what would their intended purpose be.

The second objective of the thesis (**RQ2**) is to determine the factors related to the usability of VAs. In addition to the findings from the literature presented in section 2.4.3, this chapter also aims to inform the answer to this research question, by:

2. Further examining the common cognitive effects of ABI and how these affect the usability of existing external aids.

This chapter aims to achieve these two objectives through two requirements-capturing studies:

- **Study 1:** a short online survey for people with ABI to gather general information about the experience of brain injury and the use of technological aids.
- **Study 2:** a group interview with neuropsychologists to further examine the findings of Study 1 by eliciting details about the effects of ABI, gather information about current neuropsychological rehabilitation methods, and to acquire expert feedback on the design of AT.

The outcome of the above studies and of this chapter is a set of guidelines on how to use and design ATs for people with cognitive impairments due to ABI, establishing the groundwork for examining the use and design of VAs, and thus answering research questions **RQ1** and **RQ2** in the next chapters.

3.1.1 Chapter Structure

Section 3.2 presents and discusses the results of the online survey for people with ABI (Study 1). Section 3.3 presents Study 2, and a qualitative analysis of the data gathered through the group interview. Section 3.4 discusses the findings from the two studies, and presents a list of use cases and a set of design guidelines for ATs. Finally, Section 3.5 summarises the two studies and describes how their results inform the research questions of the thesis.

3.2 Study 1: Online Survey for People with Acquired Brain Injury

3.2.1 Introduction

The study by Evans *et al.* (2003) and the subsequent survey by Jamieson *et al.* (2017) investigated the use of external aids to support memory performance. Although memory impairment is the most common cognitive difficulty among people with ABI, the literature review showed that ATs can be used to compensate for several other cognitive functions as well, and can support people with cognitive difficulties in a variety of ways. Therefore, it is important to further investigate the use of external aids by people with ABI in a more comprehensive way. Moreover, the studies reviewed in Chapter 2 did not examine the prevalence of Voice Assistants, a technology that only recently started to become commonly adopted.

This section presents a short online survey with people with ABI as participants (N=99) which aimed to outline the context of using different types of external cognitive aids after a brain injury, by examining the backgrounds of their users. Specifically, the objectives of the survey were to:

1. Investigate the prevalence of the common effects of ABI among users of external cognitive aids,
2. Examine the use of different types of external aids and how that correlates to the users' background, and
3. Acquire general information about the use of Voice Assistants among people with ABI.

Since the different types of external aids for people with cognitive impairments have been identified in previous research [61, 73, 90, 116], this study regarded aids more abstractly, categorising them to paper-based tools, electronic devices with a visual interface, and Voice Assistants. Although the previous chapter showed that ATs can be more effective than paper-based tools, examining the use of the latter and the associated challenges remains relevant in order to determine where technology can be a suitable alternative. Moreover, as the main objective of this research is to investigate the use of Voice Assistants in the context of brain injury rehabilitation, acquiring more details about the shortcomings of existing external aids will help identify the potential use cases and inform the design of VA applications in that particular context.

3.2.2 Method

Recruitment

The survey was administered through an online, cloud-based, survey development software¹, under the name "Technology for People with Acquired Brain Injury". Participants were recruited between October 2017 and March 2018, through organisations that provide services for people with ABI. Multiple organisations were contacted via email in different English-speaking countries and were asked to advertise the survey to their services users. The organisations that responded and confirmed to have forwarded the survey were: Headway, the Encephalitis Society, the Acquired Brain Injury Forum and the Quarriers charity in the United Kingdom; Acquired Brain Injury Ireland and Headway Ireland, in the Republic of Ireland; Brain Injury Network, Brainline and NeuroPsychologic Rehabilitation Services in the United States of America; Brain Injury Australia (BIA) and Headstart ABI in Australia, and Ontario Brain Injury Association in Canada. The organisations were specifically requested to distribute the survey to adults, who had experienced a brain injury and who were able to provide informed consent for themselves.

Participation in the study was undertaken anonymously, and the participants' consent was provided by completing a form before being able to access the survey. This study was approved by the University of Glasgow College of Science and Engineering ethics committee in October 2017.

115 people completed the survey in total. 16 of them provided answers to less than 90% of the survey questions, and their responses were not included in the analysis. Of the remaining 99 participants, the average completion rate of the survey was above 98%.

Survey Questionnaire

The questionnaire consisted of six sections covering different topics. The first section gathered demographic information about the participants, and contained questions about age, gender, level of education, time and severity (self-assessed) of the injury, and employment status before, and after the injury.

The next three sections addressed cognitive functioning. Specifically, the second section of the survey was focused on memory, containing questions based on the Prospective and Retrospective Memory Questionnaire (PRMQ) [38]. The questions were chosen to cover short-term, long-term, retrospective and prospective memory performance. The third section focused on executive function, with participants being asked to indicate the frequency of issues related to

¹<https://www.surveymonkey.co.uk/> - Accessed: 11/5/2021

information processing, planning, decision making, organisation and attention. The questions were drawn from the Behavioural Assessment of the Dysexecutive Syndrome (BADS) [224], Dysexecutive Questionnaire [164]. The fourth section consisted of questions related to motivation (frequency of feeling motivated to start or participate in an activity), and activeness. Five-point Likert scales were used in these three sections, to indicate the frequency of everyday issues related to poor cognitive performance, with "1" signifying "Never", "3" corresponding to "Sometimes" (neutral response), and "5" signifying "Very Often". The values of the Likert scales were different in the last two questions of the fourth section where participants had to describe their level of activity before and after the injury, with "1" corresponding to "Not active at all", "3" to "Somewhat active" and "5" to "Extremely active". These sections were not designed to objectively measure the participants' cognitive functioning, but rather intended to provide an indication of the occurring frequency of common everyday issues related to cognitive impairments, and ultimately investigate potential associations between these issues and the use of external aids (see Section 3.2.4 for the limitations of this study).

The next section consisted of questions related to rehabilitation. Specifically, participants were asked to indicate if they attended therapy, rehabilitation services or group activities for people with ABI, and if they had a carer to help them with daily activities. Additional details regarding the type of support that their carers provided was asked from people who responded positively in the last question.

The last section was focused on the use of external aids. Participants were given a description and examples for three different types of external aids, which were paper-based tools (such as notebooks, calendars and diaries), high-tech devices with a screen (such as smartphones, tablets and personal computers), and Voice Assistants. For each of the three types, participants were asked to indicate how often they used them as cognitive aids, through a 5-point Likert scale where "1" signified "Never", "3" signified "Sometimes" and "5" signified "Very Often". Next, they were asked to indicate the effectiveness of each type of tools as cognitive aids through a 5-point Likert scale with "1" signifying "Not helpful at all", "3" signifying "Somewhat helpful" and "5" signifying "Extremely Helpful". Then, they indicated the perceived mental effort required to use these aids as cognitive aids, with "1" corresponding to "No effort at all", "3" being "Some effort" and "5" corresponding to "Too much effort". Finally, participants were asked to indicate if they used or have used a Voice Assistant, and provide additional details if they responded positively, in a way similar to the other two types of aids. The questions contained in this questionnaire can be found in Appendix A.

Statistical Analysis

The majority of the data collected in the survey were non-parametric, ordinal data. Therefore, the results are presented using, for the most part, descriptive statistics. Non-parametric statistical tests were used to investigate the correlation between answers to different questions of the survey, and to examine the difference between subgroups within the sample. Specifically, Spearman's Rank Correlation was used to determine the association between answers to different parts of the survey (e.g. severity of the injury and effectiveness of external aids). To further examine the impact of different effects of the injury on the use of external aids, participants were divided in groups based on how they responded to specific questions (e.g. based on the severity of their injury to mild/moderate and severe/very severe). The Mann-Whitney U test was used to determine the level of difference between such groups in frequency of use, effectiveness and mental demand of external aids. Finally, the Wilcoxon signed-rank test was used to examine the difference between answers to different questions within the survey sample.

3.2.3 Results

Demographics

The mean age of the participants ($N=99$) was 45.5 years old (range = 18-72, $SD = 13.52$), and 61 participants were female. 71 out of the 99 participants reported having completed higher education (college/university, postgraduate or PhD studies), 27 having completed secondary education and 1 participant reported having no formal education. Regarding the severity of their injury, 11 participants described their injury as "mild", 42 as "moderate", 31 as "severe" and 15 as "very severe". When asked about their employment status, 65% of participants reported not being employed at the time of the survey, with 75% of them (80% overall) reporting that they were employed before they got their brain injury. Finally, 49% of the participants reported that they had suffered their ABI more than six years before the time of the survey, 29% three to six years before, 17% one to two years before, and 5% within one year of the survey.

Cognitive Functioning

Memory issues were prevalent amongst the majority of participants. Figure 3.1 shows how participants responded when asked to indicate how frequently memory-related issues occur in their daily life. Prospective memory problems seemed to be the most common. Indicatively, 44% of the participants reported forgetting to do things they consider important often or very often, and 21% reported forgetting to fulfil a future plan very often. The mean percentage of partici-

participants who responded either "often" or "very often" in all three questions regarding prospective-memory related issues was 51%. The frequency of issues associated with retrospective memory was lower, with the corresponding mean percentage of participants who reported having such issues often/very often being 35%.

Poor memory performance appeared to have an impact on peoples' independent functioning. Specifically, 50% of respondents reported being reminded by others to do things they would otherwise forget either often or very often, and 18% having to rely very often on others to be reminded to take their medication. A noteworthy observation is that 39 out of 99 participants answered "often" or "very often" to at least five of all nine questions about the frequency of memory-related issues in their daily life.

Figure 3.2 shows the responses to questions about issues related to executive functioning. Problems associated with attention and concentration seemed to be the most prominent in this category: 66% of participants reported often or very often having difficulty keeping their mind on something, or getting easily distracted. Issues related to decision making, planning and organisation were also prevalent. The percentage of respondents who reported having often/very often difficulties with deciding what to do, organising daily activities, and making future plans was 52%, 43% and 55% respectively (28% responded "very often" to the latter). Regarding issues related to information processing, 34% of participants responded "often" or "very often" in having problems understanding what other people mean, and 35% in finding it difficult to follow instructions. Finally, 30% of participants reported often finding it difficult to finish a task they have started doing.

There is a noticeable contrast when looking at how participants described themselves regarding their level of activeness, before and after their injury. 39% of respondents described themselves as "extremely active" and 42% as "very active" before their injury (Figure 3.3). Out of the 79 participants choosing either of these responses, only 11 (14%) described themselves being as active after the ABI, and 65% of them reported being either "not very active" or "not active at all" at the time of the survey. Overall, only 3% of participants described themselves as being "extremely active" after the injury, and 11% as "very active", while 42% reported being "not very active" and 21% not being active at all. Participants responded in an analogous way regarding their motivation after the ABI, with 60% reporting that they rarely or never (30%) felt motivated to start a new activity or hobby, and 48% that they rarely or never felt motivated to spend time on an activity they enjoy, in the last 3 months prior to the time of the survey.

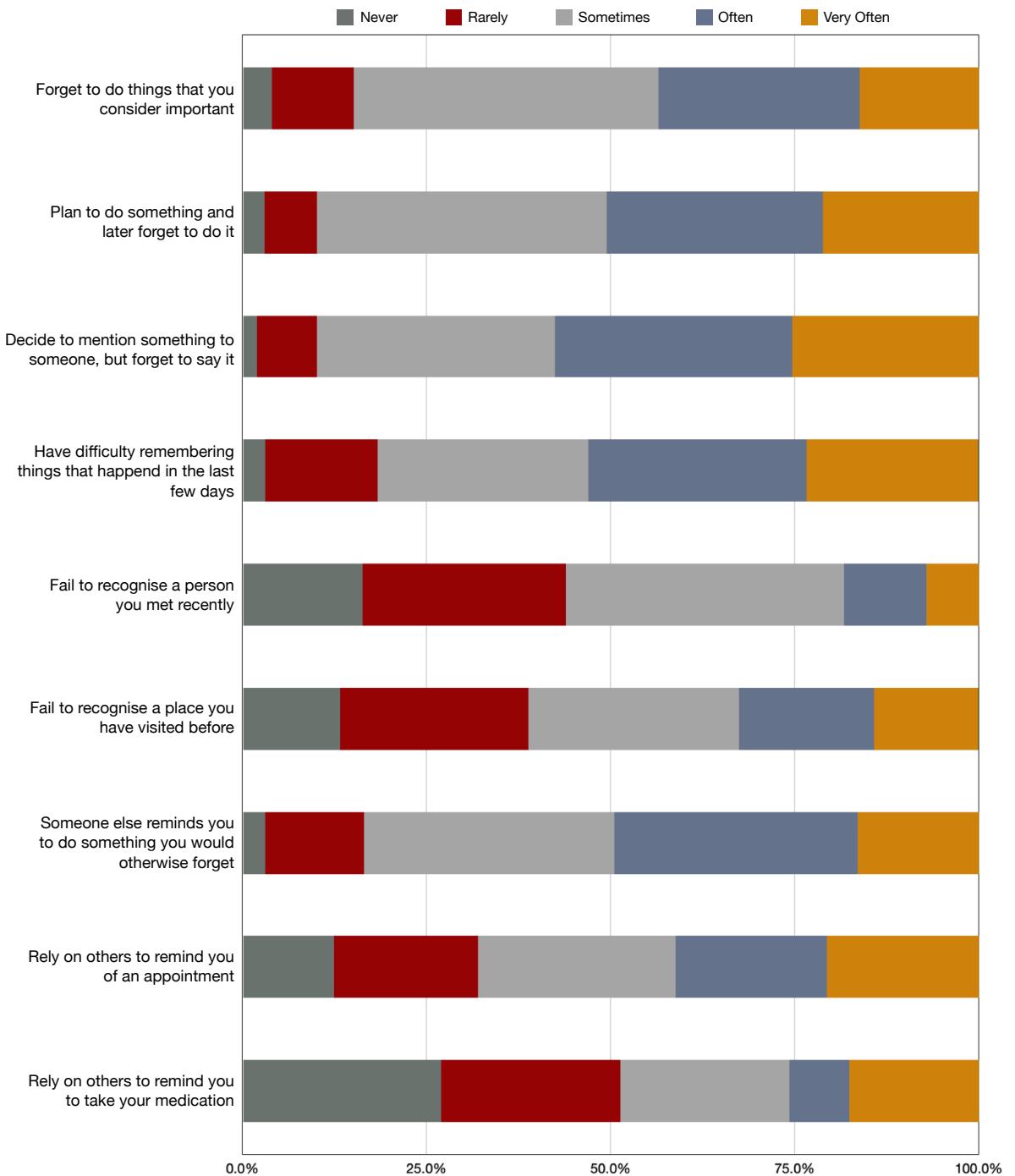


Figure 3.1: Frequency of memory-related issues in everyday life.

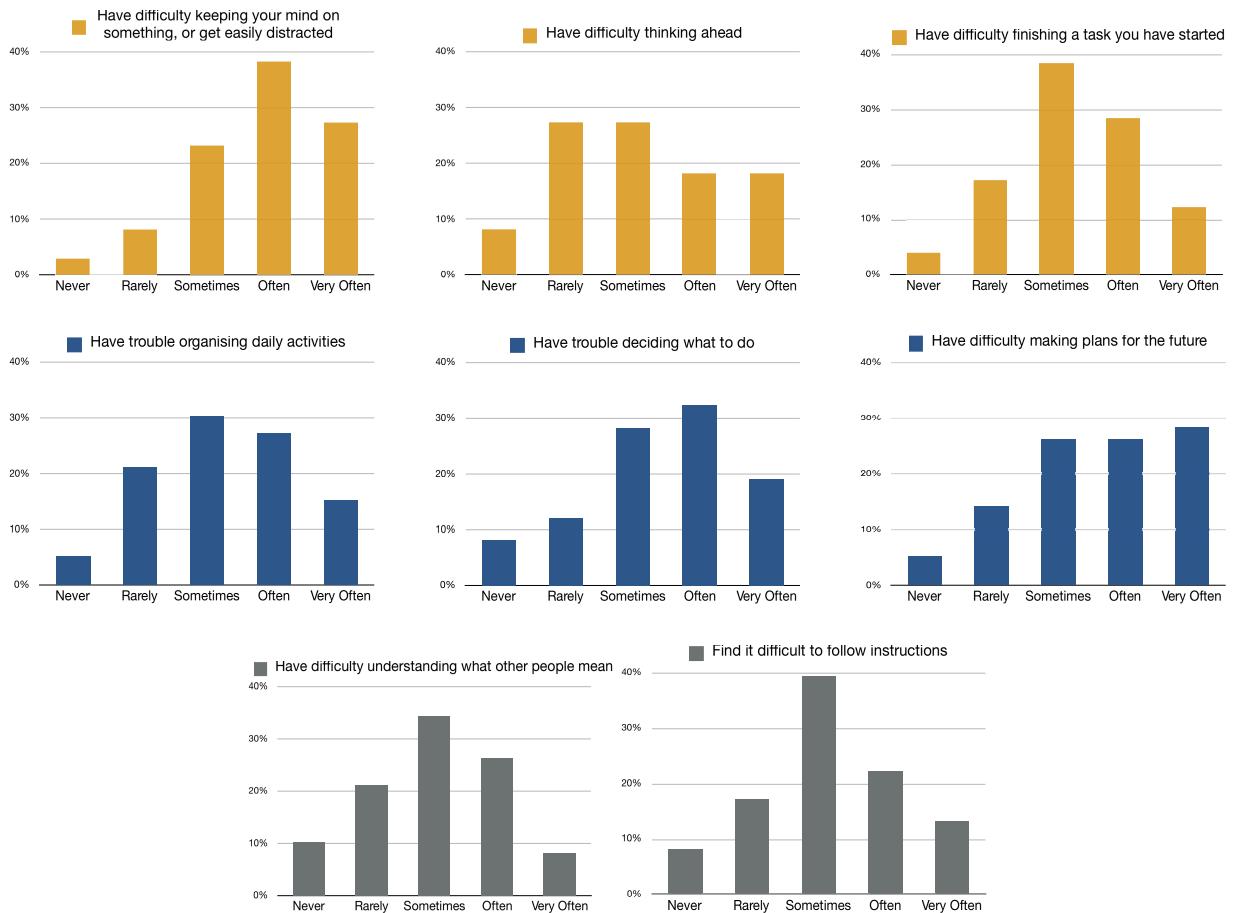


Figure 3.2: Frequency of everyday issues related to executive functioning.

Rehabilitation

In the section of the survey which gathered information regarding the rehabilitation background of participants, 42% stated that they were using the services of at least one organisation for people with ABI, 30% that they were attending group activities for brain injury survivors, and 25% that they were seeing a therapist at the time of the survey.

41% of respondents said that they have a carer to help them with daily activities, who either lives with them (28%) or visits them regularly (13%). Five participants said that they did not have a carer, but would need one. For 75% of the participants who reported having a carer (31 out of 41), that carer was a member of their family, while for the rest it was a professional. Regarding the nature of support that participants reported receiving from their carers, the majority of answers referred to providing reminders, helping them with organisation and motivation, helping them to carry out cognitively demanding tasks such as paying the bills, and assisting them with issues related to their physical impairments. Other types of support included help with everyday tasks they were unable to carry out alone due to both cognitive and physical effects of their injury, such as shopping for groceries, cooking and cleaning. In the case where the

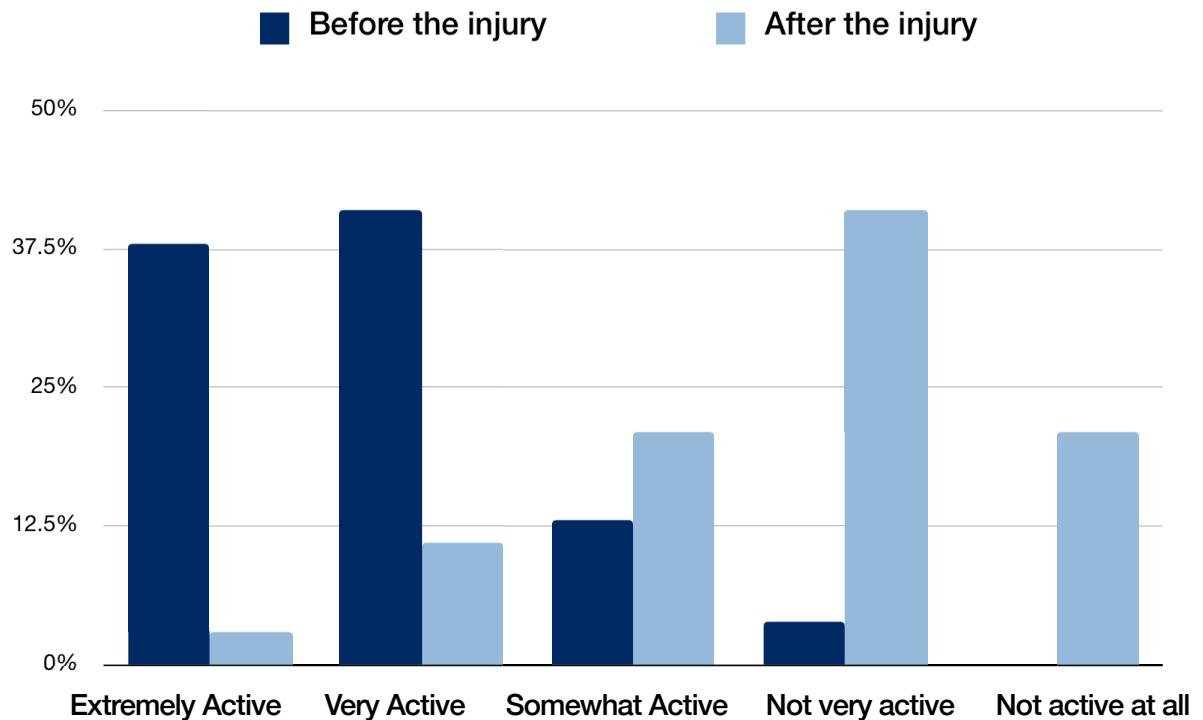


Figure 3.3: Self-described levels of activity before and after the brain injury.

caregivers were members of their family, some participants reported that they would regularly check on them to make sure they are in good health. Having a carer was found to be associated with the severity of the injury, when comparing participants who reported having an injury of mild or moderate severity, to those with a severe or very severe injury ($U=1624$, $p=.001$).

External Aids

The use of paper-based tools such as notebooks, calendars and diaries as cognitive aids was quite popular among participants. Specifically, 29% of participants said they used them often, 32% that they use them very often. In total, 82% reported that they use them sometimes, often or very often. There was no significant association found between the frequency of use of paper-based tools and the age, level of education and severity of the injury with the Spearman's Rank Correlation test.

To examine the association between memory-related problems and the use of paper-based tools, the sum of the answers to all questions about memory-related issues was calculated (a higher number corresponded to higher frequency of such issues). Similarly, the sum of the answers to all questions about executive function was calculated, with a higher number corresponding to a higher frequency of executive function-related issues in everyday life. The correlation between these two numbers and the frequency of use of paper-based aids was examined, but no significant relationship was found using the Spearmans' Rank Correlation test (Table 3.1).

When asked to indicate the effectiveness of paper-based tools as cognitive aids, the majority of respondents (65%) described them as at least somewhat helpful. 22% of participants said that they find them "Very helpful", and 26% that they found them "Extremely helpful". As with the frequency of use, there was no significant correlation between the effectiveness of paper-based aids and the participants' age, level of education, severity of injury, and the frequency of memory and executive function-related issues (determined by the sum of the scores in the corresponding questions). There was a significant positive association, however, between the frequency of use and perceived effectiveness ($\rho(96)=.737, p<.001$).

Regarding the mental demand of paper-based tools, 35% of participants said that they require either "a lot of effort" or "too much effort" to be used as cognitive aids. The subjective assessment of mental effort was not found to be significantly correlated to the participants' age or education level. There was however a significant positive correlation with the participants' severity of injury, and frequency of memory and executive function-related problems, indicating that participants with more cognitive difficulties found paper-based tools to be more mentally demanding (Table 3.1). Moreover, the Spearman's Rank Correlation test showed a significant negative association between the frequency of use and mental demand ($\rho(97)=-.263, p=.008$), indicating that participants who described paper-based tools as more helpful found them less mentally demanding.

Significant correlation? (Spearman's Rank Correlation)						
	Paper-based aids			High-tech aids		
	Frequency of Use	Effectiveness	Mental demand	Frequency of Use	Effectiveness	Mental demand
Age	NO $\rho(97)=.089, p=.386$	NO $\rho(97)=.027, p=.793$	NO $\rho(97)=-.059, p=.563$	NO $\rho(97)=.042, p=.680$	NO $\rho(97)=.013, p=.897$	NO $\rho(97)=.055, p=.589$
Education	NO $\rho(97)=.055, p=.592$	NO $\rho(97)=-.014, p=.891$	NO $\rho(97)=-.006, p=.956$	YES $\rho(97)=-.264, p=.008$	YES $\rho(97)=-.229, p=.023$	NO $\rho(97)=-.116, p=.253$
Severity	NO $\rho(97)=-.149, p=.143$	NO $\rho(97)=-.034, p=.739$	YES $\rho(97)=-.288, p=.004$	NO $\rho(97)=-.084, p=.410$	NO $\rho(97)=-.129, p=.204$	NO $\rho(97)=.084, p=.408$
Memory	NO $\rho(97)=.030, p=.771$	NO $\rho(97)=-.152, p=.133$	YES $\rho(97)=-.426, p<.001$	NO $\rho(97)=.024, p=.811$	NO $\rho(97)=-.016, p=.879$	YES $\rho(97)=-.340, p=.001$
Executive Function	NO $\rho(97)=.012, p=.903$	NO $\rho(97)=-.108, p=.286$	YES $\rho(97)=-.434, p<.001$	NO $\rho(97)=-.001, p=.994$	NO $\rho(97)=-.042, p=.678$	YES $\rho(97)=-.372, p<.001$

Table 3.1: Correlation between participants' background and use of external aids

To examine the impact of the severity of the injury on the frequency of use, the effectiveness and the mental demand of paper-based tools, two subgroups were selected from the sample of participants, as can be seen in Table 3.2. Specifically, the first group consisted of the participants who described their brain injury as mild or moderate, and the second group consisted

of those describing it as severe or very severe. Using the Mann-Whitney U statistical test, it was found that the subjective mental demand of paper-based aids was significantly higher in the second group (severe/very severe). No significant differences between the groups were found in the frequency of use and effectiveness (Table 3.3). Similarly, two subsets of participants were selected to examine the impact of memory impairment (Table 3.2): the first group consisted of participants who reported "never" or "rarely" to the majority of the questions about the frequency of memory-related difficulties in everyday life, and the second group consisted of those who answered "often" or "very often" to the majority of questions (i.e. to at least five out of the nine questions). There were no participants in either of the groups who had chosen an answer corresponding to the other group in any of the memory questions (i.e. none of the participants in group 1 had chosen "often" or "very often" in any of the questions, and *vice versa*). Participants in the group with more memory difficulties found the paper-based aids to be significantly more mentally demanding ($U=201$, $p=.017$). There was, however, no significant difference in how often they used the tools, and how helpful they found them. Finally, an analogous approach was taken to examine the impact of executive functioning, selecting a group of participants who responded "rarely" or "never" to the majority of questions about executive function, and a group with those who answered "often" or "very often". As with the previous two comparisons, the group with more frequent executive function-related issues found paper-based tools to require significantly more mental effort ($U=117$, $p<.001$), but there was no significant difference in the frequency of use and perceived effectiveness.

Sample Subgroup	Group 1		Group 2	
Severity of Injury	Participants who described the severity of their injury as mild or moderate.	N=53	Participants who described the severity of their injury as severe or very severe	N=46
Memory	Participants who answered "rarely" or "never" to at least 5 out of 9 questions regarding memory-related issues.	N=17	Participants who answered "often" or "very often" to at least 5 out of 9 questions regarding memory-related issues.	N=39
Executive Function	Participants who answered "rarely" or "never" to at least 5 out of 9 questions regarding executive function-related issues.	N=17	Participants who answered "often" or "very often" to at least 5 out of 9 questions regarding executive function-related issues.	N=41

Table 3.2: The subgroups of participants used to examine differences in use, effectiveness and mental demand of external aids.

There were more participants who reported using high-tech devices with a screen, such as smartphones, tablets and personal computers, as cognitive aids very often (45%), compared to paper-based tools (32%). However, the overall difference in the frequency of use between the two types of aids was not found to be significantly different, using the Wilcoxon Signed-

	Significant difference on Mann-Whitney test?					
	Paper-based aids			High-tech aids		
	Frequency of Use	Satisfaction	Mental demand	Frequency of Use	Satisfaction	Mental demand
Severity of Injury	NO (U=989.5, p=.128)	NO (U=1200, p=.891)	YES (U=893, p=.017)	NO (U=1015, p=.130)	NO (U=1018, p=.141)	NO (U=1152.5, p=.626)
Memory	NO (U=261.5, p=.200)	NO (U=305, p=.629)	YES (U=201.5,p=.017)	NO (U=299.5, p=.547)	NO (U=321.5, p=.850)	YES (U=171,p=.003)
Executive Function	NO (U=311, p=.506)	NO (U=316.5, p=.575)	YES (U=116.5,p<.001)	NO (U=346, p=.964)	NO (U=331.5, p=.761)	YES (U=153,p<.001)

Table 3.3: Difference between subgroups of sample, in frequency, satisfaction and mental demand of paper-based and high-tech aids.

Rank test (see Figure 3.4). As can be seen in Table 3.1, there was no strong association found between the frequency of use and the participants' age, severity of injury, total score in memory questions and total score in executive function questions. However, it was found that participants with a higher level of education reported using high-tech devices as cognitive aids significantly more often ($\rho(97)=-.264$, $p=.008$). The participants were also asked to indicate how often they use these devices for general purposes, besides using them as cognitive aids. A significant positive association was found between the two frequencies of use, using the Spearman's Rank Correlation ($\rho(97)=-.381$, $p<.001$).

Regarding the effectiveness of high-tech devices as cognitive aids, more participants described them as "extremely helpful" (39%), compared to paper-based tools (26%). 18% described them as "very helpful", and overall 72% of the participants described them at least as "somewhat helpful". The Wilcoxon Signed-Rank test was used to compare the effectiveness of the two types of aids, but there was no significant difference found. As with the frequency of use, there was no strong association found between the effectiveness and the participants' age, severity of injury, total score in memory questions and total score in executive function questions, but there was a significant correlation with level of education ($\rho(97)=.229$, $p=.023$). Moreover, participants who reported using the high-tech devices more often either as cognitive aids or for general purpose, described them as significantly more helpful ($\rho(97)=.320$, $p=.002$ and $\rho(97)=.734$, $p<.001$ respectively).

As can be seen in Figure 3.4, the participants' answers to how much mental effort is required to use high-tech devices as cognitive aids were similar to those regarding paper-based tools: 8% of participants stated that they require "too much mental effort" and 19% that they require "a lot of effort". No significant difference was found in the overall mental demand of the two types of aids, using the the Wilcoxon Signed-Rank test. Participants with more memory-related problems (higher total score in all memory questions) found high-tech aids to be significantly

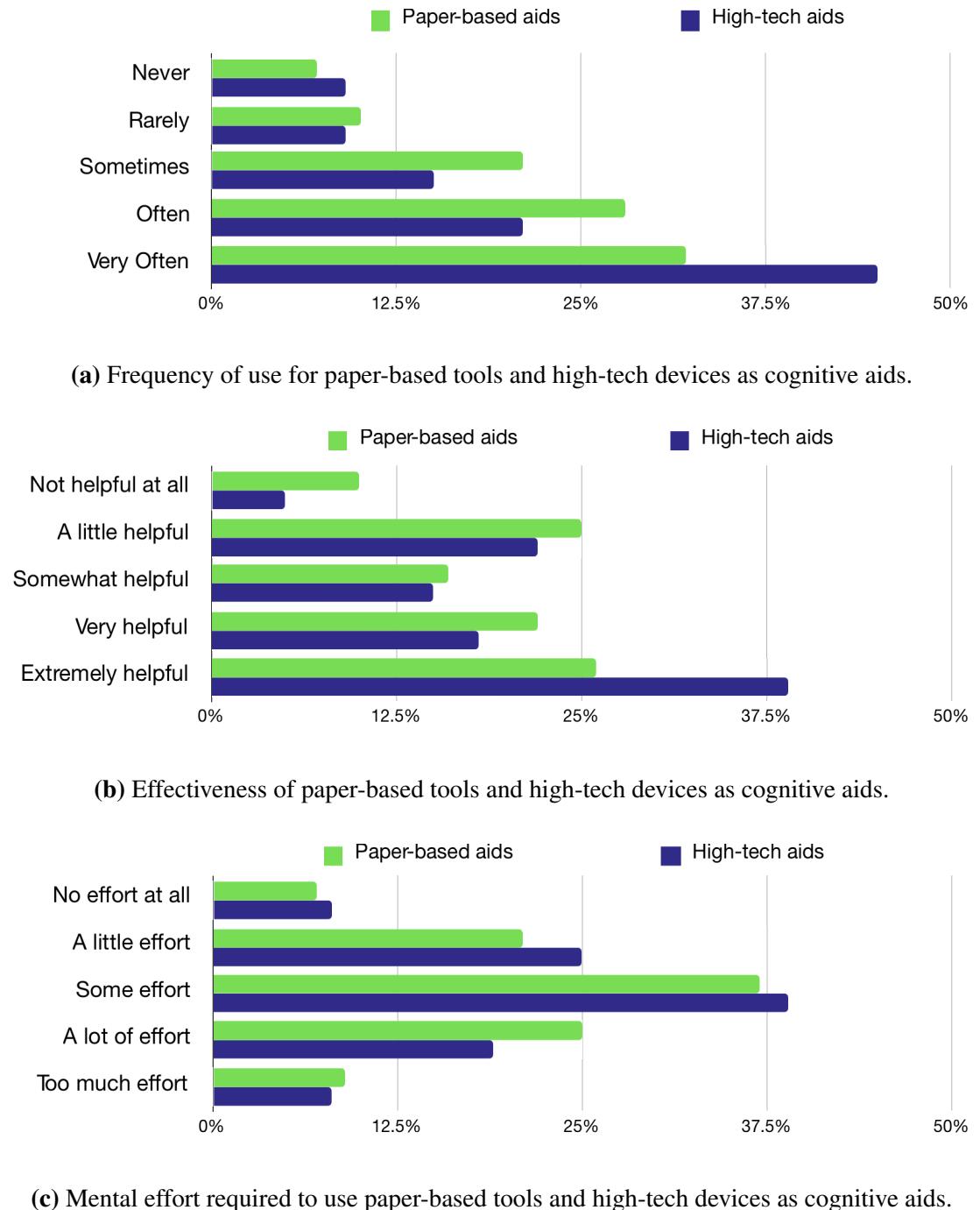


Figure 3.4: Comparison between responses for paper-based tools and high-tech devices as cognitive aids, regarding frequency of use, effectiveness and mental demand.

more mentally demanding ($\rho(97)=.340$, $p=.001$). Similarly, a significant positive correlation was also found between mental demand of high-tech aids and the total score in executive function-related questions ($\rho(97)=.372$, $p<.016$). On the contrary, no significant correlation was found between the mental effort required to use high-tech aids and the participants' age, severity of injury and level of education (Table 3.1). Participants who found paper-based aids to require more mental effort, also described high-tech aids to be more mentally demanding (significant positive correlation on Spearman's rank correlation test, $\rho(97)=.350$, $p<.001$). Additionally, as with effectiveness, participants who reported using the high-tech devices more often either as cognitive aids or in general, described them as significantly less mentally demanding ($\rho(97)=-.386$, $p<.001$ and $\rho(97)=-.229$, $p=.027$ respectively). When comparing the frequency of use, effectiveness, and mental demand of high-tech aids, there was no significant difference between the subgroup of participants with an ABI of mild or moderate severity, to those with a severe or very severe ABI (Table 3.3). Between the subgroups determined by the frequency of memory and executive function-related issues, there was a significant difference in the reported mental effort ($U=171$, $p=.003$, and $U=1527$, $p=.012$). There was, however, no significant difference in the frequency of use, and how helpful people in these two groups found high-tech aids (Table 3.3).

Voice Assistants

Voice Assistants were far less popular among the participants of the survey, compared to the other two types of aids. Specifically, 40% of participants reported that they had never used one, and 27% that they had only used them once or twice. 23% of the participants said that they use them sometimes, and 8% that they use them often or very often.

Among the 58 participants who reported having used a VA at least once, Apple's Siri was the most popular (57%). The second most popular was the Google Assistant (24%), followed by Amazon's Alexa (21%) and Microsoft's Cortana (12%). One participant mentioned that they were using Samsung's Bixby on their smartphone. Six users identified speech recognition or text-to-speech software as Voice Assistants and reported using them regularly mostly due to physical impairments that prevent them from reading text or typing. The most common task that participants reported using VAs for was searching for information online (33%). Other common tasks included navigation (20%), playing music (15%), setting alarms and reminders (15%), sending text messages (14%) and making phone calls (13%). Figure 3.5 shows the popularity of different types of VAs among the participants of the survey, and the most common use cases in people who reported using them regularly. The mean age of participants who reported using VAs was 43.1 years old (median=41 y.o., SD=14.5). There was a significant negative correlation found between the participants' age and frequency of use of VAs, indicating

that younger participants used VAs more often than older participants ($\rho(97)=-.224$, $p=.013$). No significant association was found between the frequency of use of VAs, and of the other two types of aids. Some participants commented on why they did not use VAs. The most common reason was having a speech impairment, which resulted in the VA not being able to understand them. Other reasons included having a hearing impairment, or finding it difficult to learn how to use new technologies.

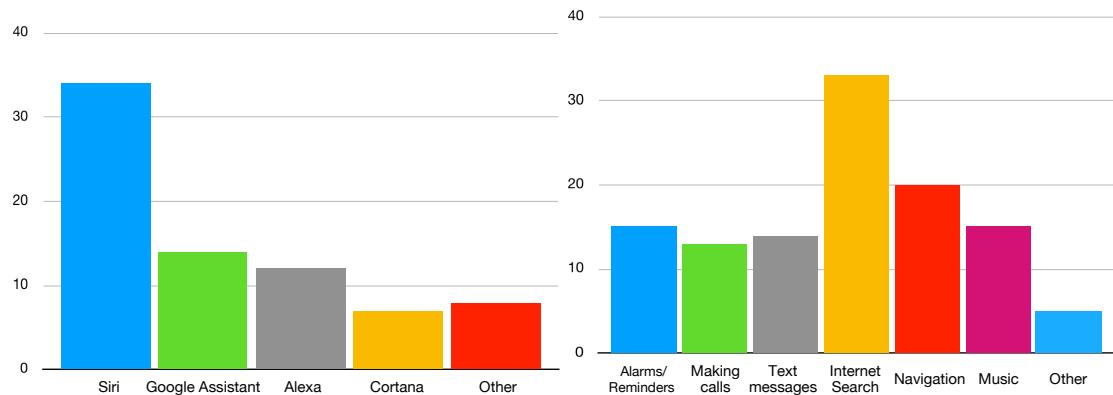


Figure 3.5: Types of Voice Assistants used by participants and the associated tasks.

Regarding the mental effort required to use VAs, out of the 58 participants who reported having used one 6 (10%) said that they require too much effort and 15 (26%) that they require a lot of effort to use. 11 participants (19%) answered that VAs require little mental effort, and 4 (7%) that they require no mental effort at all. There were no significant differences found in how mentally demanding these participants found the three types of aids using the Wilcoxon signed rank test (Figure 3.6). Similarly, no significant correlations were found between the reported mental demand of VAs, and the participants' severity of injury and frequency of memory or executive function-related issues, on the Spearman's rank correlation test.

From the review of related literature in Chapter 2, it was concluded that one of the ways that VAs can be beneficial is to support remote therapy or rehabilitation, and health monitoring. However, studies showed that several privacy concerns are associated with these technologies (e.g. [1, 37, 55]), which could present an obstacle when discussing sensitive information related to one's health over a VA. To examine whether these concerns are also prevalent among people with ABI, in the last two questions of the survey participants were asked to indicate how comfortable they would be to share personal information regarding their physical and mental health with a VA, and to receive advice about their physical or mental health from a VA. 20 out of 58 participants (36%) said they would be uncomfortable or very uncomfortable sharing such information through a VA, while 13 participants (22%) said they would be comfortable or very comfortable (33% chose the neutral response). Regarding receiving health-related advice, 18 participants (31%) said they would feel either uncomfortable or very uncomfortable, while 17

(29%) said they would be comfortable or very comfortable (29% were neutral).

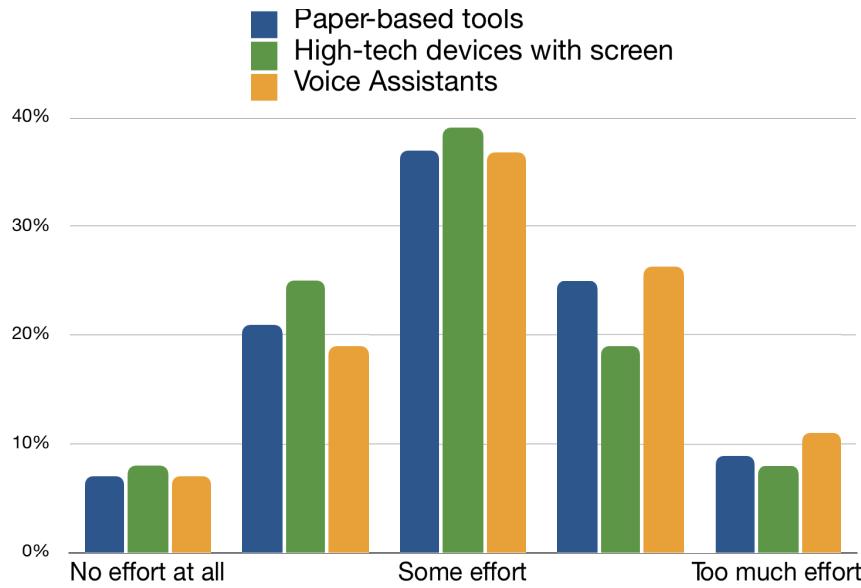


Figure 3.6: Required mental effort to use paper-based tools, high-tech devices with a screen, and Voice Assistants as cognitive aids.

3.2.4 Discussion

One of the main objectives of this survey was to examine the background and characteristics of people with ABI who use external aids. The findings of the study in that regard were in agreement with the reviewed literature [198, 220]. Specifically, difficulties related to poor memory function, and especially prospective memory, were the most common among the participants, with almost one out of two reporting that they face such issues frequently in their everyday life. Similarly, issues related to poor executive functioning were also common for many of the participants, and particularly problems with organisation and decision making.

With regard to the second objective of the study, the exact way that cognitive impairments impact the usability of external aids, and Assistive Technologies in particular, is not clear. Some studies have associated better cognitive function with higher use of aids [61, 229], which could be associated with a better awareness of their own difficulties, while other studies have associated poorer memory performance with higher use of aids [90]. In this survey, there was no strong association found between poor memory and executive function performance and use of external aids. There was, however, a strong correlation between memory / executive function performance, and the perceived mental demand of external aids. This indicates that people with more cognitive difficulties can find it harder to use external aids, and consequently may use them less or find them less helpful. Although this is not a surprising conclusion, when designing ATs for people with ABI it is important to consider that within the same user group there will

likely be a wide range of levels of impairments. Therefore, while the mental effort required to use a technological solution can be low for some people with ABI, it can be high for others. Conversely, an aid which is designed based on the needs of users with more severe cognitive impairments, might appear too simplistic to users with better cognitive abilities.

In the aforementioned studies by Evans *et al.* and Jamieson *et al.* it was found that the use of technological aids was lower compared to their paper-based equivalents [61, 90]. In this survey the use of both types of aids was high, and ATs were particularly popular with a greater number of participants who reported using them frequently. A possible reason for this is that the survey was conducted more recently, with technologies like smartphones and tablets being more affordable and mainstream. However, it is likely that, due to the way it was advertised and distributed, the survey attracted people who were keen on using technology. Nonetheless, the large number of respondents and the high ratio of participants who reported using ATs frequently and finding them helpful despite any challenges, indicates a positive predisposition and interest towards technological aids, further motivating the research aim of this thesis.

Among the participants of the survey, an important factor associated with higher use of technological aids was education. Jamieson *et al.* argued that a higher education level could be an indication of a higher socio-economic status. That can be related to higher levels of social and family support which may, in turn, contribute to a better use of cognitive aids [90], but also may relate to greater affluence and hence ability to afford devices like smartphones and voice assistants. Another factor related to more frequent use of external aids in previous research was age [61, 90]. In this survey, there was no strong association between the participants' age and the use of paper-based or high-tech tools in general. Younger age was, however, correlated with higher use of Voice Assistants, likely due to the fact that younger people are more likely to adopt new technologies earlier. Regardless of age, it was also pointed out by some participants that adopting a new technology and learning how to use it can be challenging for a person with cognitive impairments. This is something that needs to be taken into consideration when examining the design of new applications for VAs, a technology that is seemingly not yet widely adopted among people with ABI.

Another important element to consider when designing ATs for people with ABI is the person's level of participation in different activities. In the survey, three out of four participants' employment status had changed from "employed" to "not employed" after the injury. It is likely that for many this change was a result of the injury (32% of the participants whose employment status changed to "unemployed" after their ABI were below 55 years old). Moreover, the majority of participants described themselves as being inactive or unmotivated to engage in activities after the ABI. The design of ATs should therefore recognise that some people with ABI might need additional support to become engaged, or they might be less willing or unable to carry out activities to the same extent.

The majority of respondents in the survey reported having to rely on other people to perform basic daily tasks, such as taking their medication or remembering to attend appointments, even though they used external aids often and found them helpful. This can be an indication of inadequacy or ineffective use of existing aids, implying that there is room for better design and novel approaches. Moreover, a large portion of participants reported relying on the support of a carer on a regular basis. As discussed in the previous chapter, increasing the person's independence is one of the main purposes of external aids, and should undoubtedly be one of the design objectives in new ATs. Although in many cases it might not be possible for ATs to entirely replace a carer, they can be used to facilitate the communication between them and the person with ABI, by providing prompting and guidance in a way that increases the user's sense of self-sufficiency and reduce friction.

The findings of the survey regarding the use of VAs are not sufficient to lead to conclusions about their efficiency and how they compare to other types of aids, due to the small number of participants who reported using them and the discrepancy in the frequency and nature of use. Many of the common tasks that participants reported using VAs for, such as searching for information online and listening to music, were consistent with those found in other studies examining the use of VAs in different groups of users (e.g. [6, 37, 57]). The users' concerns regarding the privacy of VAs were also consistent with these studies, a factor that should be considered as a potential obstacle when examining the use of VAs to enable remote rehabilitation or therapy, and monitoring the user's mental or physical health.

Limitations

The questions related to memory and executive function in this survey intended to give an indication of the prevalence of some of the common ABI-induced difficulties among users of external aids. Carrying out a thorough assessment of a person's cognitive ability is a complex procedure, which was not be feasible to include in a short survey. Therefore, the validity of this study's findings regarding the extent of the participants' cognitive impairments and their effect on the use of external aids is subject to further confirmation. Moreover, the participants' indication of mental effort required to use external aids in this survey was subjective, and could differ based on the exact type of aid, and the way it was used. Hence, conclusions regarding the mental demand of paper-based tools or electronic devices that the survey participants referred to cannot be generalised to the entirety of paper-based or technological aids respectively.

3.2.5 Summary

This survey examined the use of three different types of external cognitive aids among people with ABI (N=99): paper-based tools, high-tech devices with a screen, and Voice Assistants. It also investigated the prevalence of common cognitive difficulties and whether these are associated with the use of external aids. Issues related to poor prospective memory, and problems with organisation, scheduling and decision making were the most common among participants. High frequency of occurrence of such issues was associated with how mentally demanding participants found external aids. More information is needed, however, to determine how cognitive impairments can impact usability. Although the majority of participants reported using at least one type of aid frequently, many reported having to rely on other people to carry out everyday tasks, indicating room for improved design of external aids. Nevertheless, the large number of participants reporting being satisfied from external aids and regular use of technology shows a positive predisposition towards assistive technologies and confirms their beneficial impact. The use of Voice Assistants was not common among participants of the survey compared to the other two types of cognitive aids. Some of the considerations and challenges related to designing VA applications for people with ABI were discussed.

This study addresses the two objectives of this chapter by investigating the occurrence of common cognitive difficulties and providing a better understanding of the background of people with ABI who use external aids, and by examining common cognitive difficulties and how they can impact the usability of existing external aids. From the information gathered by this study and the reviewed related work, there is enough evidence to suggest that technological solutions can support everyday functioning of people with cognitive impairments due to ABI. Voice Assistants may be useful in this context and provide some advantages over other types of aids. However, before being able to conclude how VAs should be used or designed to benefit this particular user group, more information is needed to specify how the deficits of people with ABI might affect the usability of this technology, and to identify the situations where they would provide a better alternative to existing solutions.

3.3 Study 2: Group Interview with Neuropsychologists

3.3.1 Introduction

As described in Section 2.2.3, a brain injury can cause a very wide range of cognitive effects, the combination and severity of which can be very different from one person to the other. The latter was also confirmed by the results of Study 1, with regard to difficulties related to poor

memory performance and cognitive dysfunction. Moreover, people with ABI are often unable to accurately describe their own difficulties due to lack of self-awareness and communication issues [86, 177]. Professionals in the field of Neuropsychology have a broad understanding and cumulative experience of the common problems that occur as a result of the effects of ABI, and can provide valuable insight into the design of Assistive Technologies aiming to alleviate these problems. Additionally, their knowledge of the common practices of Neuropsychological Rehabilitation (NR) can help determine how AT can be applied to facilitate the rehabilitation process.

Study 2 consisted of a group interview with NR professionals, to acquire the experts' view on the prevalence and impact of common cognitive effects of ABI, learn about the practicalities of NR methods, and gather the experts' feedback on the application and design of ATs. The data gathered from the interview were analysed to inform the design and use cases of AT for people with cognitive impairments due to ABI.

3.3.2 Method

Participants

The group of participants consisted of seven adults employed at the Neuropsychology and Brain Damage Rehabilitation Unit of the ELEPAP² Rehabilitation for the Disabled, a non-profit charity organisation in Athens, Greece. One participant was a graduate neuropsychology student who had been doing an internship for six months. The remaining six participants were professional neuropsychologists, two of which reported being employed at the organisation for six to eight years, and the other four reporting more than ten years of working experience at the time of the study. All seven participants reported having worked in the rehabilitation of different age groups of people with ABI including children, and at the time of the study were involved in a neuropsychological rehabilitation group treatment programme for adults with ABI.

The recruitment was done after communication with the head of the rehabilitation unit, and the study was carried out at the premises of the organisation in January 2018. The consent forms and information sheet were sent via email to the contact person, who in turn distributed them to the participants. The signed forms were returned to the researcher at the time of the study. Approval for this study was provided by the University of Glasgow College of Science and Engineering ethics committee in December 2017.

²<https://elepap.gr/en/meet-us/our-beneficiaries/adults/neuropsychology-and-brain-damage-rehabilitation-unit/> - Accessed: 11/5/2021

Procedure and Analysis

The interview was conducted in a semi-structured way, with questions evolving around the three main aims of the study: effects of ABI, NR methods and design of ATs. The participants took turns to introduce themselves and describe their role in the organisation. Then, they were asked to describe what, according to their experience, were the most common cognitive effects of a brain injury and how these impact people's everyday life and their rehabilitation progress. Next, they were asked to express their view on how technological aids should be designed to be efficient. The discussion did not focus on any particular type of technology, and did not include the topic of Voice Assistants which, at the time of the study, were not available in the Greek language and participants had no experience using them. Follow-up questions were asked by the researcher when deemed useful for clarification or to acquire additional details. Finally, the participants were engaged in a group discussion where they expressed their views on the purpose, design and challenges of ATs. The participants were encouraged to comment on their colleagues' answers and comments during the study.

Audio and video recording were used during the study and the recorded data were transcribed and analysed using Inductive Thematic Analysis, to examine how they could inform the use cases and design of ATs, therefore addressing the two objectives of this Chapter (see Section 3.1). As described by Braun and Clarke [23], the process of Thematic Analysis consisted of six phases: 1) Familiarisation with the data; 2) Generating initial codes; 3) Searching for themes; 4) Reviewing themes; 5) Defining and naming themes; 6) Producing the report. The transcribing, coding and analysis of the data using the procedure described above were conducted by the author of the thesis alone.

3.3.3 Results

The participants reported working with their clients through one-year-long intensive group treatment programmes, which run four days a week for four to five hours per day. The majority of their client population was in the chronic phase, i.e. at least one year after their injury. The programme was based on the holistic approach of cognitive rehabilitation as defined by Ben-Yishay and Diller [15, 16]. The participants reported that they had relied on this model for years and that they found it very effective. They described the goals of their work to be the following: 1) Helping the clients become aware of their condition; 2) Restoring and compensating for cognitive dysfunction; 3) Helping clients adapt to new conditions, and 4) Helping clients modify their behaviour when they had disinhibition or lack of initiation.

The interview and group discussion evolved around the method and objectives of the programme, the common difficulties of their clients, and the requirements for assistive technologies.

The initial codes generated by the inductive analysis were the following: 1) Effects of ABI; 2) Use of technology; 3) Use of external aids and strategies; and 4) Rehabilitation practices and methods. Four main themes emerged after the analysis of the data, each of which contained several sub-themes. Specifically these themes were: 1) The need for prompting (sub themes: Memory and organisation; initiation and motivation; self awareness); 2) Family Involvement (sub themes: Assessment; support; challenges); 3) Social participation (sub themes: Lifestyle changes; reward; social acceptance); 4) Personalisation and adaptivity (sub themes: holistic approach; adjustable goals and monitoring; trust and acceptance; complexity of technology). The initially generated theme of "Technology design recommendations" was discarded for being too broad, while the theme "Holistic approach of rehabilitation" was initially considered a main theme, before it was converted to a sub-theme of the main theme "Personalisation and Adaptivity". The main themes and their sub-themes are presented below.

The Need for Prompting

The majority (n=5) of participants reported that the main type of support that most people with ABI need is prompting, and that this should be the main focus of an assistive tool. It was also reported that several cognitive functions are usually affected in each person with ABI, and that it is extremely rare, if at all possible, for someone to have trouble with only one specific function (e.g. memory). Therefore, prompting should aim to support multiple functions:

"I think aids should provide prompts. Prompts to help people remember, to stimulate them, to set boundaries, to organise things." (P2).

In general, the participants expressed the need for a prompt to be simple, concise, specific and short, in order to work effectively for people with cognitive impairments. There were, however, several remarks about prompting and the use of aids that were related to specific cognitive functions and impairments, which are described below.

Memory and Organisation

The participants agreed that the most commonly impaired function was memory, and especially prospective memory. It was also highlighted that most of their clients depended on some sort of memory aid, either to make notes of things they should remember or to receive reminders. However, poor memory function was also associated with the inability to use aids efficiently. One way that this can happen is that the person forgets to use the aid: either forgetting to create a note/reminder, or forgetting to look at the tool where the reminder had been written. Another way is, in the case of alarms or reminders, to forget the purpose of a received prompt:

"Even if the reminder goes off, they can see it and not remember what it's about. Or they just dismiss it. The very problems that prompting is supposed to help overcome, become obstacles in

the process of using the prompts." (P5)

Other cognitive difficulties could also contribute to the inability to use memory aids efficiently, such as lack of concentration (e.g. getting distracted before carrying out the task they were prompted to do), or problems with organisation:

"Another issue is with organisation. How to look for something in their notes, or how to find a reminder. Having a schedule is good, but being able to use it in an organised way is difficult. For example, putting an appointment on the correct day, and not on the same day that they are making the note." (P2)

Organisation was also mentioned as an area where the use of AT could be beneficial. Suggested solutions included aids that would help the person schedule their day, and facilitate the process of taking specific steps to complete each activity. According to the participants, such a solution would also be required to provide prompts to ensure that the user stays on track with the schedule.

Initiation and Motivation

Another important issue where prompting would be useful is to support lack of motivation and initiation, by helping people engage in activities:

"I believe that the help needed by people with ABI comes down to [...] continuous prompting. You see people that don't take initiative, and even if they begin doing something they can't stay on it. There is a need for prompting in order to make people get involved in something." (P3)

The participants explained that this inactivity is sometimes the result of a psychological issue such as depression, or of the person's social environment, but for the most part it usually is a direct result of the brain damage. It was reported that continuously providing prompts and cues as often as possible can help the formation of routines and habits, which can alleviate the effect of lack of motivation and initiation.

Self Awareness

Lack of self-awareness was another common effect of brain injury. The participants mentioned that the majority of their clients believed that they did not have any difficulties when they join the programme, and that they are usually referred due to intervention from their families. Lack of self-awareness can have a negative impact on the person's social life, when accompanied by problematic behaviour:

"They don't understand that they talk abruptly to others; they think that only the others are being rude towards them. So eventually they either withdraw, or they become aggressive." (P6)

As with the difficulties described above, prompting was the suggested solution here as well, by providing cues to induce self-control. Besides aggressiveness, self control was also associated

with lack of inhibition. The purpose of the prompts in these cases should be to tell the person what to "not do", thus increasing their awareness of their own behavioural issues and minimising the social impact. Similarly to the other cognitive impairments mentioned above, lack of self awareness could also become an obstacle to the efficient use of external aids, as people might believe that the aids are not important to them:

"For instance, a client who has very serious memory difficulties, he keeps saying that 'I wont set a reminder because I will remember to do it'. Or they usually say 'If it's something important, I will remember it'. But that doesn't happen." (P3)

Finally, the ability to automatically adjust the prompt's content and timing based on the context of use was described as something that could be beneficial:

"Another kind of prompt would be to tell him what to not do. I don't know how realistic that is, the device should be able to detect when to give the prompt and tell them 'don't do that'." (P6)

Family Involvement

The next theme that was identified in the data was the family's involvement in the rehabilitation process. The participants highlighted the importance of regular communication with the client's family (or carer, if the person providing the support is not from the family circle) to discuss the progress of the person with ABI. This is usually done on an individual basis due to practical reasons, and feedback is provided from the therapists to the family, but also the other way around.

Assessment

One way that the family is involved in rehabilitation is by providing assessment. The participants reported that the standard way to assess their client's condition and progress was through standardised psychometric tests, which are carried out regularly to evaluate the performance of specific cognitive functions. However, they argued that information gathered from observations of the person's family related to their everyday behaviour can be a more reliable source:

"Another important method is the observations of people around them. Sometimes a test might show improvement or progress, but reality can show the opposite." (P5)

Feedback from the family can also be important in cases where the client shows a different behaviour in front of the group and the therapists, compared to when they are at home. The family (or carer) is instructed to keep notes or call the programme when something significant happens.

Support

Family can also provide support to the person with ABI, facilitating the rehabilitation process. This usually requires the family member (or care-giver) to be trained by the therapists on providing the appropriate prompts at the correct times, or to help the client use external aids as instructed by the programme. This becomes especially important in the case of children, where the use of external aids like notebooks and calendars is limited, and most of the support is given by the parents. In that context, the communication between the therapists and the family is crucial:

"For the most part, strategies [between adults and children] are the same. The interaction with the parents is the main difference. The parent needs to be involved in every intervention, to be able to help. The parents might have to be trained along with their children, so that everyone works together in harmony." (P2)

Finally, the family can also play an important role in raising the person's awareness on a specific issue. It was reported that when people join the programme, the issues they are mostly aware of are the ones for which they receive feedback from their families.

Challenges

There are, however, certain challenges associated with the involvement of the person's family. One such challenge is when the family member is not suited to provide the appropriate support:

"When we meet [the family] regularly, we inform them that e.g. this week we are working on this particular issue, so they need to be aware. But it's not always easy. For example, one client is trying to work on staying concentrated during conversation, he is 50 years old, and his father is 90." (P2)

Another challenge is that the interaction with the family member providing the support can be a source of conflict. This was reported to be seen more often with children, who can react in a negative way when they are constantly being told what to do (or not do) by their parents. Although not as common, this was reported to be an issue with adults as well:

"If someone has reached the point where they are completely independent... Imagine being 25, 30 or 40 years old, and having your mum or dad tell you what to do." (P2)

With regard to this issue, the participants raised the argument that external aids should also aim to increase a person's independence. Finally, in the case of children, conflicts can also arise in the communication between the therapist and the parent, when the therapists can disagree with the practices used by the parents and find them to be obstructing the rehabilitation process.

Social Participation

The theme of social participation was identified in several of the responses. Taking part in social activities and the perceived reactions of other people were considered to be important factors in determining the process and desired outcome of the rehabilitation, and can therefore inform the design of external aids.

Lifestyle Changes

The participants reported that ABI often results in a sudden change of one's lifestyle. This can be a result of either cognitive or physical impairments, which do not allow the person to take part in many activities that they used to do before the injury. When this happens, facilitating the person's scheduling becomes more important:

"Sometimes going back to work is not realistic. In that case, you need a program that provides a daily schedule, a simple routine, some daily activities; things that would simply fill up everyday life, in a meaningful way." (P3)

Not being able to function independently and participate in social activities can be detrimental, especially for people who used to be very active before their injury. For instance, in the case of children with orientation difficulties:

"...they need to ask for help to go to their friend's place. 'I can't go by myself, my mum needs to take me there'. It's both demeaning and also puts them out of context." (P7)

Moreover, the realisation of this sudden inability to carry out activities can also have negative consequences to the person's psychology, and it is something that needs to be taken into consideration when their self-awareness gradually increases through the course of rehabilitation. Once a level of acceptance is reached, the goal should be for the person to acquire new interests and to start being involved in new activities.

Reward

The participants reported that social participation, managing to carry out tasks independently and receiving positive feedback from others were the most desired outcomes of rehabilitation. Being part of a group of people with difficulties similar to their own during the course of the programme was also beneficial:

"Perhaps the biggest motivation is involvement. Participating in social activities. All people with ABI, at least to a certain extent, have significant problems in their social life. So, making them part of a group, where they just participate and interact with others, without having the fear of failure or punishment, being in a safe environment, that is something that has incredibly reinforcing results. Seeing new people... All these social aspects are, at least in the beginning, the strongest motives." (P5)

A common method that the participants reported applying in the programme was to set realistic and measurable weekly goals, which are simple enough for the clients to assess by themselves whether they have been accomplished. The clients present their goals and their progress in front of the group, and they are encouraged to provide feedback to each other. According to the participants, being able to accomplish these goals and receive positive feedback from their peers can be its own reward. A positive feedback is also important even when the goal is not achieved, as long as it is acknowledged that there had been an issue and the goal is readjusted.

Social Acceptance

The significance of social participation and feedback from other people is also a factor to consider in the interaction design of AT. The participants argued that, although an aid should aim to increase independence and therefore facilitate social participation, it should be designed in such a way that it does not cause social embarrassment:

"A client said that he would need something to help him control his behaviour, like something that would provide a cue or prompt whenever he raises the volume of his voice. If for instance there is a device that vibrates and they are the only ones to see it, so that they are not exposed... Something that wouldn't cause further difficulties in their social interactions, or wouldn't make them the centre of attention, but would be useful and effective for them." (P4)

Personalisation and Adaptivity

The last theme identified was that of personalisation and adaptivity, which is related to the design of assistive technologies. This refers to responses that indicate the need for external aids to be customisable in order to support people with different characteristics and needs.

Holistic Approach

The holistic model of NR discussed in Section 2.3.1 considers the cognitive effects of ABI to be interlinked with the emotional, social and functional effects. This approach was also described by the participants, who highlighted the importance of taking all these aspects into consideration when planning an intervention, and therefore an assistive tool. They reported that the ultimate objective for their clients is to be functional in their everyday life. This requires improving their cognitive functions, to the extent that is possible, building their awareness, and improving their mental health. It was also stated that these aspects are usually interdependent, meaning that the improvement of each one depends on the improvement of the other two.

An initial requirement in this approach is to thoroughly examine the person's background. This includes an assessment of their mental health. It was reported that emotional disorders such as anxiety, stress and depression, which were commonly seen in the participants' clients, need to be identified and taken into consideration in the design of assistive tools, either as targets

of the tools or as factors that can affect their usability. Additionally, it is important to examine the person's social environment, which can also influence the purpose and applicability of assistive tools. The above requirements can be identified in how participants envisioned the design of a prompting system, where the needs and characteristics of the individual would need to be considered in order to increase its effectiveness:

"An aid should have a lot of flexibility, [it should be] fully customisable. Because it would work very differently on each individual. Even the same stimulation could be perceived in very different ways from one person to the other." (P6)

Adjustable Goals and Monitoring

The importance of personalisation and customisability was also identified in the reported need to regularly monitor the person's progress to adjust the rehabilitation goals accordingly. This can either be about readjusting the goal to a more achievable one in the case of failure, or determining the next objective in the case of successful completion:

"Something important for people who have reached the point of being somewhat active, and doing some everyday activities, to figure out what to do next; what's the next step." (P2)

Monitoring people's progress was also reported to be important in order for them to realise their own accomplishments in completing the assigned goals, and that they are able to move to the next step. According to the participants, this can be extremely rewarding and motivating. However, this can be harder to apply in children, who are often unable to comprehend the final outcome of a long term goal, making it more challenging to keep them engaged in the rehabilitation process.

Trust and Acceptance

Trust was something that was described as important. In the case of a prompting aid, trust can determine the effect of the prompt who gives the prompt can be more important than how the prompt is conveyed

"A prompt does not always have the same effect. It depends on the person's situation, who gives the prompt and what is the person's relationship with the one giving the prompt. It's possible that someone might give the same prompt often, and it can have negative results instead of positive. Because it can irritate them. On the other hand, if someone else gives the prompt and even in a worse manner, but because they trust you, they can comply immediately." (P3)

Trust is something that can be built over time, through the relationship between the person providing the support, and an important factor when building trust was reported to be honesty. This was about not trying to hide their problems and their consequences, but uncovering everything and trying to solve it. Other factors mentioned were respect, not criticising, and not being punishing. The need for trust was also associated with the lack of self-awareness:

"Very few people have awareness of their difficulties. That's where trust is important. If a person doesn't realise that they have a behaviour problem, only if they trust you will they do what you tell them, even if they don't understand why. Because they trust you." (P5)

Complexity of Technology

Finally, personalisation could also refer to the type of tool that can be used, as some types might be unsuitable for people with certain characteristics or difficulties. One such remark was related to older people, who were reported to have a much greater difficulty in using modern technologies that they were not familiar with before their injury, compared to younger people who already knew how to use them. As another example, the participants described smartphones as something that can seem very challenging for people with cognitive impairments due to their complexity, and once more highlighted the need for simplicity in AT:

- *"We have spent a lot of time trying to train clients to use the phone's calendar. How to add events, set notifications etc. That's all very difficult." (P1)*
- *"What are the difficulties?" (R)*
- *"It could be anything, even the most simple thing like finding and starting the app, browsing the calendar visually, remembering the steps needed to follow to insert something. They forget the steps. Or they accidentally delete reminders. It has to be something very simple to be practical." (P1)*

3.4 Discussion

The findings from both studies described in this chapter provide information regarding the prevalence of cognitive difficulties in people with ABI, and show different ways that cognitive impairments can affect the use of external aids. In particular, Study 1 found memory and organisation problems to be most common among participants. These issues were also described as very common by participants in Study 2, who also reported reduced self awareness, and lack of initiation and motivation to be among the most frequent effects of ABI. These findings can inform the design of Assistive Technologies, and therefore Voice Assistants, by helping to determine what their objectives should be, namely to help support the impaired cognitive functions, but also by helping to identify how people with ABI interact with technology and what are the potential usability issues. For instance, the survey results showed a significant association between cognitive difficulties and the perceived mental demand of external aids. Once more, this was also confirmed by participants in Study 2, who reported that mainstream technologies can be too complex for people with ABI, and highlighted the need for simplicity in the design. This issue of cognitive accessibility due to the complexity of technology, as well as other identified factors that can affect the use of external aids, such as physical impairments and social accep-

tance, agree with findings in other studies [12, 92, 179].

Another finding that was confirmed in both studies was the very wide range of cognitive impairments in people with ABI, and the fact that the severity and nature of impairments can differ greatly between individuals. Moreover, although the results show more usability challenges in people with more prominent impairments, there were no findings to suggest that AT cannot be as beneficial for these users. On the contrary, the high number of participants who reported using and benefiting from technological aids in Study 1 implies a positive opinion of AT across all users. The above, however, also indicate that when designing a technological solution to support a specific cognitive function, impairments of other functions are also likely to exist among users and need to be taken into consideration. For example, besides assisting with memory performance, a memory aid should also be designed so that it can be used efficiently by people with reduced attention or organisation skills.

Participants in Study 2 described prompting as the most suitable way to support people with memory difficulties, lack of self awareness and behaviour issues. This comes in agreement with the literature discussed in section 2.3.2, where the majority of aids presented were prompting systems (e.g. [63, 194, 203]). Besides supporting the performance of these impaired functions, the participants also reported that prompting can help permanently improve functioning of people with ABI through the formation of routines and habits. However, receiving positive reinforcement and being aware of the purpose of the prompt were described as essential for the person's motivation and engagement. These findings can also been seen in literature examining the effect of reminders and cues on habit-formation [195, 196].

Both studies examined the motivation and activeness after an ABI and found that there is a significant change in the number and type of activities that people participate in. Participants in study 2 reported that being active and taking part in social activities can be very important, and one of the main objectives of NR. Design of AT for people with ABI aiming to facilitate scheduling and task completion should therefore: 1) Support taking up new activities and being engaged in them; 2) take into account that users might not be able to complete tasks as frequently as an average user.

The survey results showed that there was a significant number of respondents who had a care-giver, and an even larger number who reported relying on others to support their everyday functioning. Similarly, participants in Study 2 reported that the participation of family members and carers in the rehabilitation process is essential in providing monitoring and support. Although these findings motivate the use of AT to support independence, they also indicate that the involvement of other people in the support of someone with ABI is very likely. Therefore, AT can aim to facilitate the communication and collaboration with family members or carers, to improve the rehabilitation process and reduce conflicts.

The wide range of ABI effects and diversity between individuals can make the design of AT for this user group particularly challenging. This makes user-centred design even more essential, and highlights the importance of determining the use of AT based on the characteristics of the individual [116]. According to the holistic model of NR, examining the person's background and taking their environment into consideration is crucial for a successful rehabilitation process. Arguably the best design approach to incorporate all these factors is to provide personalisation, i.e. flexible interfaces that can be customised based on the needs, shortcomings and goals of the individual user. As was discussed in Section 2.4.3 and can be seen in related studies (e.g. [41, 135]), personalisation can improve the user experience of technology. Given the many ways that cognitive impairments can hinder their usability, personalisation could be critical in determining whether AT is used efficiently or even used at all.

<i>Use Cases of Assistive Technologies for people with ABI</i>
1. Support impaired cognitive functions such as memory, organisation, initiation and motivation through timely cues to prompt action.
2. Increase awareness of inappropriate behaviour through regular prompting.
3. Facilitate communication between family members/carers and people with ABI to improve support and reduce conflicts.
4. Facilitate collaboration between family members/carers and therapists to improve monitoring, assessment and support.
5. Support engagement to the rehabilitation process by increasing motivation through goal completion.
6. Increase activeness and participation in social activities.
7. Facilitate task completion through suitable guidance, and by supporting concentration and attention.

Table 3.4: Use cases of assistive technologies for people with ABI.

<i>Design Characteristics of Assistive Technologies for People with ABI</i>	
Personalisable	Offer customisation to support users with different levels of impairment, cognitive capabilities and rehabilitation goals.
Adaptive	Automatically adjust the content of prompting based on the context and the user's behaviour.
Trustworthy	Provide support in a friendly and intimate manner that appeals to the individual and inspires trust.
Discrete	Provide efficient prompting in a discrete manner that avoids unwanted attention and social embarrassment.
Rewarding	Provide a goal-oriented sense of achievement and positive reinforcement to increase motivation.
Simple	Use concise and straightforward interaction to support users with limited cognitive capacity.
Autonomous	Provide timely support without relying on the user's input and initiative.

Table 3.5: Design characteristics of assistive technologies for People with ABI.

All the above can be used to inform the design of AT for people with cognitive impairments due to ABI. Tables 3.4 and 3.5 present an attempt to apply these findings to create a set of guidelines that can be used in the design of AT, and therefore Voice Assistants. Specifically, Table 3.4 presents a list of use cases of AT for people with ABI, i.e. situations where technology can be helpful and what its intended purpose should be. Table 3.5 presents a list of characteristics that AT should have in order to be used more efficiently and be more beneficial for people with ABI. Although these guidelines are not specifically about Voice Assistants, they present an initial framework to examine the use and design of VAs in the subsequent chapters.

3.5 Conclusions

The objectives of this chapter were 1) to identify the needs and purposes of AT for people with ABI and, 2) to examine how cognitive effects of ABI can affect the usability of AT. The chapter described two requirements-capturing studies: an online survey which gathered information about the experience of ABI and the use of external aids, and a group interview with neuropsychologists, which acquired additional data about the common effects of ABI, looked into the common cognitive rehabilitation methods and examined the application and design of external aids.

The two studies found issues related to poor memory, organisation, self awareness and initiation to be the most common among people with ABI. Moreover, behaviour issues such as lack of inhibition or inappropriate behaviour were also reported. These issues can help determine the purpose of AT, which can be to compensate for the impairment of the corresponding functions, therefore indicating a potential purpose for Voice Assistants, which will be examined in the subsequent Chapters. The findings also introduce a number of ways that these impairments can affect the usability of technology. These indicate key considerations for examining the factors that can affect the usability of VAs, which will be further investigated in the next Studies. Furthermore, results showed that participation in activities is an important issue after an ABI, suggesting that technological aids should support activeness, and that their design should account for the significant change in people's lifestyle. This also indicates a potential purpose for VAs, and an issue to consider when examining their design. Finally, the studies identified a frequent involvement of family members of carers in the support of people with ABI, indicating that AT could incorporate the participation of these people to improve monitoring or assessment and to provide more efficient prompting. This also highlights an area where the use of VAs can be beneficial.

The findings of this Chapter regarding the use cases of ATs and the factors related to their usability lay the groundwork for examining the use cases and usability of Voice Assistants,

which will be investigated more thoroughly in the next Chapters.

Chapter 4

Examining the Use of Voice Assistants

4.1 Introduction

In the previous chapters, it was reported that ABI can result in the impairment of several cognitive functions, the effect of which can be alleviated by rehabilitation and the use of external aids. VAs, which offer the benefits of Conversational User Interfaces and Digital Assistants, provide functionality equivalent to computers and smartphones, and can therefore be an alternative to other aids in supporting cognitive functions and facilitating rehabilitation. Additionally, Chapter 3 identified several situations where the use of Assistive Technologies can be beneficial for people with ABI (Table 3.4). Although useful, these use cases are general recommendations for any type of technology that can be used in that context. Therefore, the following questions arise: 1) which of these use cases also apply to Voice Assistants? 2) are there situations where VAs can be more appropriate than other types of aids, or *vice versa*? 3) are there use cases that are unique to VAs, that were not previously identified?

The first objective of this chapter is to determine the use cases of VAs for people with ABI, thus addressing the first research question of the thesis (**RQ1**). This is accomplished by: i) further examining the need for VAs and their usability from the users' perspective, ii) acquiring the view of people with ABI on how VAs can be used to benefit them, and iii) examining how people with ABI use VAs in their everyday life.

Chapters 2 and 3 also identified issues in people with ABI that can affect the use of ATs. Similar to the use cases, these issues are not specific to any particular type of technology. It is therefore essential to examine the extent to which they can also affect the usability of VAs, and whether there are other challenges that occur only during the interaction with VAs. Hence, the second objective of the chapter is to investigate the usability of VAs, addressing the second research question of the thesis (**RQ2**). This objective is accomplished by: i) acquiring additional

details about the factors that affect the usability of external aids and analysing them to determine how they would affect the use of VAs, and ii) identifying the common usability issues in VAs by interviews with people with ABI who use them regularly.

This chapter presents two studies addressing the above objectives:

- **Study 3:** a set of focus groups with people with ABI further examining the findings of Studies 1 and 2 by eliciting details about the use of Assistive Technologies (ATs), as well as introducing the concept of VAs as cognitive aids and acquiring initial feedback.
- **Study 4:** a set of interviews with people with ABI who are regular users of VAs, to acquire information about how they use them and what are the features and aspects of interaction they find useful or challenging.

4.1.1 Chapter Structure

Section 4.2 presents and discusses the results of the focus groups with people with ABI (Study 3). Section 4.3 presents the results from the interviews with regular users of VAs (Study 4). Section 4.4 discusses the findings from the two studies, presenting a list of use cases for VAs, and a set of identified factors that affect their usability when used by people with ABI. Finally, Section 4.5 summarises the two studies, and describes how their results inform the research questions of the thesis and motivate the next chapters.

4.2 Study 3: Focus Groups with People with Acquired Brain Injury

4.2.1 Introduction

Before being able to conclude in which scenarios VAs are appropriate as aids for people with ABI, and what their purpose of use should be, it is necessary to acquire more information about how their use compares to other types of aids. The findings from Study 1 showed that people with ABI find the use of VAs beneficial. However, only a small portion of the participants were using them regularly, and participants in Study 2 had no experience with VAs due to lack of availability of the technology in the Greek language. Moreover, as discussed in Chapter 2 there is little research examining the use of VAs for people with ABI. Therefore, this study aims to inform the use and design of VAs by deriving relevant information from discussions with their potential users.

Specifically, this section describes a set of focus groups with brain injury survivors. The study aims to: 1) gather information about the effects of ABI; 2) gather details about the use of external aids, and 3) receive feedback on the concept of using VAs as cognitive aids. Examining the purpose and shortcomings of common aids will help to determine the use cases of VAs and identify potential challenges in their use and design. These will be further informed by acquiring the view of people with ABI on how VAs can be used to their benefit.

4.2.2 Method

Participants

Five focus groups were conducted, with a total of 29 participants. The participants were users of three different services in Scotland and Greece: The Brain Injury Experience Network (BIEN) in West Dunbartonshire¹, Scotland (Group 1, n=6), Headway Glasgow² (Group 2, n=7; Group 3, n=3), and the ELEPAP Neuropsychology and Rehabilitation Unit for Brain Injuries³ in Athens, Greece (Group 4, n=7; Group 5, n=6). Table 4.1 shows demographic information about the participants. The average age of the participants was 42.9 years old (range 20 to 64). The time and cause of injury was not reported by some participants due to inability to remember.

The recruitment of participants for Groups 1,2 and 3 was conducted by attending the corresponding service's regular meetings, where the study's information sheet and consent forms were handed to the service users who expressed interest. The recruitment for Groups 4 and 5 was facilitated by the professionals running the service (participants of Study 2), who were responsible for distributing the related documents to the participants and confirming their eligibility to take part in the study. The focus group sessions were held at the premises of the corresponding service, between February 2018 and April 2018. The study was approved by the University of Glasgow College of Science and Engineering Ethics Committee in January 2018.

Procedure and Data Analysis

Each focus group session consisted of three parts. During the first part the participants took turns to introduce themselves to the group and were asked to briefly describe their brain injury and its effects, and the common difficulties they face in everyday life as a result of these effects. In the second part the participants described the tools and strategies they used to compensate for their cognitive deficits, and were asked to discuss the advantages and disadvantages of each

¹<http://www.wdhscp.org.uk/adults-with-disabilities/acquired-brain-injury/bien-group/> - Accessed: 11/5/2021

²<https://headwayglasgow.co.uk/about-us/> - Accessed: 11/5/2021

³<https://elepap.gr/en/meet-us/our-beneficiaries/adults/neuropsychology-and-brain-damage-rehabilitation-unit/> - Accessed: 11/5/2021

Participant	Group	Service	Age	Time of Injury	Cause of Injury
1	1	B.I.E.N.	62	1974 - 1983 - 2002 & 2007 2001	TBI Stroke Brain disease TBI TBI + Stroke TBI
2		B.I.E.N.	64		Stroke
3		B.I.E.N.	34		Brain disease
4		B.I.E.N.	50		TBI
5		B.I.E.N.	47		TBI + Stroke
6		B.I.E.N.	37		TBI
7	2	Headway	55	2005 2014 2003 2002 & 2010 2014 2015 2014-2015	Stroke
8		Headway	50		-
9		Headway	45		-
10		Headway	59		Stroke
11		Headway	50		TBI
12		Headway	64		Stroke
13		Headway	49		Stroke
14	3	Headway	28	2011 2011 -	Encephalitis
15		Headway	33		TBI
16		Headway	20		Brain disease
17	4	ELEPAP	35	2005 2006 2013 - - - -	TBI
18		ELEPAP	25		TBI
19		ELEPAP	51		Stroke
20		ELEPAP	57		Stroke
21		ELEPAP	38		Encephalitis
22		ELEPAP	46		Stroke
23		ELEPAP	50		Stroke
24	5	ELEPAP	25	- 2008 2012-2013 - 2013 1995	Heart attack
25		ELEPAP	29		TBI
26		ELEPAP	27		TBI
27		ELEPAP	30		-
28		ELEPAP	34		TBI
29		ELEPAP	51		TBI

Table 4.1: List of Participants of Focus Groups in Study 3.

presented aid. In the final part, Voice Assistant technology was presented to the participants through a short set of slides explaining its functionality. Then a Google Home⁴ device was introduced to the group, and the participants were encouraged to try it by performing some simple tasks, such as asking for the weather or setting an alarm. Finally, they were asked to provide their thoughts on how such a device could be beneficial to them in different contexts, and how they would compare it to previously described tools.

Audio and video recordings of the sessions were made and transcribed. The transcribed data were analysed using Deductive (theoretical) Thematic Analysis. Compared to the Inductive Thematic Analysis which was applied in Study 2, the deductive approach is driven by specific research objectives, searching for particular aspects of the data that address these objectives [23].

⁴[https://en.wikipedia.org/wiki/Google_Nest_\(smart_speakers\)](https://en.wikipedia.org/wiki/Google_Nest_(smart_speakers))Original Google Home

As in Study 2, the transcribing, coding and the deductive thematic analysis of the data were conducted by the author of this thesis. The framework for the deductive analysis was determined by the objectives of the chapter (Section 4.1) and the aims of this study (Section 4.3.1), as well as on the results from Study 2 and the findings from the literature review regarding the effects of ABI and the design of Assistive Technologies, to identify themes across the coded data that can inform the use and design of VAs. Specifically, the study aimed to further examine the effects of ABI and how these can affect the use of technology, and to further investigate the use of external aids by people with ABI. Therefore, the initial codes used to categorise the collected data were: 1) Physical effects of ABI; 2) Cognitive effects of ABI; 3) Difficulties in using external aids due to physical effects; 4) Difficulties in using external aids due to cognitive effects. The initial analysis generated the following codes, which were used to categorise the data based on the Chapter's objectives: 1) Difficulties in everyday life due to cognitive impairments; 2) Paper-based tools; 3) Technological aids; 4) Voice assistants. The new themes emerged from the deductive thematic analysis were: 1) Lack of independence; 2) Change in abilities; 3) Change in activities; 4) Use cases for Assistive Technologies. These results from the coding and the identified themes are presented and discussed below.

4.2.3 Results

Difficulties in Everyday Life due to Cognitive Impairments

The participants reported a variety of challenges in their daily lives resulting from different cognitive impairments, with difficulties related to poor memory functioning being the most common. Many participants mentioned issues with long-term memory, namely the inability to successfully memorise things they experienced after their injury:

"My memory is terrible. It's absolutely terrible. Give me 3 days and I will forget all about this [the study]. It's just the way it goes." (P2).

A frequently mentioned impact of poor long-term memory was the inability to learn and remember people's names. Participants reported considering this especially important because it could have negative social consequences. Similar consequences were associated with the inability to recall important information during social interactions, which, as participants mentioned, can make others perceive people with ABI as being ignorant. Poor prospective memory was another effect of ABI that was reported to result in difficulties, often preventing people from completing tasks they considered important, such as attending doctor appointments, taking medication or turning off the stove after cooking.

Participants' responses also indicated that successful remembering can be associated with

attention and concentration. For instance, if one is distracted while in the middle of a task, they are less likely to remember to complete it afterwards. On the other hand, if the person considers a task or a piece of information to be particularly important, they are more likely to pay attention to it and therefore remember it. Generally, however, concentration and attention were associated with difficulties in completing tasks, especially when the tasks are visually demanding.

Several of the reported issues were related to difficulties in processing new information and being able to think clearly. According to the participants, these effects can impact the ability to comprehend environmental cues, determine which information is relevant, as well as cause delayed reactions. These, in turn, can prevent people from being able to carry out mentally demanding activities, such as driving:

"There's a noise in your thinking. You are slower, your reactions are slower." (P8)

Apart from poor memory performance, participants also associated the inability to complete everyday activities with lack of initiation:

"It is very difficult for me to start doing things. And even if I do, I can't complete them. Even if I start something, usually after being prompted by other people, it's very difficult to complete it. Even if I know how to do it." (P26)

Several participants who reported experiencing a lack of initiation mentioned being sedentary even though they were aware that being active can lead to independence. The strategies that were reported to be helpful in these cases were having a well-defined schedule, being prompted by others and creating habits.

Some participants also mentioned their everyday functioning being impacted by poor organisation skills. This can impair the ability to make plans, and to identify the steps needed to be taken to carry out a task. Participants with such difficulties reported that writing tasks down and applying a strict schedule can help overcome such difficulties. However, poor time management was also reported as a factor that can prevent the completion of everyday activities, even when there is a schedule in place:

"At times I have a very bad sense of time. That means that things can get timetabled for me and structured, but I then take longer to do things, and everything gets queued." (P3)

Issues related to inappropriate behaviour were also frequently mentioned as obstacles to successful everyday functioning. As with memory, this was also considered especially problematic due to potential social consequences. Reports of inappropriate behaviour included being easily irritated, responding abruptly or being aggressive due to lack of patience. It was also reported that aggressiveness can sometimes be a result of increasing awareness of one's limitations after the injury. Inappropriate behaviour can sometimes be exacerbated by impaired communication

skills:

"Another issue is communication, either having difficulty understanding what people tell me, or expressing myself correctly. The result sometimes is to react abruptly. Sometimes I might become rude, because I misunderstand what others tell me" (P28)

Consequently, communication problems were reported to make people avoid social interactions, often leading to withdrawal and isolation.

Although some reported experiencing difficulties with one particular cognitive function, the majority of participants described problems associated with several cognitive impairments. Regardless of the combination, however, most participants agreed that cognitive difficulties often result in lack of self esteem. As with poor information processing, this was also mentioned as a factor that can prevent people from engaging in mentally demanding activities:

"I got my driver's license back a couple of years ago. I was worried. I kept thinking: 'I know I can do it physically, but can I do it mentally as well?' Maybe it's just the way you feel after the brain injury; that you're not on top of things. It's stressful." (P10)

Paper-Based Tools

The paper-based tools that were most commonly reported to be used by participants were the diary and the calendar. These were mostly used to support prospective memory performance (i.e. fulfilling future intentions) and scheduling. Additionally, some participants with long-term memory difficulties reported using a diary to keep a record of their experiences and accomplished tasks. Participants from Group 4 and Group 5, who were attending a rehabilitation programme at the time of the study, mentioned the use of diaries or notebooks as tools to support the rehabilitation process. This was most frequently done by writing down information from the rehabilitation sessions that they needed to remember, such as instructions for establishing routines and advice about how to improve their behaviour.

Several other strategies were also mentioned by the participants, the purpose of which was mainly to help remember important information at the correct time. They included post-it notes, carrying a piece of paper with notes in one's pocket, and writing things on one's arm. As was derived from the discussion between the participants, however, the use of these strategies can be rather limited:

-*"If I need to remember something I write it here [on their arm]. Sometimes I also write things down on a paper. Other people probably do it as well."* (P7)

-*"And what if you lose the paper?"* (P10)

-*"But how does that work if you have 2 or 3 things you need to remember?"* (P13)

- "I just stick to one thing at a time." (P7)

The group discussion also brought up ways that cognitive deficits can impact the efficient use of paper-based tools. Namely, in the case of diaries and calendars, it was reported that people with memory difficulties can: 1) forget to write things down on the diary or calendar; 2) forget to look at the tool at the appropriate time; 3) forget to take it with them when going out, or 4) forget where they placed it. Additionally, several participants reported that paper-based tools like diaries and calendars can be too complicated for them to use. This complexity referred to either being overwhelmed when having to read and process the written information, or finding it difficult to write things in a way that they would be able to understand later.

According to the participants, the use of paper-based tools can also be hindered by being unable to recognise their value, or by considering them unnecessary, usually due to not being fully aware of their own difficulties:

"I considered it [the calendar] unnecessary. That I didn't need it. But in the end I was in trouble. I could've done the things that I had set reminders for, and change the course of my everyday life; but I didn't, and now..." (P17)

Finally, some practical issues were also associated with the inefficient use of paper-based tools, such as finding writing too bothersome, and not wanting or being able to carry them all the time.

Technological Aids

Several participants reported using technological aids to support the performance of impaired cognitive functions, usually by receiving reminders. Smartphones were certainly the most popular devices among the users of technology, some of whom considered them essential for their everyday functioning:

"I use the [smartphone] calendar. I set an alarm for everything. Everything literally. Without it I'm completely lost, because I do not remember anything. I have to rely on my phone." (P25)

Apart from reminders, smartphones were also reported to be used for other purposes, which included navigation and communication. The latter referred to contacting family members in the case of emergencies, or being contacted by family members on a regular basis to confirm their well-being.

Other electronic devices were mentioned as aids, including personal computers for calendar management and note keeping, and electronic watches with alarm functionality. Three participants also reported using both paper-based tools (diary or calendar) and smartphones, to increase the chances of successfully remembering and completing tasks. When comparing smartphones

to other tools, participants reported the advantage of carrying it with them at all times, making the received reminders more efficient:

"For instance, there could be something that I have to do and have it written in the diary, but I might not read the diary early enough. By getting the reminder on my phone, I make sure that I do what I have to at the correct time." (P28)

Some participants reported being able to use technological aids efficiently without any problems. Others, however, described different challenges that can impact the devices' benefits. Similarly to paper-based tools, several of these challenges were related to poor memory functioning: forgetting to fulfil the intention after receiving the reminder, or not being able to recall what the reminder was about when they received it. It was also mentioned that memory difficulties can be an obstacle in learning how to use electronic devices, for those who did not know how to use them before their injury:

"I'm open with these things, you know? I can learn something new; I've done it a dozen times. But the next day it's gone. It's just totally gone." (P2)

However, it was also reported by some participants that even if they were familiar with a technological tool before their injury, they now often find it too complicated to use. For example, two participants (P7,P8) mentioned not being able to operate the self-checkout technology at supermarkets out of worry that they might make a mistake.

Another matter that was described as a factor that can obstruct the use of technology was physical impairments. These included vision problems such as double vision, not being able to see well when looking vertically, and optical agnosia. Most participants who mentioned these issues reported having difficulties when using devices with a screen. One participant (P7) mentioned using larger fonts on the phone as a solution. Another factor was motor impairments, which can prevent people from using their fingers to successfully operate an electronic device. Finally, some participants reported not wanting to use technology due to the fact that it is dependent on electricity and internet connection, or that it can replace communication between people.

Voice Assistants

When the Google Home device was presented to the groups, the general response of the participants was quite positive. Many reported being impressed by the technology's capabilities, and said that they could definitely benefit from having a device like it. When asked to try using the device, at first the participants approached the interaction in a playful way, and performed a variety of simple tasks such as internet queries, asking for the weather and setting reminders.

When discussing how a device like Google Home could be beneficial for people with ABI, many participants said that they would use it to set reminders for things that they consider important, such as taking their medication and medical appointments. Other ways of using it included to walk them through the steps of carrying out a task (e.g. making a meal) and to prompt them to exercise. One participant mentioned that he would use it to monitor his own well-being:

"I would definitely use it for recording every day how I'm feeling, or for when I'm feeling particularly low or frustrated." (P14)

Only two participants reported having experience in using VAs. P14 reported using Siri to control her smartphone to make calls and send text messages, which she found difficult to do otherwise due to motor impairments. P9 reported owning an Alexa device, which he found very helpful; he reported using for setting reminders, listening to music and shopping.

When asked to compare the VA to other technological tools, the majority of participants agreed that performing a task through speech seemed easier than doing it through the screen of a smartphone. An element of VAs that was described as an advantage was that they do not require visual engagement, something that would benefit people with impaired vision. Moreover, two participants with motor impairments reported that they would use it to control other electronic devices in their house. Finally, one participant (P10) argued that a smart speaker device like Google Home would be more helpful if it combined the speech interface with visual feedback, mentioning the example of using it as a guide for physiotherapy exercises. He also argued that a feature like that would enable people to carry out exercises at home, which they would otherwise neglect.

However, there were also some disadvantages of VAs that were pointed out by participants. The first was that they would not be suitable for people with speech impairments. This concern referred to either the VA not being able to recognise people with pronunciation difficulties, or not giving enough response time for people who have difficulty in finding the right words. The second disadvantage was about the lack of portability of smart speaker devices:

- *"This is good when you are staying in the house. But when you're out and about..." (P11)*
- *"Then it's no good. Definitely." (P7)*

Finally, the participants did not express any particular concerns when asked about the privacy and security of VAs. In contrast, many reported that they would feel comfortable receiving advice from, or sharing personal information with a VA, in the context of rehabilitation:

"I don't know if this makes me sound like a weirdo, but I would feel more comfortable maybe discussing those things with a piece of machine. I think if I was talking to a psychologist or something, I would think 'what happens if I say this'. Also, if they were someone nice-looking and young, I would try and act like everything was fine. So maybe that thing takes any kind of

acting off of it. I would be more comfortable talking to it than talking to a healthcare professional." P(14)

Other Themes

In addition to the categories of responses described above, the thematic analysis produced four themes related to the effects of ABI and the use of external aids. These themes emerged when investigating the collected data to determine factors that can address the two objectives of this chapter, namely to identify situations where VAs would be beneficial and what their purpose of use should be, and to identify factors that can inform the design of VAs.

1. Lack of Independence

A common theme across many of the responses was the reliance on other people. This referred to the participants' inability to carry out everyday activities without the help of others, or the inability to use external aids on their own. Regarding the former, the participants mentioned activities for which they considered memory performance to be crucial, such as cooking or shopping, or where there is a high demand for processing information, like going to the bank. The reported solution was either to do these tasks together with a family member, or to completely rely on a family member to do the task for them. Regarding external aids, some participants reported having to rely on the prompting of other people (family members or carers) to use them, or that other people were compensating for their poor cognitive functioning or physical impairments by helping them use the aids efficiently:

"My wife puts everything up on the calendar, because I forget. I'm checking the calendar every day to know where I'm going and all that." (P2)

Another way that participants reported depending on others was to provide them with cues and prompts in order to be active, in the case of lack of initiation. Finally, being more independent was described as a primary objective for many of the participants, especially those in Groups 4 and 5 who were in attending a rehabilitation programme at the time of the study.

2. Change in Abilities

Another matter that was seen often in the participants' responses was that cognitive performance can change over time. Several participants reported that cognitive difficulties related to memory, orientation and organisation were especially troublesome after the brain injury, but have improved with time, mostly thanks to rehabilitation:

"In the beginning, my memory was awful. But with time I'm starting to recover. At first the recovery was faster, but now it's slower." (P25)

Some participants associated the improvement in their everyday performance with gaining awareness of underlying cognitive difficulties, or with developing strategies to help them cope with their deficits.

Apart from consistently improving, it was also reported that cognitive functioning can differ from time to time, or depending on the situation. According to some participants, tiredness can impact the ability to process information or to produce speech efficiently. Furthermore, issues related to behaviour can be more prominent on certain occasions:

"I get annoyed sometimes, when people tell me what to do. But sometimes I'm all right. It's just the way things are going." (P2)

3. Change in Activities

Similarly to findings in Chapter 3, the data in this study also indicated a change in lifestyle for many people. Several participants reported not being able to work after their brain injury. Others reported not participating in social activities, either because they would find discussions too overwhelming, or due to cognitive difficulties that would hinder the interaction with others:

"I'm in a way lucky, because I'm not very social, so the occasions where it's necessary for me to remember something are not many. When I go out, I go by myself. Or I will go with someone who knows that I might forget things." (P17)

Moreover, lack of initiation was also a factor that was commonly reported to obstruct involvement in activities. Consequently, participating in more activities was the rehabilitation goal for many of the participants.

As mentioned above, some people's cognitive performance can improve over time. This was a factor that was reported to broaden the range of tasks that people can carry out. This positive change was also reported to be facilitated by the application of aids or strategies to support organisation, allowing the person to be involved in more activities. For instance, P22 reported being inactive after her ABI, due to significant difficulty in determining the steps required to complete a task. However, after consistently applying a specific problem-solving strategy as advised by rehabilitation experts, she was able to increase the number of activities that she could complete independently.

4. Use Cases for Assistive Technologies

The last theme that emerged was about use cases for technological aids that were identified in the participants' responses. These were either suggested directly by the participants as ideas of how technology can be beneficial to them, or drawn from descriptions of their rehabilitation goals and strategies.

The most commonly reported requirement was to receive prompts that support memory performance. Participants often mentioned the need to receive timely reminders that

would be dynamically adjusted based on the situation. For instance, two participants (P5,P8) reported that they often need to be reminded to lock the door at the moment they leave the house. Other participants mentioned a similar need for dynamic prompts like being reminded to turn off the oven if it's on for a long time, or being reminded to buy specific items when they are at the store:

"I often have problems remembering what shopping I need. I mean, you can take a shopping list, but what if you also forget that? So I was thinking what if you had something that could let you know as you get down to the shop? That might allow a bit more independence. I guess potentially it could know for example that you are on the vegetable isle, and tell you what you need. That would have been quite helpful for me. It would help with my concentration issue." (P14)

Similar use cases were mentioned that would require a dynamic way of prompting based on the situation, included receiving alerts regarding changes in the transportation schedule when commuting, or receiving prompts that would remind users to control their behaviour when they act inappropriately.

Another identified use case for ATs was note keeping and monitoring one's activity. Several participants who reported experiencing a lack of initiation said that they found it useful to write down their completed activities on a daily basis. This would help them determine whether they are being active enough or not, and that it is beneficial and motivating for them to realise the tasks they have accomplished. Similarly, participants with memory difficulties reported that the act of writing down the tasks they have to do helps to memorise them, and therefore increases the chances of accomplishing them.

Finally, when discussing the role of technology, some participants expressed the concern that over-reliance on technology could make one's brain "*lazy*", and that one "*needs to make the brain work*". Although this was communicated as an argument against using technological aids, it can also be regarded as a use case for AT. Specifically, several participants reported that they went through cognitive training during rehabilitation, often with the use of external aids, which helped them recover some of their impaired cognitive function. Similarly, participants with speech impairments reported doing speech exercises as part of a speech therapy programme, and two participants with optical agnosia reported doing reading exercises. Technological aids can be used to support the execution of such exercises.

4.2.4 Discussion

As described in Section 4.1, the objectives of this chapter are to 1) determine how VAs can be used to benefit people with ABI, and 2) investigate the usability of VAs for this particular

user group. Voice Assistants are a relatively new technology and as can be seen in the previous chapter, the number of people with ABI using VAs regularly is limited. Therefore, this study aimed to address the chapter's objectives by focusing instead on the impact of the effects of ABI in everyday life, and the use of other types of external aids by people with ABI. The corresponding gathered data can be used to derive information that informs the use and design of VAs. Furthermore, the participants' feedback on the idea of using VAs as aids, can provide additional information about how they can be used to benefit people with ABI.

Use of Voice Assistants

The participants in this study reported a wide range of cognitive effects of ABI, the most common of which included problems with memory, limited attention and concentration, difficulties with organisation, lack of initiation, lack of self-awareness and slow information processing. These effects were also identified in the literature review (Section 2.2.3), and in the results of Study 1 and Study 2. The prevalence of these issues indicates one of the main ways that technology in general, and VAs in particular, can be used to help people with ABI: to support the performance of the impaired cognitive functions. From the findings of this study, and the information provided by the professionals in Study 2, it can be concluded that the most effective way to support most of these functions is through prompting. Based on the results of this study, the purpose of the prompts depends on the cognitive function they aim to support and can therefore be: 1) to increase fulfilment of future intentions (prospective memory), 2) to increase task engagement and task completion (initiation, concentration and attention), 3) to notify or remind people of their inappropriate behaviour (lack of self-awareness), and 4) to provide a specific schedule or plan and promote habit formation (organisation). Several of these purposes were also identified in Study 2 (Table 3.4). The flexible Conversational User Interface of VAs, as well as their reminder and calendar functionality, can be utilised to provide all of these types of prompts, by adjusting the dialogue content based on the prompt's purpose.

Besides prompting, additional use purposes of technology can be derived from the different strategies described by participants, as well as from the reported ways of using external aids. One such purpose is to support long-term memory. The participants reported using paper-based tools to write down information, such as the outcome of rehabilitation sessions, advice from professionals, or events that occurred during the course of the day. They stated that this process can either help them learn that information, or allows them to review it at a later time. The functionality of Voice Assistants can be utilised for this purpose as well, facilitating the process of note-keeping through the development of appropriate speech-based applications. Similarly, VA applications can also be developed to facilitate self monitoring. According to participants in this study, keeping a record of one's level of activity can help them evaluate their progress.

Moreover, the professionals in Study 2 reported that monitoring the activity of the person with ABI can improve their motivation, and facilitate the rehabilitation process by providing valuable information to the therapists (also one of the identified use cases in Table 3.4). The CUI of VAs can simplify that process, allowing users to record their activity through hands-free, dialogue-based interactions.

Some participants reported having communication difficulties. Depending on their nature and severity, such difficulties could potentially affect the usability of a speech-based technology, and should be taken into consideration in the design process. However, the existence of communication problems in people with ABI can also inform the research question regarding the use of cases of VAs. Specifically, some participants reported undergoing speech therapy after their injury to overcome their communication difficulties, which typically includes different types of speech exercises. As discussed in Section 2.3.2 technology has been successfully used to support speech exercises for people with aphasia or apraxia of speech [124–126, 210]. The dialogue capabilities of VAs make them suitable for developing applications with speech exercises, which would allow people with ABI to train, in order to overcome their communication difficulties. Training methods are also being applied in brain injury rehabilitation for different purposes (e.g. to improve the use of compensation strategies [89, 191]). Additionally, the requirement for practising was highlighted by participants who expressed the need to "*train their brain*". Therefore, besides practising communication, VAs can also be used to develop other types of training applications that would benefit people with ABI.

The above findings inform the answer to the first research question of the thesis regarding the use cases of Voice Assistants (**RQ1**).

Design of Voice Assistants

Apart from ways that VAs can be used to benefit people with ABI, the results of this study can also inform the question regarding their usability. With regard to cognitive effects, poor memory was one of the most frequently reported factors that can impact the usability of external aids, in the following ways: 1) Users forget to use the tool; 2) Users forget to take the tool with them, or misplace it; 3) Users forget to carry out the task after receiving a reminder, or forget what the reminder was about. The first issue can be addressed by designing VA applications so that they do not rely on the user's initiative (also identified in Chapter 3, Table 3.5), or to provide unsolicited prompts which can encourage the use of the application [94]. The optimal way to convey a notification with minimal user action through a smart speaker needs to be examined. Regarding the second issue, VAs in the form of smart speakers have the advantage of allowing interaction from a distance, while placed at a fixed location in the house, thus eliminating the risk of being misplaced. This lack of portability, however, makes VA integration with other devices

(e.g. smartphones) a particularly important aspect of their UX that needs to be examined. Finally, regarding the third issue, the conversational capabilities of VAs can be utilised to increase the efficiency of reminders, by explaining the purpose of the prompts and using dialogues to confirm task completion. The way that this can be achieved, however, is another aspect of the interaction design of VAs that needs to be investigated.

The complexity of external aids was described by participants as another factor that can impact their use. This issue was also observed in Chapter 3 where it was discussed that ATs for people with ABI should be designed to be as simple and as straightforward as possible. Although the conversational UI of VAs allows for rich interactions, it should be taken into consideration that brief and concise dialogues might be more suitable for some users. The sense of complexity, however, might differ between a speech-operated system and tools that employ other modalities. Therefore, further examination is required to determine how people with ABI perceive the complexity of the interaction with a VA. Finally, physical impairments such as vision difficulties and reduced motor function were reported as potential obstacles to the usability of external aids. Regarding this issue, VAs can have an advantage over other tools, as they can provide hands-free and eyes-free interaction. However, the interaction with VAs on some devices (e.g. smartphones) is not always entirely speech-based [37, 104]. Moreover, some participants in the study argued that VAs could benefit from having a screen. Given the challenges that vision and touch-based interaction can introduce, it can be concluded that VA applications for people with ABI should not rely on the use of a screen, which should be employed as a complementary interaction method.

One of the themes that was identified from the thematic analysis was lack of independence, which was also prominent in the findings of Chapter 3. As discussed above, VAs could increase independence through efficient prompting that supports cognitive functions, and encourages task completion or participation in activities. Moreover, by taking into consideration the factors discussed above (e.g. memory demand, and reliance on user's initiative), appropriate design of VA applications may reduce the issues that make external aids difficult to use without the help of others. Another matter that emerged from the thematic analysis was the change in people's activities and abilities after the injury, but also during the course of rehabilitation. This issue further highlights the need for personalisation and adaptivity of AT that was discussed in Section 3.4. The option to customise the interface of a VA application as well as the type of support it provides, can ensure that the aid remains beneficial despite changes in the user's abilities or needs. Regarding adaptivity, the integration of VA applications with other services and devices can provide context awareness (e.g. user's location, concurrent use of other devices in the house, etc.) can allow the dynamic adjustment of a prompt's content, to increase its relevance and efficiency. Similarly, in the case of VA applications aiming to aid users with behaviour issues, the user's dialogue input could be automatically analysed to detect frustration or aggressiveness,

and adjust the prompts accordingly.

Although the participants' impression of Voice Assistants was rather positive, the number of people who reported having experience in using this technology was very small. Additionally, even though some of the functionality of VAs was demonstrated in the focus groups, most participants were unable to provide insights on how they could be used to benefit people with ABI, or how they would compare to other types of aids. This is likely due to the fact that the participants were not fully aware of the range of the technology's capabilities. Several participants stated that performing certain tasks through speech can be easier compared to other interaction methods. To confirm this hypothesis, and to identify potential unforeseen challenges that might emerge, it is necessary to further investigate the interaction between people with ABI and VAs.

The above findings identify potential obstacles to the interaction of people with ABI with VAs, and therefore inform the second research question of the thesis regarding the factors that can affect the usability of VAs (**RQ2**). Moreover, they identify areas to consider when examining the design of VAs, and will be examined in the subsequent Studies to answer the third research question of the thesis regarding ways to improve the usability of VAs (**RQ3**).

4.3 Study 4: Interviews with People with ABI who use Voice Assistants

4.3.1 Introduction

As described in Section 4.1, the first objective of this chapter is to determine the use cases of VAs for people with ABI. The previous section addressed this objective by identifying the users' needs, by investigating the use of other types of external aids, and by acquiring the participants' feedback on using VAs as aids. Although several ways that VAs can be helpful were reported, the majority of identified use cases can be regarded as ways that technology, in general, can be utilised to aid people with ABI and are therefore not specific to VAs. Moreover, the information acquired from the participants' feedback was rather limited due to their lack of experience interacting with the technology. This section further clarifies the role that VAs can play in the support of people with ABI, and how their use compares to that of other tools.

The second objective of the chapter is to investigate the usability of VAs. The previous section concluded that several factors may affect usability, and discussed how these can inform the design of VA applications. As with the first objective, this section aims to address this matter in a more direct way, acquiring information from people with ABI who have a better understanding of the functionality of VAs.

Specifically, this section describes Study 4, a set of online interviews with people with ABI ($N=10$) who use VAs on a regular basis. The interviews addressed the aforementioned goals by focusing on: 1) what the participants used VAs for; 2) how they compared VAs with other tools, and 3) what aspects of VAs they found particularly useful or problematic.

4.3.2 Method

Participants

The recruitment of participants was carried out through organisations that provide services for people with brain injuries in English speaking countries. The organisations listed in Section 3.2.2 were contacted via email and were asked to advertise the study and distribute the relevant documents to their clients who expressed their interest in participation by returning the signed consent form. The participants who responded were service-users of the following organisations: Headway, the Encephalitis Society and Stroke Association in the United Kingdom, the Brain Injury Network in the United States of America, and the Ontario Brain Injury Association in Canada. Details about the participants are reported in the next section (Table 4.2).

The interviews ($N=10$) were conducted online using Skype and Zoom software, depending on the participant's preference. The audio of the interviews was recorded to be transcribed and analysed. The transcribed data were anonymised. The interviews were carried out from October 2019, to July 2020. The study received approval from the University of Glasgow's Ethics committee in October 2019.

Interview Process

The duration of each interview was between 30 and 40 minutes. A semi-structured approach was applied, with predefined questions focusing on three major areas: 1) the participant's background, aiming to gather information related to their injury and its effects, as well as the types of cognitive aids or strategies they use; 2) the use of VAs, aiming to acquire information about how the participant uses VAs and how they experience the interaction with the specific technology, and 3) information that can inform ideas about potential features of VAs or applications that can benefit people with ABI. Apart from the predefined questions, follow-up questions based on the participants' responses were asked where deemed relevant.

Data Analysis

The transcribed data were analysed using Deductive (theoretical) Thematic Analysis [23]. The framework for the deductive analysis was determined by the objectives of the chapter (Section 4.1) and the aims of this study (Section 4.3.1). Specifically, the data were examined to identify elements that inform the research questions regarding the cases and the usability of Voice Assistants. The deductive thematic analysis was conducted by the author of the thesis. As in the previous Study, the initial coding was conducted using a framework based on the previous findings and the objectives of this Chapter. This study 4 aimed to acquire more detailed information regarding the use of VAs and other previously identified external aids and strategies, to determine the use cases of VAs for people with ABI. The initial codes used to analyse the data were: 1) Effects of ABI; 2) Use of external aids and strategies; 3) Use of Voice Assistants; 4) Comparison between VA and other external aids. The new themes that emerged from the analysis were: 1) Limitations of Voice Assistants; 2) Learning how to use VAs; 3) Privacy and Security; and 4) Design recommendations. Results initially categorised under the theme "Disadvantages of VAs" were later framed under the themes "Comparison between VAs and other aids" and "Limitations of VAs", as the initial theme was too broad, and it was deemed that the new themes would contribute more towards determining the use cases of Voice Assistants. Additionally, results initially framed under the themes "Discovering new features" and "Learning difficulties" were combined with other findings to create the larger theme "Learning how to use VAs", which highlighted learning as an important issue in the use of VAs by people with ABI, also examined in later studies.

4.3.3 Results

Effects of ABI

Table 4.2 shows demographic information about the participants. Their average age was 47.3 years (range: 25 to 71), and 5 out of 10 participants were female. The reported causes of brain injury were: TBI (n=3), stroke (n=3) and viral encephalitis (n=4). Regarding the physical effects of the ABI, four participants reported having reduced mobility issues, three participants reported suffering from chronic headaches, and two from chronic fatigue. When asked to describe the cognitive effects of their injury, most participants (n=9) mentioned issues related to poor memory performance. The majority of these issues referred to either forgetting to fulfil future intentions (prospective memory), or being unable to memorise recent events. Four participants reported having issues associated with executive function, such as poor planning and organisation skills, and two participants reported difficulties with information processing. Moreover, two participants reported having vision problems, two experienced cognitive fatigue,

and three mentioned speech related difficulties. One participant (P5) reported having physical impairments but no cognitive difficulties as a result of his ABI.

Regarding the impact of the cognitive effects of ABI on daily life, the participants' responses were analogous to those of Study 3, referring to: loss of independence due to having to rely on others to carry out everyday activities, forgetting to do things they consider important, being unable to carry out mentally demanding tasks such as working, and not participating in social activities such as group discussions.

Participant	Age	Gender	Time of Injury	Cause of Injury	Physical Effects	Impaired Cognitive Functions	Other ABI Effects	VAs Used	Frequency of VA Use	Other tools/strategies
1	31	Female	2016	TBI	Headaches, Dizziness	Memory (short-term, long-term, prospective), information processing, attention, concentration	Speech difficulties	Siri (phone)	High	Wall calendar, phone reminders,
2	25	Female	2013	TBI	Chronic migraine, chronic fatigue	Memory (short-term, long-term, prospective), scheduling, planning	Cognitive fatigue, depression, anxiety	Siri (phone), Google Home	High	Notebook, phone calendar, phone alarms/reminders, text-to-speech software
3	30	Male	2013	TBI	-	Memory (short-term & prospective)	-	Google Home, Google Assistant (phone)	High	Notebook, post-it notes, PC calendar, phone calendar & reminders
4	71	Male	2011	Stroke	Reduced mobility on right side (arm & leg)	-	-	Alexa (Echo)	Low	Mobility aids
5	62	Male	2016	Stroke	Unable to walk	Memory (short-term)	Cognitive fatigue, anxiety, depression	Alexa (Echo)	High	Phone calendar
6	69	Male	2018	Stroke	Left side weakness (arm & leg)	Memory (prospective), planning, executive functions	Partially sighted	Siri (phone), Alexa (Echo)	Medium	Timetable, phone calendar, wall calendar
7	38	Female	1998	Encephalitis	-	Memory (short-term), executive function, speech	Prosopagnosia	Google Assistant (phone), Alexa (Echo)	Low	Phone calendar, phone alarms/reminders, smartwatch
8	60	Female	2014	Encephalitis	Chronic fatigue	Memory (long-term, prospective)	Speech difficulties	Alexa (Echo), Smart TV	Low	Journal, phone timers/alarms
9	42	Female	2005	Encephalitis	-	Memory (short-term, prospective)	-	Alexa (Echo), Google Home	Medium	Wall calendar, white board, diary, phone calendar, phone reminders, Sat Nav (car), dictaphone
10	45	Male	2019	Encephalitis	Right side weakness (arm & leg), headaches	Memory(short-term, prospective), information processing	Speech difficulties	Google Assistant (phone), Alexa (Fire TV Stick)	Medium	Phone reminders, diary

Table 4.2: Demographic information of participants in Study 4. "-" signifies no reported effects in this category.

A theme identified in relation to the cognitive effects of ABI was that of change in cognitive performance and in the impact of cognitive impairments over time (also identified in Study 3). One of the areas where such a change was reported was speech performance. All three participants who mentioned having speech impairments (P1, P8 and P10) reported that the associated difficulties were more prominent during the time closer to their injury but improved significantly over time. Although speech difficulties still existed at the time of the study, the participants reported that they only caused problems occasionally, usually resulting in having to think longer before being able to verbalise their thoughts correctly. Another area where change was reported was memory performance. Four of the participants who reported memory difficulties mentioned that their memory at the time of the study had improved compared to the first few months or years after the ABI. Even after improvement, however, memory issues were described as more impactful than speech-related problems. Additionally, improvement over time was also reported in issues related to physical impairments. These improvements in cognitive and physical functioning were reported to increase self-reliance, allowing participants to accomplish tasks by themselves and to carry out activities that grant them independence, such as driving.

One of the main factors for improvement in cognitive performance was reported to be rehabilitation. The majority of participants mentioned that they went through a rehabilitation programme for a period after their injury, which usually consisted of a short inpatient phase at a hospital, and a longer, less intensive outpatient phase. These programmes included speech therapy, which participants associated with the improvement in their communication skills. Another factor that was associated with an improvement in cognitive functioning was the use of external aids and strategies. Although they were not reported to permanently improve cognitive capabilities, cognitive aids and strategies allowed participants to function more independently and accomplish more activities:

- *"Do you have to rely on other people to remind you to do things that you consider important?"*
- *"Since I've had three years of practice in this area, I've gotten actually really good at using strategies. So, no. I'm pretty good at being able to organise that myself now, as long as I keep up with my strategies." (P1)*

Use of External Aids and Strategies

The last column in Table 4.2 gives an overview of the external aids that participants reported using (besides Voice Assistants which are presented separately below). Seven of the participants reported using paper-based tools alongside technology, the most common being diaries, notebooks and wall calendars. The participants reported placing wall calendars usually in common areas of the house that they visit regularly (e.g. kitchen), and using them to organise their daily schedule and to note things that they need to remember. It was also reported that wall

calendars are often used in a collaborative way with family members or carers, who support the person with ABI by writing down their schedule or reminders. Notebooks and diaries were also reported to be used as memory and scheduling aids. Some participants also mentioned using them as self-monitoring tools to note down issues that happen to them during the day, which they would like to review at a later time. Compared to wall calendars, notebooks and diaries were reported to sometimes be used for more private or personal purposes.

Regarding electronic tools, smartphones were by far the most popular cognitive aid for participants ($n=9$). The most common use case for smartphones was to support prospective memory, either through the reminder functionality of calendar applications, or through labelled alarms. Some participants also mentioned using their phone's timers to help them stay on schedule. Also, two participants mentioned using a shared online calendar with family members and carers for reminders and scheduling purposes. Besides smartphones, other devices were also reported to be used occasionally as cognitive aids by some participants. Those included smartwatches and personal computers, utilising their calendar and reminding functionality to support cognitive function.

When asked to compare these two types of aids, the participants reported several reasons why they prefer paper-based tools over their technological equivalents. One such reason was trying to limit the time spent using technology in general, or as mentioned to "reduce screen time". Some physical effects of the injury like vision problems and headaches were also reported as reasons to reduce screen usage. Another justification for preferring paper-based tools, and particularly wall calendars, was that they offer easier collaboration between family members, which, in some cases can be rather complicated with electronic devices (e.g. in the case of smartphones from different manufacturers). Finally, some participants based their choice of using paper-based tools on simple preference (e.g. preferring the "feel" of pen and paper).

One of the most commonly reported advantages of smartphones over other tools was their portability. Most participants described them as something that they have with them at all times, in contrast with other tools which they use in specific occasions, or leave at home:

"For the first few years after the injury I did use an old fashioned pencil and paper notebook to keep track of stuff. The issue with that is that you leave it at places. There were times that I had put a note there that was important for my memory, and I left the notebook at home. So it became less useful for me. When I started learning, I thought "What do I have with me at all times?" and it was my phone. There's many different application, like cloud-based, that you can access from anywhere." (P3)

Participants reported being better at remembering to take their phone with them, compared to other tools, because they also need it for other essential tasks like communication. Some even mentioned applying different strategies when leaving the house to reduce the possibility

of leaving it behind. In general, however, poor memory performance was a factor associated with difficulties in using both types of aids. These difficulties were similar to the ones reported by participants in Study 3, and included forgetting to use the aid, or being unable to remember what the prompt/note is about. Regarding the latter, one participant (P7) mentioned applying a customisation strategy to increase the efficiency of smartphone reminders, which included colour coding of prompts and using appropriate wording. Finally, some participants described smartphones as generally easier to use as memory aids, compared to paper-based tools or other electronic devices like personal computers.

Use of Voice Assistants

The participants' responses regarding the use of Voice Assistants varied in terms of technologies and use cases, with several participants using multiple assistants on different devices (Table 4.2). Amazon's Alexa was used by seven of the participants, six of whom reported using it through smart speakers (Echo devices) and one through a portable video streaming device (Fire TV Stick⁵). Google's Assistant was used by six participants, two through a smart speaker (Google Home), two through their smartphones, and one (P3) through both methods. Three participants reported using Apple's Siri on their smartphones (iPhone). Furthermore, several of the smart speaker users reported owning more than one device, which they had placed in different rooms of their house.

The majority of participants (7/10) reported using VAs on a daily basis. Table 4.2 shows three different values for usage frequency: High frequency refers to using VAs multiple times a day, and for a variety of tasks; Medium frequency refers to regular use for one particular main task, and occasional use for additional tasks; Low frequency refers to occasional use, generally for entertainment purposes.

Five out of the seven participants who used VAs regularly (high and medium usage frequency) reported using them to set and receive reminders for everyday activities. For these participants, this was the feature of the VAs they used most often, and the one they found more helpful. The second most commonly reported use case after reminders was communication, which was mentioned by four participants. Communication related tasks included sending and receiving text messages, placing phone calls, and sending recorded voice messages between smart speaker devices (Alexa's announcement feature⁶). Three participants reported using VAs to set alarms and timers, which helped them to follow their schedule and supported memory performance. An equal number of participants mentioned using VAs for playing music, either through an integrated music streaming service or the radio. For these participants, music was the main task they

⁵<https://developer.amazon.com/apps-and-games/fire-tv> - Accessed: 11/5/2021

⁶<https://developer.amazon.com/en-US/docs/alexa/acm/announcements-acm.html> - Accessed: 11/5/2021

used VAs for. Another common task was to control smart devices in the house such as lights and robot vacuum cleaners. This was described as a particularly important feature for participants with mobility difficulties. Additionally, several participants reported occasionally using VAs to perform online queries. These included asking about the weather, asking for information about local services, and getting answers for general knowledge questions. Two participants (P3 and P10) reported utilising the routine functionality of VAs, which enables users to programme the assistant to perform a series of actions with a single command⁷. Other, less commonly reported VA tasks included managing one's calendar to support scheduling and organisation, keeping notes and managing shopping lists to support memory performance, using text-to-speech to read books, and playing movies on television.

Participants reported accessing VAs both through smartphones and smart speaker devices. Several of the tasks described above, such as setting reminders and alarms, were carried out using both types of devices. There were, however, some tasks that were performed exclusively with one type of device. Specifically, participants who used VAs to listen to music reported doing so only with smart speakers. Smart speakers were also the only type of device that was reported to be used collaboratively between family members (e.g. using the announcement feature, or to set reminders for other family members). The most common VA tasks that were exclusively reported to be carried out through smartphones were the ones associated with the telephone's functionality, such as sending text messages and placing phone calls. However, setting reminders with a VA through a smartphone was also reported to serve a different purpose for some participants:

- *"Do you use the assistant differently on the phone compared to the smart speaker device?"*
- *"Yes, a little bit. I've thought of all the occurrences where I've used that [through the phone] and it's almost always "remind when I get to work" and things like that. It's more like when I'm on the go and I can't think, I can't stop. I just want to remember something immediately when I'm e.g. walking out the door and I won't be at a good spot to look at my calendar." (P3)*

Comparison Between Voice Assistants and Other Aids

The participants generally described VAs as helpful tools and, especially the ones using them more frequently, regarded them as essential for their everyday functioning:

- *"Do you use the voice assistant on your phone?" - "Oh yes. Me and Siri are best friends." (P1)*

When asked to compare VAs to other types of aids and explain the reasons why they preferred to use a particular type of aid over another, the participants reported several benefits in using

⁷<https://support.google.com/googlenest/answer/7029585?co=GENIE.Platform%3DAndroid&hl=en> - Accessed: 11/5/2021

a Voice Assistant. A commonly reported benefit was the speed of interaction. According to several participants, performing some tasks through the speech interface of a VA consists of less steps and is significantly faster than on a device with a screen. It was reported that this quick interaction allows users to perform tasks immediately, without having to remember to do them later, something that would increase memory load and therefore reduce the possibility of completing the task. Besides being quick, the interaction with VAs was also generally characterised as simple and convenient. Simplicity was also associated with being able to avoid using mobile or desktop applications, which several participants described as complicated and overwhelming, and in the case of playing media (music or video) with being able to accomplish the task with a single utterance, without having to search through long lists of available options:

"At the moment I find Alexa easier. I've got Spotify on my phone but again I find it confusing because the range of available music for me to scroll through is mind boggling. It's hard. It's like trying to get from A to B but there are all these side roads and you don't know which way to turn when. With technology I just get lost, it's like being in a maze. Because you can make a decision and go down one route, but then decide that's wrong you need to go back. But I can't remember how to get back. With the Alexa it's easier because you just talk to it." (P8)

Furthermore, several participants reported that what makes VAs more convenient to use is the fact that they do not have to type, which in some cases, and especially in devices with a touch-screen, can be tedious and cumbersome.

Another reported benefit of Voice Assistants was accessibility. This was especially important for participants who reported having vision impairments, which would make a device with a screen difficult to use, and for those with impaired motor function. Accessibility referred either to using applications and services that are commonly provided by smartphones and computers, but also to operating other devices in the house which can be controlled through VAs. Other benefits of the VAs' speech-only interaction mentioned by participants included having to rely less on using the phone, which was considered positive due to the reasons related to reducing "screen time" discussed above, and offering the ability for collaborative interaction with other people in the house.

Besides the different benefits of VAs, however, several participants mentioned advantages of visual interaction that constitute reasons for not choosing to use a VA for certain tasks. One such advantage is related to the feedback that is conveyed to the users when receiving reminders and prompts. Some participants mentioned that they are more likely to remember something when they see it written:

I would say that I much prefer visual feedback than audible feedback. The feedback that I get through the Google Assistant that is audible is not usually things that I would need to remember for a long time. It's more like instant information that I requested or something. If I ask it to

give me my reminders, it's going to be things that will also be in my calendar for me to check if I have to. Reading it [the reminder] off to me through the google assistant is something that I wouldn't love. I would understand it for that one instant, and then it may be on the top of my mind for a little while. But then other things come about. If it's not logged somewhere where once I have a bit of free time I can go do those tasks I will forget about it. (P3)

Although the quick and short interaction with VAs was described as beneficial by many participants, there were some who viewed it as a disadvantage. Specifically, one participant (P9) reported that the fact that performing a task like setting a reminder through a smartphone requires additional steps to complete gives the activity more importance, and therefore increases the chances of it being memorised. Similarly, another participant mentioned that not having to complete the task "in one go" offers the possibility to complete it at their own pace:

"It's stored on the phone so when I go away from it, it's still there, half processed so I can finish it off later. When with the VAs you can't do that." (P7)

Another reported advantage of visual interaction offered by smartphones was in the way that notifications are conveyed to the user. Participants mentioned that critical notifications and reminders delivered through a smart speaker can be missed if the user is not within the required range from the device, while in the case of smartphones the notification will remain on the screen until dismissed. Finally, some participants reported not choosing VAs for calendar management because they were already using a specific calendar software, which is either incompatible with VAs, or too complicated to integrate.

The advantages of VAs and tools that offer visual interaction such as smartphones, however, do not necessarily make one type generally more preferable than the other, but rather more suitable to use in different contexts. One factor that seemed to determine which tool to use for a specific task is the user's location:

"I don't think it [VA] would replace the phone, or the computer, or the paper-based tools, just be alongside it. It might have something to do with its mobility and the fact that the mobile phone is in my back pocket and when I go out of the house it's still there. Whereas Alexa, I've only got one in the lounge and I have to be within ear shot, in my lounge"" (P9)

Several participants reported using both smart speakers and smartphones in combination to carry out certain tasks. For instance, one participant (P5) mentioned using an Echo (Alexa) device to add items to their shopping list through speech, then using the smartphone application to view the list when shopping at the store. Furthermore, the two participants who reported using the routine feature used the mobile application to create the routines, which were then delivered through the smart speaker. Similarly, another participant (P1) reported using a VA to send "one-off" text messages, but switching to the smartphone when texting with someone for a

longer time.

Limitations of Voice Assistants

The advantages of other tools over Voice Assistants and *vice versa*, can help to determine the suitability of the latter as cognitive aids in different contexts. Additionally, the thematic analysis revealed several factors that can impact the technology's usability, which can also help to determine their suitability and inform their design.

The most commonly reported issues in the interaction with VAs were related to speech recognition. As participants described, VAs occasionally fail to accurately recognise what the user is saying, which can result in being unable to complete the desired task, inserting the wrong information, or receiving false information from the VA. Some participants (n=3) reported such issues to be more frequent when the user speaks in a less common accent, or when the user's query contains names or addresses. Inputting the wrong information when creating a reminder can be particularly problematic for users with memory difficulties who, as they discussed, may not remember what the reminder is about when they receive it and will have to trust it as correct. Although participants reported that speech recognition errors can be frustrating, they did not regard them as reasons for not using VAs. Many reported applying certain strategies to overcome them, such as speaking more slowly and clearly, slightly changing their accent or rephrasing the query:

"We occasionally have speech recognition issues, but it's easy to correct it. You shut it down and start again. It's not really a problem, just a slight irritation" (P4)

Furthermore, some participants mentioned noticing that their VA got better at understanding their voice after a few months of use. Finally, the reported frequency and impact of speech recognition errors did not seem to differ for participants who mentioned having a speech impairment.

One aspect of VAs that participants with speech difficulties found more troublesome was their timing, i.e. the amount of time that the technology gives to the users to complete their query or respond to a question. Two participants who reported this issue also mentioned that it can happen more often when they are tired. According to some participants, however, experience of use can improve the efficiency of interaction, and help to develop strategies to overcome such issues:

"You really have to know what you're going to say before you say it. You can't like say "Hey Google" and then think about what you're going to say for a second. It's a little bit awkward but once you've learned how to do that it goes pretty quickly. There's a learning curve." (P3)

However, this strategy might not be feasible for some users. Specifically, one participant mentioned that having to give all the required information to complete a task in one sentence is too mentally demanding and often feels overwhelming.

As mentioned earlier, participants commented negatively on the VAs' lack of portability, which was reported to be a potential cause for missed reminders and notifications. A similar reported issue was the VAs' dependence on internet connection. As some participants stated, VAs cannot be used to perform any tasks if there is a disruption in the internet connection, which can hinder their reliability as prompting aids.

Other issues that can affect the overall experience of interacting with a VA reported by some participants were: complexity in setting up integration with third party services and applications, unwanted activation (either due to the user unintentionally saying the trigger phrase, or for no apparent reason), sounding too "robotic" when reading text, and occasionally responding with too much information

Learning How to Use Voice Assistants

The majority of participants used VAs for a limited number of tasks. Even the ones who reported relying on VAs very often (high frequency of use in Table 4.2) took advantage of only a few functions, compared to the wide range of available functionality that the technology offers. Two participants (P2 and P3) reported that the frequency with which they are using VAs has increased over time, as they discovered more ways that they can benefit from them. The other eight, however, reported that the way they use VAs has not changed after their injury. Additional questions were asked to participants during the interview to find out why they did not make use of other functionalities that VAs can provide, even though they reported being generally satisfied by the technology. The thematic analysis identified the theme of learning how to use VAs in the participants' responses.

When participants were asked to explain why they have not replaced other external aids with VAs for carrying out certain tasks like setting reminders or managing their calendar, some reported that it was due to habit mainly formed in rehabilitation, during which they were instructed to use specific tools (mostly notebooks and diaries). Others, however, stated that they were simply unaware that the VAs could support such tasks. Follow up questions investigated if and how participants search for and discover VA features that are unknown to them. Three participants (P2, P3 & P5) said that they were actively looking for new features, in order to discover additional ways that they can benefit from VAs. The reported methods for accomplishing that included subscribing to related email newsletters with updates in features and functionality, searching on the manufacturer's website, reading relevant posts on social media, and learning

from the way other people use VAs.

The majority of participants (7/10), however, reported that they do not actively try to learn for alternative ways to use VAs or for new features. This was generally not because participants believed that there are no additional ways that VAs can benefit them. On the contrary, many acknowledged that they are not taking full advantage of what the technology has to offer:

"I don't look for new features etc. I realise that I'm missing out on potential stuff. If I had the opportunity to have a guide that it could tell me what I can get in a plain simple language. I don't know where I can find that. But to be fair I don't look." (P4)

Regarding the reasons why these participants did not try to learn additional ways that they can use VAs, even though they knew they can be beneficial to them, the most common response was that doing so would be difficult. Specifically, it was reported by some participants that searching for relevant information online can be too mentally demanding, and that trying to learn how to use a new technology would require to understand technical terminology which can be complicated. Participants also reported that memory problems can make the learning process more troublesome, making it difficult to memorise the required information or forgetting how to use the technology if they do not practice using it regularly. Furthermore, some participants stated that they do not have the required energy to actively search for the information required to learn how to use Voice Assistants, due to their injury-induced chronic fatigue:

"I wouldn't have had a second thought about trying to do these things beforehand. You can figure everything out and get through it, can't you? But not now, because I get lost, trying to work it out, and then become overwhelmed with fatigue and then you have to start from the beginning again next time. It's easier to give up and just do with what you've got." (P8)

Many participants reported that the reason why they started using a specific tool (smartphone or VA) was the encouragement from another person, usually a family member. Also, according to the participants, the most efficient way to learn how to use a new technology, in general, is to be taught by someone else. However, that is sometimes not possible as support from others is not always available. Moreover, some participants mentioned that they do not want to constantly ask for help from others, out of fear of becoming a burden to them.

"My husband set [Alexa] up. It's also frustrating. Again, I know that I need these technologies. I mean, in modern life you can't live without it. But I can't manage it. If ever I didn't have my husband to help me with this stuff I'd be completely stuck. [...] It's also, when you need to have to keep asking people... It's not so much embarrassing but, you know, I don't like bothering other people." (P8)

Privacy and Security

Three of the identified purposes of AT for people with ABI in Chapter 3 (Table 3.4) were to: 1) Facilitate communication between family members/carers and people with ABI, to improve support and reduce conflicts; 2) Facilitate collaboration between family members/carers and therapists to improve monitoring, assessment and support, and 3) Support engagement to the rehabilitation process by increasing motivation through goal completion. In order to use VAs for any of these purposes, it would potentially require using the technology to collect and share personal information, or to convey rehabilitation-related advice and prompts. As discussed in Section 2.4.3, users of Voice Assistants often express privacy and security concerns, which could impact their use in the aforementioned contexts. Moreover, the interviewed professionals in Study 2 reported that trust was an important factor in order for support to be effective. This study examined whether these concerns are prevalent in people with ABI, in order to determine if VAs would be an appropriate tool to use in these contexts.

When asked about privacy concerns, some participants reported being aware of risks related to personal data use, and expressed the view that the technology manufacturers are not always forthright about what data are collected, and how the collected data are being used. However, the majority of these participants also reported that these concerns are not serious enough to prevent them from using VAs, and that their trust in the technology has increased after using it for a long time and benefiting from it. Moreover, some participants believed that the types of data that can be collected through a Voice Assistant are not different to what is already being collected through other devices such as smartphones. Moreover, the majority of the participants reported that there are no personal information that VAs could collect which they would want to withhold:

"I understand the sensitivity, but I wouldn't say that I have anything worth hiding. Google knows pretty much everything there is to know about me, and I don't really have anything that I don't want people to know.." (P3)

All of the participants stated that they would be willing to share information about their mental or physical health through a VA, in the context of rehabilitation. Specifically, they reported that they would not consider the shared information to be too sensitive, and that they would trust the medical or rehabilitation professionals to handle their data appropriately. Furthermore, some expressed the view that the shared information would be similar to what is already stored electronically on medical records. However, some participants reported that they would be more comfortable sharing such information if they were provided with some sort of assurance on how that information would be used.

Similarly, most participants reported that they wouldn't have any privacy or security concerns

about receiving advice related to their rehabilitation or personal health and well-being through a VA. Some, however, were doubtful whether the advice provided in such manner would be trustworthy:

"It would be kind of weird because it wouldn't be able to understand what you're going through, it would be just an automatic reply. They can't convey emotion back to you because they lack empathy." (P2)

Some participants reported that, although they understood the benefit of using a VA to support remote rehabilitation, they would feel more comfortable discussing with professionals face-to-face. They, however, expressed the view that while VAs could not replace face-to-face sessions, they could be used to facilitate the process by collecting information about their progress before the actual session.

One situation where privacy could be an obstacle, when it comes to using VAs for rehabilitation purposes, was when they are used in public or semi-public areas. Although participants generally stated that they wouldn't feel embarrassed speaking to a VA in the presence of other people, there can be potential issues when others are able to hear the information that is conveyed to the user through the VA. Specifically, some participants mentioned that rehabilitation-related advice can sometimes be considered personal and would therefore feel embarrassed others can hear it. Moreover, one participants expressed the concern that if voice prompts are received frequently they can be annoying to others who can hear them.

Design Recommendations

The last theme that was identified in the participants' responses was recommendations about the design of VAs and the development of VA applications. These were either reported as improvements that the participants would like to see in the technology, or ideas about VA applications that can benefit people with ABI.

Some participants stated that the interaction with a VA should be personalisable, based on the user's needs and abilities, referring either to the way users insert information, or to the way the VA conveys information to the users:

"For example if you could change the way that it listens to you, or if you could change the response rate, for example make it slower, or speed it up. Whatever is easier for you. Maybe customisable features for every individual." (P2)

Moreover, one participant (P4) suggested that the VA should be able to recognise the voice of the person talking to it to support use from multiple users, and adjust its functioning accordingly

when the person with ABI is the current user⁸.

Several participants referred to the need for being taught how to use VAs. The suggested ways that this could happen included having a guide written in simple language that presents the main features that can be beneficial to people with ABI and explains how to use them, or receiving guidance by another person. It was also reported that getting to know how to use VAs can lead to understanding their potential benefits, which is essential to motivate people to spend the required effort:

"You need to be able to know what the benefits are for you. Because once you know the benefits, you can put effort into using it. Probably I can adapt with the right support, but obviously I choose what to adapt to." (P7)

Some participants also suggested additional ways that VAs can be used to benefit people with ABI. One such way was to facilitate communication, including supporting the exchange of voice messages between the person with ABI and their family or therapists, or between brain injury survivors who are users of the same service. According to participants, this could benefit people with communication difficulties, enabling them participate in social interactions, but also could provide a more accessible way of communication, when other methods are more challenging due to physical and cognitive impairments. Additionally, it was suggested that VAs could be used to benefit people with Aphasia, by allowing them to practice speaking and improve their communication skills.

Another beneficial use could be to increase their motivation and encourage ABI survivors to become active, through suitable prompting:

"Some of the survivors I've spoken to at the encephalitis society, some of them are very much "couch potatoes". Basically they are very sedentary, they stay at the same place all day, they don't leave their home and their sofa. Maybe some of those people could be persuaded to do more exercise, be more physically active. Maybe they should have reminders that it's worth putting on their trainers and stepping outside. Give them a nudge." (P9)

However, it was mentioned that, in order to have the desired effect and not become annoying, the prompts should be conveyed in a polite and supportive way, and their content should be tailored to the individual's disposition. According to participants, the latter can be achieved with the contribution of a family member or a carer.

⁸The "voice match" functionality is supported by current Voice Assistant technology.

4.3.4 Summary

The section presented Study 4, a set of online interviews with participants with ABI who use VAs on a regular basis. The study examined how the participants used VAs and how their use compared to that of other tools, identifying the factors that affect their effective use.

The difficulties induced by the effects of the injury reported by the participants were, for the most part, the same as the ones identified in the previous studies. Namely these were problems with memory, executive dysfunction, slow information processing, pathological fatigue, limited mobility and impaired vision. Some participants also mentioned speech difficulties, which, however, had reduced over time. The impact of other deficits was also, in some cases, reported to reduce over time, mostly due to rehabilitation and the use of strategies.

Participants used both paper-based tools and electronic devices (mainly smartphones) to support their cognitive functioning. Voice Assistants were reported to be used through smart speakers and smartphones for a variety of tasks, the most common of which were setting reminders for upcoming events, communicating with other people, setting alarms or timers, controlling smart devices in the house, searching for information online, and listening to music. Different advantages and disadvantages were associated with the three types of aids (paper-based, smartphones, and VAs), which can make each type more suitable to use in different contexts. Voice Assistants were reported to enable users to complete certain tasks more quickly, and their eyes-free and hands-free interaction was described as simple and convenient, offering increased accessibility. On the other hand, the fast, non-visual interaction can make conveyed information harder to memorise, and the smart-speakers' lack of portability can decrease the efficacy of prompts.

The most common issues with VAs that participants mentioned were related to poor speech recognition, which, however can improve with time and was not regarded as an obstacle preventing their use. Another identified issue was the lack of knowledge of the technology's capabilities, mainly due to difficulties in discovering and learning additional features. Regarding privacy and security, although the participants expressed some concerns, they reported that they would be willing to share personal information through a VA for rehabilitation purposes. Privacy, however, can become an issue when using VAs to receive prompts containing sensitive personal information, if these can be heard by other people.

Finally, the participants discussed how VAs can be used or be improved to better support people with ABI. Regarding their design, suggestions included being able to personalise the way that VAs receive or convey information, automatically adjusting their functioning depending on who is using them, and offering guidance to users on how they can be used. Regarding their application, it was suggested that VAs can be used to facilitate communication between the user and their carer/therapist, or other brain injury survivors, and to increase motivation for people

who remain inactive.

4.4 Discussion

Use Cases of Voice Assistants

The studies by Ammari *et al.* [6] and Dubiel *et al.* [55] investigating the use of Voice Assistants in healthy users found that the most common tasks were: searching for information, listening to music, controlling other devices in the house, and asking for jokes. The most common task among Study 4 participants, however, was setting reminders. Although this was one of the common use cases of VAs in people with visual impairments, as reported by Abdolrahmani and colleagues [1], that was not the case among healthy users. The study with visually-impaired users also reports sending messages and placing phone calls as common tasks, which was also the case in participants of Studies 3 and 4 who mentioned having difficulties with using a screen or with typing. Otherwise, the findings of this chapter regarding how people with ABI use VAs are comparable to those examining their use in other user groups [1, 6, 37, 55], with only a small portion of their available functionalities being used regularly.

Besides how people with ABI use them, the ways that VAs can be beneficial can also be determined by identifying the users' needs. The impaired cognitive functions reported by the participants in both studies described in this Chapter were analogous to those identified in Chapters 2 and 3, including prospective and short-term memory, organisation, attention, concentration, initiation and processing of information. As discussed in Section 4.2.4, VAs can be used to support the performance of most of these functions by providing timely prompts. Another way that prompting can benefit people with ABI, as identified in Chapter 3, is to increase awareness of inappropriate behaviour. This was also reported as a reason for using external aids by participants in Study 3. Although participants of Study 4 reported using VAs for reminders, alarms and timers to support memory, organisation, attention and concentration, none of them mentioned having issues related to inappropriate behaviour, and therefore did not use VAs for this purpose. VAs could be used to provide prompts to help with behaviour issues, by reminding them of rehabilitation practices to control their behaviour. However, in the situation where these issues coexist with lack of self-awareness (which was found to be a possible case in Study 2) the setting of the prompts would likely require the help of other people (e.g. family member, carer or therapist).

Apart from prompting, VAs can also be used to support the performance of cognitive functions in different ways. One such way is through note taking, to support long-term memory. Although this use case was discussed in Section 4.2.4, the findings from Study 4 indicate that

using VAs for this purpose would require taking privacy concerns into consideration, especially if doing so would require sharing personal information in public, e.g. to store autobiographical memories in a way similar to SenseCam [17]. Section 4.2.4 also discussed the possibility of using VAs to facilitate communication, by enabling users with communication difficulties to practice speaking. The findings of Study 4, regarding participants using VAs to send text or voice messages and to place phone calls, and the related recommendations given by some participants, reinforce the argument that VAs can be beneficial in the context of communication, acting as a medium between the person with ABI and their carer or family, but also between brain injury survivors. Moreover, besides being used to practice communication skills, VAs could also be used to provide speech-based cognitive exercises, as is indicated by the participants' requirements and recommendations in Studies 3 and 4.

The findings of Study 3 identified several ways that the cognitive and physical effects of ABI can hinder the usability of external aids. The reports from participants of Study 4 that the eyes-free and hands-free interface of VAs can make the completion of certain tasks simpler and more convenient, in addition to the reported issues related to typing and using a screen, reinforce the assertion made earlier in the thesis that VAs can increase accessibility to different services. This is also indicated by the fact that participants used VAs to control other devices in the house, which would be difficult to control otherwise. Therefore, VA applications could provide an alternative interaction method for some tools and services that people with ABI are currently using as cognitive aids, to increase their accessibility and bypass some of the barriers induced by cognitive and physical deficits.

Section 3.4 presented different ways that Assistive Technologies can be used to support the rehabilitation process, namely by facilitating communication between people with ABI and carers or therapists, and by increasing adherence to rehabilitation goals. Moreover, although the use of VAs might not be enough to replace face-to-face rehabilitation and therapy sessions (as reported by participants of Study 4), they can be used to monitor user progress and assess performance, thus facilitating the rehabilitation process. As discussed earlier, using VAs for these purposes could require the manipulation of personal and/or sensitive information, and therefore privacy and security concerns, which are prevalent among users of VAs [1, 6, 37] could become potential obstacles. The findings of Studies 3 & 4, however, indicate that, if there is proper assurance of how the data are being used and appropriate measures are taken to avoid conveying personal information in public, the privacy and security concerns should not prevent people with ABI from sharing personal information through VA applications that support the rehabilitation process. Another matter that needs to be taken into consideration when examining the use of VAs to support rehabilitation is the phase of recovery the user is in. According to related literature [187], there are three main phases in the brain injury recovery: the acute phase (typically within 3 months from the injury), the subacute phase (between 3 and 6 months), and the chronic

phase (more than 6 months from the injury), with the rehabilitation in each phase being carried out in different contexts (hospital care, inpatient, outpatient), and having different goals. Additionally, as found in Study 4, the cognitive functioning of brain injury survivors can change significantly from one recovery phase to another. Therefore, the application of VAs should be aimed at a specific rehabilitation phase, or support the change in the user's cognitive abilities and rehabilitation goals when transitioning from one phase to the next.

The findings from all four studies show that people with ABI use a variety of tools and strategies, which have certain advantages and can serve different purposes depending on the context of use. For instance, the mobility of smartphones provides reliable access to prompts and communication regardless of the user's location, while paper-based tools offer more privacy and easy collaboration with family members. Additionally, participants reported using certain tools efficiently and effectively due to training they had received by professionals during rehabilitation, which they no longer had access to. Therefore, although Voice Assistants could be used to replace other tools in some situations, when examining their use cases for people with ABI it would be valuable to consider their use alongside other external aids or strategies. The purpose of VAs in that context could be: 1) to complement the use of other tools by expanding their functionality or compensating for their shortcomings; 2) to support or encourage the consistent use of other tools through prompting; 3) to provide an alternative interaction method for controlling other electronic aids. In the case that a VA application is designed to complement other software applications, it is imperative that they provide effortless integration with the existing platform or service, as this is a matter that was reported to be problematic by some participants.

Table 3.4 in Section 3.4 presented an initial list of general use cases for Assistive Technologies for people with ABI, which were based on the analysis of the findings from Studies 1 and 2, and the review of the related literature in Chapter 2. The findings from the two studies described in this chapter introduced additional information, which was analysed to determine how Voice Assistants can be used to benefit people with ABI. Table 4.3 presents a comprehensive list of specific use cases of VAs for people with ABI, based on the analysis of the results from Studies 1-4.

Usability of Voice Assistants

As mentioned in Chapter 1, according to Nielsen [152], there are five components that determine the usability of a system: *learnability* (how easy the system is to learn), *efficiency* (being able to use the system efficiently to achieve maximum productivity), *memorability* (how easy it is to remember how to use after a certain period), *errors* (number of errors made and easiness of recovery), and *satisfaction* (pleasant to use). The findings of the four studies so far have shown several factors that can impact these usability components, and potentially preventing people

Targeted Area	Use Cases
Prospective memory	Reminders, alarms and timers to remind users of upcoming tasks and events
Organisation	Calendar management, reminders, speech-based applications for applying problem solving strategies
Long term memory	Note taking, storing autobiographical memories, self monitoring
Inappropriate behaviour	Prompts to notify users when behaving inappropriately, reminders for relevant rehabilitation strategies
Initiation and motivation	Prompts to encourage activity, self-monitoring and rewards
Communication	Speaking practice and exercises, send/receive messages to/from carers, family members, therapists and other ABI survivors
Cognitive training	Speech-based cognitive rehabilitation exercises
Support from carers/family	Convey messages indirectly from carers/family, to reduce conflict and increase sense of self-dependence
Assessment	Monitor task completion and gather data to inform rehabilitation and therapy sessions
Accessibility of external aids	Provide alternative speech-based interaction method for currently used external aids
Efficiency of external aids	Encourage and facilitate use of other external aids

Table 4.3: Use cases of Voice Assistants for people with ABI.

with ABI from benefiting from the use of Voice Assistants. These factors were identified either indirectly by examining the effects of ABI and the reported difficulties with other tools (Studies 1, 2 & 3), or directly by investigating the use of VAs (Studies 3 & 4). The different factors are discussed below.

- 1. Memory:** As mentioned earlier, there are different ways that poor memory can impact the use of external aids, some of which also apply to Voice Assistants. Specifically, poor memory performance could result in users forgetting to use the device or, in the case of reminders, failing to carry out the task after receiving the prompt or not being able to remember what the reminder is about. Additionally, the results of Study 4 showed that memory difficulties can make learning how to use a new technology more challeng-

ing, and that the quick and non-visual interaction of VAs can make conveyed information harder to memorise. Section 4.2.4 discussed that some of these issues could be overcome by providing prompts in an unsolicited manner, and with the appropriate content. This approach, as well as different ways to make conveyed easier to process and retain will be examined in the subsequent Chapters.

2. **Complexity:** The findings of studies 1, 3 and 4 indicate that both paper-based and technological tools can be too mentally demanding for users with cognitive difficulties, depending on the extent of the user's impairment and the task they are being used for. Additionally, the professionals who participated in Study 2 highlighted that simple assistive tools are essential in order to be used effectively. Although the interaction with VAs was generally described as simple and convenient, the majority of participants used them for simple tasks, and some reported preferring to use different methods for tasks that require longer interaction (e.g. text messaging for a longer time, creating VA routines). Furthermore, other aspects associated with the UX of VAs were described as complex, such as setting them up, managing integration with third party services, or learning about new features. It is, therefore, necessary to further examine the perceived cognitive demand of VAs, and how it might differ between simple tasks and tasks that require a longer interaction. The cognitive demand of different types of tasks will be investigated in Chapter 5. Additionally, Chapter 6 will examine ways to reduce the complexity of certain VA tasks.
3. **Lack of Portability:** The reports of participants who used VAs through smart speakers indicate that their lack of portability [173] can result in users missing reminders, or being unable to use the provided services when needed. Although smartphones allow interaction with VAs while on the move, some participants reported using VAs only through smart-speakers. Those who did use VAs through smartphones when being outside mentioned using them for different tasks, compared to when using them at home through a smart-speaker. Moreover, using a VA through a smartphone while being in public places can sometimes be problematic. Therefore, it is essential to examine ways to provide reliable interaction with VAs when the user is not within the proximity of their smart speaker.
4. **Speech Recognition:** Issues related to poor speech recognition were reported as a cause for frustration, often resulting in users being unable to complete tasks or inputting incorrect information. Three participants of Study 4 reported having minor speech impaired, which caused either poor pronunciation or difficulties producing speech ("*finding the right words*"), especially when tired. These difficulties, as well as uncommon accents, were reported to increase the frequency of speech recognition errors when using a VA. The findings of Study 4, however, indicate that speech recognition issues do not prevent people with ABI from using VAs, and the frequency in which they occur can decrease after using the technology for a certain time. These findings were also true for participants who re-

ported having speech difficulties. While not all users with speech difficulties will be able to use VAs efficiently, this indicates that people with mild speech impairments can benefit from the technology. Although poor speech recognition should be recognised as a factor that can impact the usability of VAs, its improvement is beyond the scope of this thesis. What can be investigated, however, is how errors caused by poor speech recognition are handled, to provide easy recovery. This will be further examined and discussed in the next chapters.

- 5. Lack of Motivation, Initiation and Self-Awareness:** The findings of Studies 2 and 3 show that the lack of initiation and motivation caused by ABI can hamper the efficient use of external aids and is, therefore, a factor that can also impact the usability of VAs. As with poor memory functioning, providing prompts without relying on the user's initiative and adjusting their content to encourage the system's use and increase motivation can be a way to overcome this obstacle. Chapter 6 will examine how to increase the efficacy of conveyed prompts.
- 6. Change in Abilities:** Apart from speech-related difficulties which can improve over time and through therapy or rehabilitation, the cognitive performance of users can also change. According to the findings in this Chapter, that change can either refer to a consistent improvement of cognitive functioning over time, or a variation of the user's functioning depending on the situation. This could impact a system's usability if the latter is designed to target users with a specific level of cognitive capacity. As previously discussed, this can be overcome by designing VA applications that offer flexibility of interaction based on the user's performance [117, 184].
- 7. Learning Difficulties:** According to the findings of studies 2, 3 and 4, cognitive effects of ABI and injury-induced fatigue can make learning a new technology especially difficult. This also seems to be the case with Voice Assistants, for which the majority of users in Study 4 reported being unsuccessful in learning how to use them for more than a few tasks. Moreover, the learnability of voice user interfaces is generally challenging [36]. However, being able to use a system with the minimum possible effort is essential for its usability. Therefore it is important to examine which learning methods are more appropriate for people with ABI to improve the usability of VAs
- 8. Privacy and Security:** The following situations where privacy concerns are present were identified: receiving prompts from the VA in front of other people (at home or in public), talking to the VA in front of other people (at home or in public), and sharing personal information with therapists/carers, or with the VA's manufacturer. As discussed above, the concerns regarding the privacy and security of VAs, although prevalent among people with ABI, were found not to be serious enough to hamper the use of the technology, even

if it would require sharing personal information. However, it was also found that using VAs in front of other people can be problematic [57]. Receiving a prompt regarding a personal matter can be embarrassing when other people are present and able to hear it, or users might feel embarrassed to start talking to the VA in front of others. This highlights the importance of finding ways for people with ABI to interact with the VA in a discrete manner (to avoid unwanted attention and social embarrassment, as identified in Chapter 3 (Table 3.5)).

4.5 Conclusions

This list of use cases presented in Table 4.3 delineates the ways that VAs can be used to benefit people with ABI, identified by the review of the related literature and the findings of studies 1-4, and therefore answers the first research question of this thesis:

RQ1: What are the use cases of Voice Assistants for users with cognitive impairments due to an Acquired Brain Injury?

Additionally, the acquired information regarding the difficulties in using external aids induced by the cognitive effects of ABI, together with the relevant challenges in the use of VAs, were analysed to identify factors that can impact the usability of VAs, which were presented in Section 4.4. These factors address the second research question:

RQ2: What are the factors that affect the usability of Voice Assistants when used by people with ABI?

Identified factors provide valuable information on the aspects that need to be considered when designing VA applications for people with ABI. However, the extent to which some of these factors can affect the usability of VAs is unclear. Moreover, the types of interaction that participants in Study 4 reported using VAs for was rather limited. Therefore, additional information is needed regarding the experience of using VAs for a bigger variety of tasks, and further investigation is required to determine how better design can improve the usability of VAs.

Chapter 5

Investigating the Usability of Voice Assistants

5.1 Introduction

Chapter 4 examined the use of Voice Assistants and identified different ways that the technology can be utilised to benefit people with cognitive impairments due to Acquired Brain Injury. These findings, together with information regarding the impacts of ABI on the use of external aids, were analysed to determine the factors that can affect the usability of VAs. The gathered data regarding the use of VAs, however, was based solely on the subjective reports of the participants. Chapter 4 also discussed ways that the impact of some of the factors can be mitigated with the improved design of the Conversational User Interface of VAs. However, the Chapter concluded that the manner and the extent in which these factors determine the usability in different tasks should be further investigated.

This Chapter aims to: 1) Further investigate how people with ABI experience the interaction with VAs in a wider range of tasks; 2) Examine the prevalence of the identified usability factors in different tasks and types of interaction, and 3) Further explore how the design of a CUI can alleviate the impact of these factors. Addressing the first two objectives will further inform the answer to the second research question of the thesis regarding the factors that affect the usability of VAs in people with ABI (**RQ2**). Addressing the third objective will inform the answer to **RQ3**, regarding how to improve the usability of VAs for people with ABI, through the design of their CUI.

To accomplish the above, an experimental study was conducted:

- **Study 5:** An experiment examining the usability of VAs for people with ABI (n=15),

who were asked to use a VA (Google Home) to carry out different tasks and evaluate their experience.

The findings of the study were analysed to clarify the manner and the extent in which the different identified factors impact the usability of VAs, and to discuss ways that potential obstacles can be overcome through the design of CUIs.

5.1.1 Chapter Structure

Sections 5.2.1 and 5.2.2 describe the objectives and the design of Study 5. Section 5.2.3 presents the results of the study and Section 5.2.4 discuss the study's findings and how these inform the second and third research questions of the thesis. Finally, Section 5.2.5 summarises the key findings of the study, and identifies the additional information required to provide a complete answer to the final research question, which will be acquired and analysed in Chapter 6.

5.2 Study 5: User Experience of Voice Assistants for People with ABI

5.2.1 Introduction

As presented in Section 2.4.3, Voice Assistants can be used to carry out a very wide range of tasks, and offer an alternative way to access many of the services typically provided by smartphones and personal computers. As shown by related studies, however, the majority of users take advantage of only a fraction of the available functionality of VAs [6, 55]. This was also found to be true in people with ABI (Studies 3 and 4), where several participants reported using other tools such as wall calendars, notebooks and smartphones, despite being satisfied with VAs. Apart from indicating the existence of several challenges in the use and design of VAs, this also limits the generalisability of the findings regarding the factors that can affect their usability (Section 4.4). Moreover, these findings are not a result of direct observation and analysis of how people with ABI interact with VAs, but are rather based on the participants' subjective reports. Furthermore, Study 4 also identified several challenges in learning how to use Voice Assistants and in discovering unknown features.

The aim of the study described in this Section is to address the above issues by: 1) further examining how people with ABI interact with VAs; 2) investigating the prevalence of factors that affect usability in a variety of tasks, and 3) examining whether certain types of tasks performed

with VAs can be more demanding or problematic than others.

Specifically, the participants were asked to use a Voice Assistant to carry out three sets of tasks (divided based on the type of interaction) and assess their experience by completing relevant questionnaires. Additionally, the participants' interaction with the VA was observed to identify elements affecting usability. The results were analysed to examine the difference between the tasks in terms of subjective workload, as well as the impact of different issues that occurred during the interaction on the experience of the users.

5.2.2 Method

Participants and Study Procedure

As in Study 4, the participants ($N=15$) were recruited through organisations providing services for people with ABI, specifically: Headway UK, Headway Glasgow, the Encephalitis Society and Stroke Association in the United Kingdom, and the Brain Injury Network in the United States of America. The services distributed the information sheet and consent form to their clients, who expressed their interest to participate by contacting the researcher via email. The eligibility criteria were: being 18 years old or older, having experienced an ABI, and being able to provide informed consent for themselves, and were confirmed by the employees of the corresponding organisation of those who volunteered to participate.

The experiments were carried out from February 2020, to December 2021, and were conducted at the University of Glasgow ($n=5$), and online ($n=10$) using videoconferencing software (Zoom or Skype). The majority of the sessions were carried out online due to the restrictions imposed by the COVID-19 pandemic. The online sessions were designed to ensure that the participants' experience was similar to that of the lab set-up. During the study sessions the participants were asked to interact with a smart speaker device (Google Home) to carry out a variety of tasks, the description of which was shown to them on the screen of a computer (the researcher's laptop in the lab studies, and through the screen-sharing feature of the videoconferencing software in the studies carried out online). In the lab set-up, the smart speaker was placed in front of the participants, while in the online set-up it was shown to the participants using a webcam, and was operated remotely through the videoconferencing software. The audio of the sessions was recorded to analyse the participants' interaction with the smart speaker. The recorded audio was then transcribed, and the transcribed documents were anonymised. The completion of the questionnaires was carried out anonymously using Google Forms¹ on the researcher's laptop (using screen-sharing for the online sessions). The study received approval

¹<https://www.google.com/forms/about/> - Accessed: 11/5/2021

from the University of Glasgow's Ethics committee in December 2019.

Study Design

The sessions started with participants being asked to complete a short background questionnaire including demographic information, and indicating their experience with electronic devices such as smartphones and personal computers, the frequency of using such electronic as cognitive aids, their experience with using VAs, and the frequency of using VAs as cognitive aids. Then, the participants were asked to interact with the VA (Google Home device) to perform two simple tasks (asking for a joke, and asking to hear the sound of an animal), to learn the trigger phrase ("*OK/Hey Google*") and familiarise themselves with how the interaction with the VA was carried out. The performance of these tasks was not evaluated.

For the main part of the experiment, the participants were asked to use the VA to perform three sets of tasks (T1, T2 and T3). The different tasks were selected from the pool of available built-in features of mainstream VAs, so that they include the use cases identified in Chapter 4 and the most popular tasks among users of VAs. Additionally, they were chosen so that they included the three common types of interaction with VAs, with each of the three sets of tasks corresponding to one type of interaction: receiving information (T1), inserting information (T2), and exchanging information in a conversational manner.

The first set (T1) consisted of ten tasks, which required the user to perform a single query to acquire certain information from the VA. These tasks included asking for the weather, asking for the news, asking about the traffic, asking for flight prices to a specific destination and checking the calendar for events on a specific date. The first set also included a task which the VA was unable to carry out (asking for the TV programme of the day), to induce the experience of attempting to execute an unsupported task, similar to Myers *et al.* [151]. The second set (T2) consisted of nine tasks which required participants to insert some information to the system. These tasks included setting an alarm on a specific day and time, setting a count-down timer, adding a specific event to the calendar, creating a reminder for an upcoming event on a specific day, adding items to the shopping list, and making a note. The set also included a task which required the use of a feature that was likely to be unknown to the participants (asking the VA to remember something for them), to observe how they attempted to discover the correct way of carrying it out. Finally, the third set (T3) consisted of eight tasks which required the participants to exchange information with the system in a conversational way. In particular, the participants were asked to acquire certain information from the VA by performing a single query, then performing a follow-up query based on the information in the VA's initial response. For instance, one of the tasks in this set required participants to ask for nearby restaurants, then choose one restaurant included in the VA's response and enquire about its address. Other tasks in this set

included asking for nearby supermarkets and then finding out the opening times for one of them, asking for events in the calendar on a specific day and creating an event on a time that is free, asking to hear what is on the shopping list and then adding missing items, and finding out about attractions at a certain location and then asking for directions to one of the locations included in the results.

Although the number of tasks varied between the three sets, they were designed to require approximately the same amount of time to complete. The participants' interaction with the VA was observed to identify issues that prevented successful task completion. When unable to complete a task successfully, the participants were asked to try a total of three times until the task was marked as failed, to reduce the possibility of the participants becoming frustrated or demotivated. A reduced Latin square design [21] was applied to minimise the learning effect between tasks. The participants were divided in three groups, with each group beginning the experiment with a different set of tasks. Specifically, the order in which the three sets of tasks were carried out in the three groups were: *ABC*, *BCA* and *CAB*, where A corresponds to the first set, B to the second and C to the third set of tasks. This ensured that an equal number of participants ($n=5$) performed each set of tasks at every possible position in the sequence (first, second or third).

After the completion of each set of tasks the participants were asked to fill in a NASA-TLX questionnaire [80], to provide a subjective assessment of the tasks' workload. After completing all three sets, the participants were asked to fill in a User Experience Questionnaire (UEQ) [106] to evaluate their overall experience of interacting with the VA. At the end of each session there was a short discussion where participants were encouraged to describe their experience of interacting with the technology and potential aspects of the interaction they found particularly positive or problematic.

The total duration of each session was approximately 45 minutes, with the time during which participants interacted with the Voice Assistant to complete the three sets of tasks being approximately 30 minutes. The duration of the study was made known to the participants in advance through the information sheet. Additionally, the participants were verbally informed about the duration of the study at the beginning of the session, and were encouraged to ask the researcher to stop the study, if they felt tired or wanted to take a break. After the completion of each set of tasks, the participants were asked if they wanted to take a break, stop, or continue with the study. When asked, all of the participants declared that they were able to complete the study without stopping.

Data Analysis

Observational analysis was used on the recorded audio of the sessions to investigate the different issues that emerged during the participants' interaction with the VAs, which identified different types of user errors preventing successful task completion. One-way ANOVA with Bonferroni post-hoc tests were used to examine the statistical difference of the different types of errors between the three sets of tasks. Independent t-test were used to examine the difference in the number of tasks between participants who reported using VAs frequently and those who reported using them less often. Friedman's ANOVA test was used to investigate the difference of subjective workload between the three sets of tasks, and the Wilcoxon was used to identify differences in workload between specific pairs of task sets. The Mann-Whitney test was used to examine the difference of subjective workload in the three sets of tasks between frequent and infrequent users of VAs. The Spearman's Rank Correlation test was used to examine the correlation between user errors and workload, as well as between the total workload of tasks and the participants' answers in the User Experience Questionnaire. Finally, Wilcoxon tests were used to examine the difference in how frequent and infrequent users of VAs responded in the UEQ.

5.2.3 Results

Participants

The participants' ($N=15$) age ranged from 29 to 69 years (mean=45.07, SD=11.96), 8 participants were female and 7 were male. The causes of the participants' brain injuries were encephalitis ($n=6$), TBI ($n=5$) and stroke ($n=4$). The majority of participants ($n=13$) reported having memory difficulties as a result of their brain injury. Other reported ABI effects included cognitive fatigue, headaches, issues with concentration, anger and frustration. One participant (P1) mentioned having a sensitivity to noise and loud sounds, which she associated to frequent headaches. Two participants (P1 and P14) reported having injury-induced speech impairments which they described as "minor", causing their speech to be more slurred when tired. Also, two participants (P3 and P9) had a strong Scottish accent.

Through the background questionnaire at the beginning of the study, the participants were asked to indicate the frequency in which they use mobile electronic devices (such as smartphones and tablets) for general purposes and as cognitive aids, as an indication of their familiarity with modern technology. The majority of participants ($n=12$) reported using such devices as aids on a regular basis (at least a few times a week). The participants were also asked to indicate their experience in using Voice Assistants, with four participants reporting using them every day, three using them a few times a week, two using them a few times a month, two participant

reporting having tried to use a VA once, and four reporting never having used one (Figure 5.1). From the answers to this question, the participants were categorised in two groups: frequent users of VAs (those who reported using them at least a few times a week, n=7), and infrequent users (those who used them a few times a month or less, n=8). Out of the seven participants who were frequent users of VAs, five reported using electronic devices as cognitive aids regularly (at least a few times a week), and two reported using them a few times a month. The most popular VA among participants was the Google Assistant (n=8), the second most popular was Amazon's Alexa (n=7), and the third most popular was Apple's Siri (n=4), with five participants reporting using more than one VA.

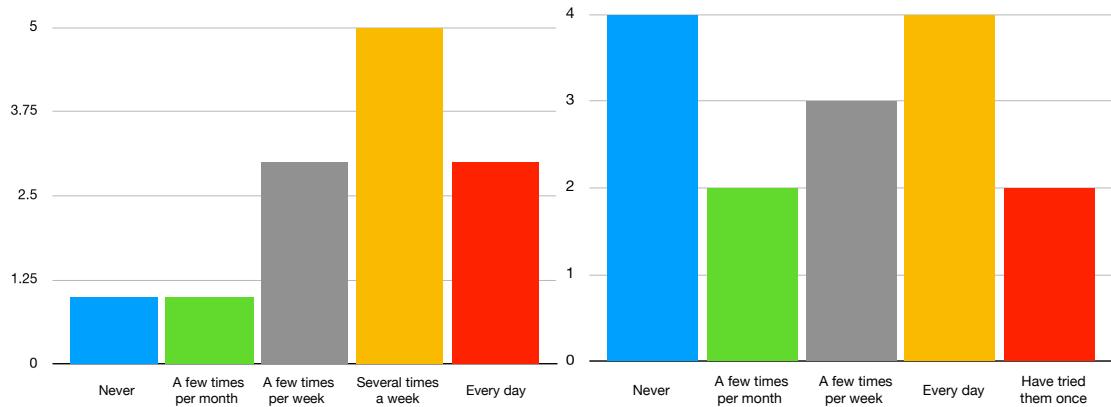


Figure 5.1: Frequency of using smartphones as cognitive aids (left), and frequency of using Voice Assistants (right).

User Errors

The participants' interaction with the VA while performing the three sets of tasks was observed to identify errors that prevented successful task completion. There were two main categories of errors identified: 1) speech recognition errors, referring to instances where the VA was unable to correctly parse the words contained in the user's query, and 2) incorrect phrasing errors, referring to instances where the VA was unable to match the intended action to the user's input, due to the latter being phrased incorrectly (e.g. asking to create an "appointment" instead of an "event", in tasks related to calendar management), or due to the user attempting to perform an action that was not supported by the system (e.g. asking two questions in one query). The second category also included timing errors (i.e. not being able to complete the query on time), which were observed twice (P5 in T2, and P10 in T3), as they occurred due to the participants being unsure of how to phrase the query correctly.

Table 5.1 shows the number of user errors in the three sets of tasks. The third column (Total Errors) contains the summary of speech recognition and incorrect input errors. The fourth column (Tasks completed incorrectly) contains the number of tasks in each set which were com-

pleted incorrectly, i.e. with the user inserting incorrect information (e.g. a reminder set on the wrong day or time), and the fifth column (Failed tasks) shows the number of tasks in each set that the participants were unable to complete (it is reminded that a task was marked as failed after three unsuccessful attempts).

	Speech recognition	Incorrect phrasing	Total Errors	Tasks completed incorrectly	Failed Tasks
T1	12 (mean=.80, SD=.561)	12 (mean=.80, SD=.561)	24 (mean=1.60, SD=.828)	2 (mean=.13, SD=.352)	0
T2	17 (mean=1.13, SD=1.187)	39* (mean=2.60, SD=1.682)	56* (mean=3.73, SD=1.981)	15* (mean=1.00, SD=.535)	6* (mean=.40, SD=.507)
T3	25* (mean=1.67, SD=0.976)	43* (mean=2.87, SD=1.685)	68* (mean=4.53, SD=1.885)	13* (mean=.87, SD=.743)	14* (mean=.93, SD=.961)

* = Significantly higher than T1 (one-way ANOVA, Bonferroni post-hoc)

Table 5.1: The number of user errors, tasks completed incorrectly, and failed tasks in the three sets of tasks.

As mentioned above, T1 (the first set of tasks) intentionally contained a task that was not supported by the VA at the time of the study (asking for the TV programme on a specific day). After attempting to carry out this task and receiving the VAs corresponding response ("I can't help with that yet" or similar), the participants were prompted to proceed to the next task. Additionally, T2 (the second set of tasks) contained a task (asking the VA to remember something) that required users to phrase their query in a very specific way², which was presumed to be unknown to the majority of participants. The user errors that occurred while participants attempted to execute these two tasks were not calculated in the total number of errors of the corresponding set of tasks. However, observational data were collected, which are discussed later in this section.

One-way ANOVA with Bonferroni post-hoc tests were used to determine whether there is a statistically significant difference in the number of the different types of errors between the three sets of tasks. Regarding speech-recognition errors, the ANOVA produced a statistically significant result ($F(2, 28) = 4.93, p = .015$) and the post-hoc test showed that these errors were significantly higher in T3 compared to T1 ($CI_{.95} = .172(lower), 1.56(upper), p = .013$), but no significant difference was found between the other two pairs of task sets ($p = 1.00, p = .122$ for T1T2 and T2T3 respectively). There was also a significant difference found between the sets of tasks in the number of errors due to incorrect phrasing ($F(2, 28) = 10.89, p < .001$), with the post-hoc test showing a significantly higher number of errors in T2 compared to T1 ($CI_{.95} =$

²<https://support.google.com/googlenest/answer/7536723?hl=en> - Accessed: 11/5/2021

.469(*lower*), 3.13(*upper*), $p = .008$), and in T3 compared to T1 ($CI_{.95} = 1.02(lower)$, 3.11(*upper*), $p < .001$), but no significant difference between T2 and T3 ($p = 1.00$). Similarly, there was a significant difference between the sets of tasks in the total number of errors ($F(2, 28) = 16.180, p < .001$), with the post-hoc test showing a significantly higher number of total errors in T2 compared to T1 ($CI_{.95} = .57(lower)$, 3.7(*upper*), $p = .007$), and in T3 compared to T1 ($CI_{.95} = 1.84(lower)$, 4.43(*upper*), $p < .001$), but no significant difference between T2 and T3 ($p = .396$). The results were analogous regarding the number of tasks completed incorrectly in each set, with the ANOVA showing a significant difference ($F(2, 28) = 9.662, p = .001$), and with the Bonferroni post hoc test showing that they were higher in T2 compared to T1 ($CI_{.95} = .418(lower)$, 1.32(*upper*), $p < .001$), and also in T3 compared to T1 ($CI_{.95} = .113(lower)$, 1.36(*upper*), $p < .019$), but showing no difference between T2 and T3 ($p = 1.00$). Finally, regarding the number of failed tasks in each set, Mauchly's test indicated that the assumption of sphericity had been violated ($chi^2(2) = 6.99, p = .30$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = .71$). The results showed a significant difference in the failed tasks between the three sets ($F(1.41, 19.78) = 9.128, p = .003$), and the Bonferroni post-hoc test revealed there were significantly more failed tasks in T2 than in T1 ($CI_{.95} = .04(lower)$, .756(*upper*), $p = .026$), and in T3 than in T1 ($CI_{.95} = .26(lower)$, 1.61(*upper*), $p = .006$), but no significant difference between T2 and T3 ($p = .167$).

As mentioned above, the participants were categorised in two groups based on the frequency of using VAs (as per Dubiel *et al.* [55]) to frequent (n=7) and infrequent users (n=8), with the former group consisting of participants who reported using VAs at least a few times a week, and the latter consisting of the ones who used VAs a few times per month or less. Table 5.2 shows the total number of different categories of user errors in the two participant groups. As can be seen from the table, the number of errors due to speech recognition and incorrect phrasing, as well as the number of tasks completed incorrectly is lower for the group of frequent VA users, while the number of failed tasks was slightly lower for the infrequent users group. Independent t-tests, however, did not show any significance in the difference of different types of errors between the two groups ($p=.858$ for speech rec. errors, $p=0.50$ for phrasing errors, $p=.977$ for total errors, $p=.497$ for incorrect tasks, and $p=.910$ for failed tasks).

P1, who had reported having a speech difficulty, had a total of 10 errors throughout all tasks (1 in T1, 6 in T2 and 4 in T3), while P14 had a total of 14 user errors (3 in T1, 5 in T2 and 6 in T3). P3 and P9 (participants with Scottish accent) had six (0 in T1, 2 in T2 and 3 in T3) and zero (0) speech recognition errors, and a total of 10 (0 in T1, 5 in T2 and 5 in T3) and 5 (0 in T1, 2 in T2 and 3 in T3) user errors respectively.

	Frequent Users	Infrequent Users
Speech recognition	24 (mean=3.43, SD=1.902)	30 (mean=3.75, SD=2.435)
Incorrect phrasing	44 (mean=6.29, SD=3.684)	50 (mean=6.25, SD=1.832)
Total Errors	68 (mean=9.71, SD=3.498)	80 (mean=10.00, SD=3.295)
Tasks completed incorrectly	11 (mean=1.57, SD=1.134)	19 (mean=2.38, SD=0.744)
Failed Tasks	10 (mean=1.43, SD=1.134)	9 (mean=1.13, SD=1.126)

Table 5.2: The number of user errors in participants who were frequent and infrequent users of Voice Assistants.

Workload of Tasks

The participants were asked to provide a subjective evaluation of the workload of the three sets of tasks through the NASA TLX questionnaire. The participants were explicitly asked to not consider the unsupported task (T1) in their responses. Figure 5.2 shows the mean values of the six scales of the questionnaire. As can be seen from the figure, the physical and temporal demand remained very low for the three sets of tasks (the majority of participants selected the minimum value of the scale for the former, for all three sets). A Friedman's ANOVA test showed a significant difference between the total workload (sum of all scales of the questionnaire) of all three sets of tasks ($\chi^2(13) = 20.28, p < .001$). Wilcoxon tests were used for a more detailed comparison between the three sets (level of significance at 0.02 after a Bonferroni correction), showing that the total workload was significantly higher in T2 compared to T1 ($Z = 3.205, p = .001$) and in T3 compared to T1 ($Z = 3.415, p = .001$), but no significant difference was found between T2 and T3 ($p = .042$).

The same method used for the total workload was applied to examine the difference in each of the individual scales of the TLX questionnaire. The Friedman's ANOVA showed a significant difference between the three sets of tasks in mental demand ($\chi^2(13) = 20.80, p < .001$), performance ($\chi^2(13) = 7.04, p = .030$) and effort ($\chi^2(13) = 19.08, p < .001$). The Wilcoxon tests showed that the mental demand was significantly higher in T3 than in T1 ($Z = 3.100, p = .002$), and in T3 than in T2 ($Z = 3.217, p = .001$), but no significant difference was found between T1 and T2 ($p = .033$). Regarding performance, the test showed that participants reported being significantly less successful (higher value in the performance scale signifies lower perceived success in the task) in T2 than in T1 $Z = 2.437, p = .015$, but no significant differences be-

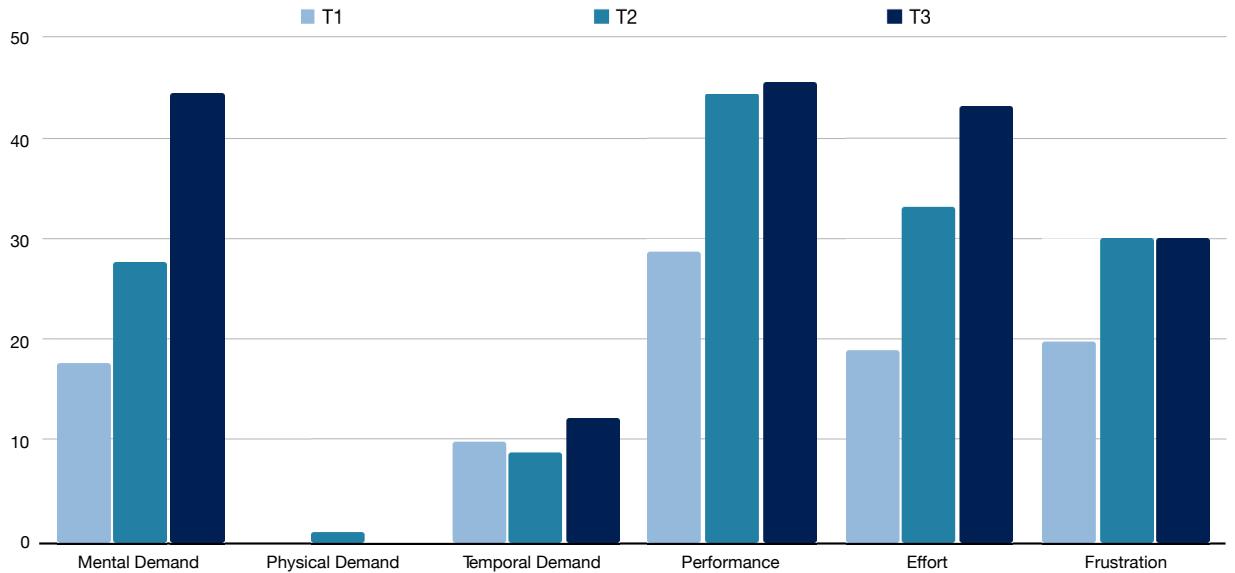


Figure 5.2: Means of the six different scales of the NASA TLX questionnaire, for the three sets of tasks.

tween the other two pairs ($p=.042$, and $p=.710$ for T1T3 and T2T3 respectively). Finally, the required effort of T1 was shown to be significantly lower than that of T2($Z = 2.968, p = .003$) and of T3($Z = 3.256, p = .001$), but no significant difference was shown between T2 and T3 ($p = .029$).

The correlation between the number of total errors (speech recognition + incorrect phrasing) in each set of tasks and how participants assessed their workload was examined using Pearson's test, which showed no significant relationship between the two ($p=.199$ for T1, $p=331$ for T2, and $p=.072$ for T3). Similarly, there was no significant correlation found between the number of failed tasks and the total workload ($p=.190$ for T2, $p=.184$ for T3).

Additionally, a Mann-Whitney test was used to examine the difference in the total workload of the three sets of tasks, between frequent and infrequent users of VAs. Although the mean workload was lower in frequent users for every task (Table 5.3), the test showed no significant differences between the two groups of participants ($p=.302$ for T1, $p=.246$ for T2, and $p=.249$ for T3).

	T1	T2	T3
Frequent VA users	27.39	35.73	40.48
Infrequent VA users	33.73	40.87	45.65

Table 5.3: Means of total workload in three sets of tasks for frequent and infrequent users of Voice Assistants.

User Experience

After completing all three sets of tasks, the participants evaluated their overall experience of interacting with the VA through the User Experience Questionnaire (UEQ). The UEQ consists of 26 questions (using 7-stage Likert scales), which correspond to six scales (the first scale contains 6 items, and all other scales have 4 items): 1) Attractiveness, measuring the users' overall impression of the system; 2) Perspicuity, measuring the learnability of the system (how easy it is to learn); 3) Efficiency, evaluating the extent to which users could solve the tasks without unnecessary effort; 4) Dependability, measuring whether users feel in control of the interaction; 5) Stimulation, evaluating how motivating to use the system is, and 6) Novelty, assessing the innovation, creativeness and user engagement of the system. The value of each scale is calculated from the mean of the scale's items, and is shown in Figure 5.3 (error bars represent 95% confidence intervals). According to the standard interpretation of the UEQ scales [106], values between -0.8 and 0.8 typically represent a neutral evaluation of the system, while values > 0.8 represent a positive evaluation and values < 0.8 a negative evaluation. As can be seen in the figure, the participants' overall evaluation of their interaction with the VA was generally positive. The scale with the lowest value was Dependability (1.033, SD=0.870), and the scale with the highest value was Efficiency (1.583, SD=1.059). Stimulation was the scale with the highest variance (2.30, SD=1.517), and Dependability the one with the lowest variance (0.76, SD=0.870).

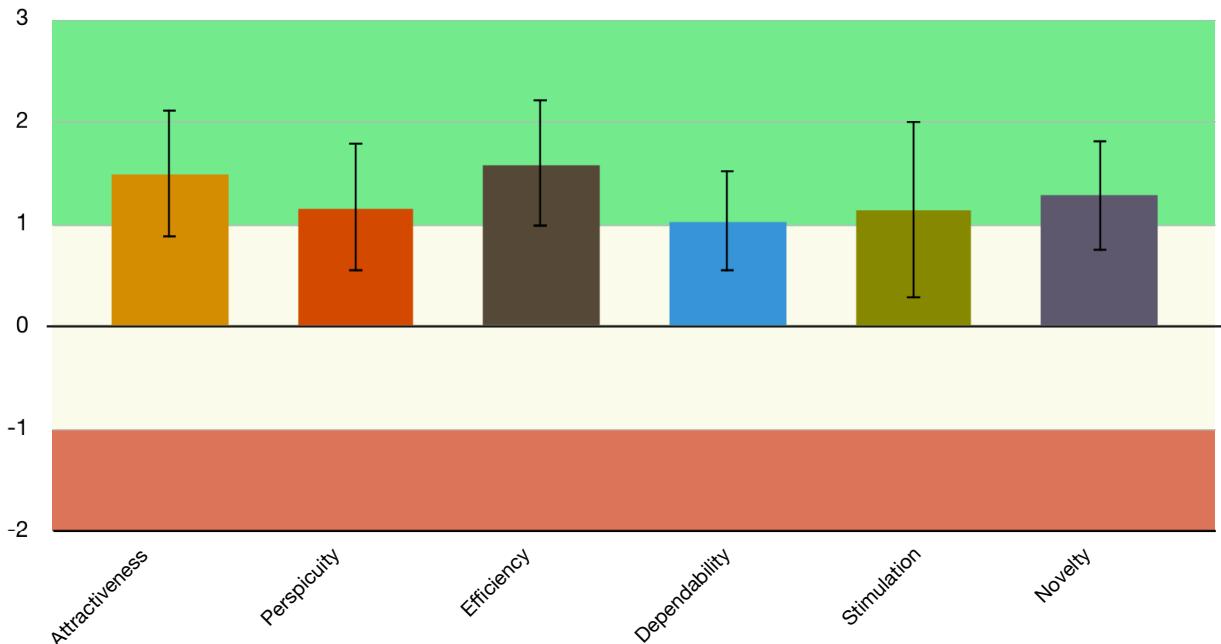


Figure 5.3: Mean values of the six different scales of the User Experience Questionnaire. The error bars represent 95% confidence intervals.

The association between the different user errors and the participants' responses in the UEQ

was examined, with the Spearman's Rank Correlation test showing no significant correlation between total errors or failed tasks and the mean values of the six different scales. Additionally, the relationship between the total workload of the tasks (sum of the total workload of each task) and the participants' responses in the UEQ was investigated. The Spearman's Rank Correlation test showed a significant negative correlation between the total task workload and the value of the Attractiveness ($\rho(13)=-.783, p=.001$), Perspicuity ($\rho(13)=-.675, p=.006$), Efficiency ($\rho(13)=-.743, p=.001$), Dependability ($\rho(13)=-.672, p=.006$) and Stimulation scale ($\rho(13)=-.782, p=.001$), indicating that the higher the participants perceived the workload of the tasks, the lower their responses were in the questions corresponding to these five scales. No significant correlation was found between the total workload of the tasks and the Novelty scale ($p=.273$).

The participants who had reported using VAs more often in the background questionnaire (frequent users) responded with higher values in five scales of the UEQ (attractiveness, perspicuity, efficiency, dependability and stimulation), while the mean of the responses in the novelty scale was higher for the infrequent users (Table 5.4). However, the Wilcoxon test did not show a significant difference in the mean responses of the two groups for all the six scales ($p=.642$, $p=.861$, $p=.522$, $p=.482$, $p=.728$, $p=.292$).

	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
Frequent VA users	1.74 (SD=0.908)	1.21 (SD=1.159)	1.61 (SD=1.306)	1.07 (SD=1.097)	1.32 (SD=1.143)	1.00 (SD=0.901)
Infrequent VA users	1.29 (SD=1.267)	1.13 (SD=1.126)	1.56 (SD=0.884)	1.00 (SD=0.694)	1.00 (SD=1.852)	1.53 (SD=0.958)

Table 5.4: Means values of the six scales of the User Experience Questionnaire for participants who reported using VAs frequently (at least a few times a week), and infrequently (a few times per month or less).

The participants' responses for each individual item in the questionnaire can be shown in Figure 5.4. As can be seen in the figure, the mean values for all 26 items of the questionnaire are above zero, with the value of only 4 items being in the neutral zone (between -0.8 and 0.8), indicating an overall positive evaluation of the participants' interaction with the VA. The lowest mean values were in questions regarding predictability (mean=0.4, SD=1.2), security³ (mean=0.5, SD=2.1), complexity (mean=0.7, SD=1.4) and annoyance (mean=0.7, SD=1.6). The highest mean values were in questions regarding the system's friendliness (mean=2.2, 1.1) and speed (mean=1.9, SD=1.4).

³According to Laugwitz et. al [106] this question intends to examine whether the interaction is safe and controllable by the user. However, it is often misinterpreted by participants who associate it with data security and privacy. This is likely to have happened in this study, therefore the dependability scale should be interpreted with caution.

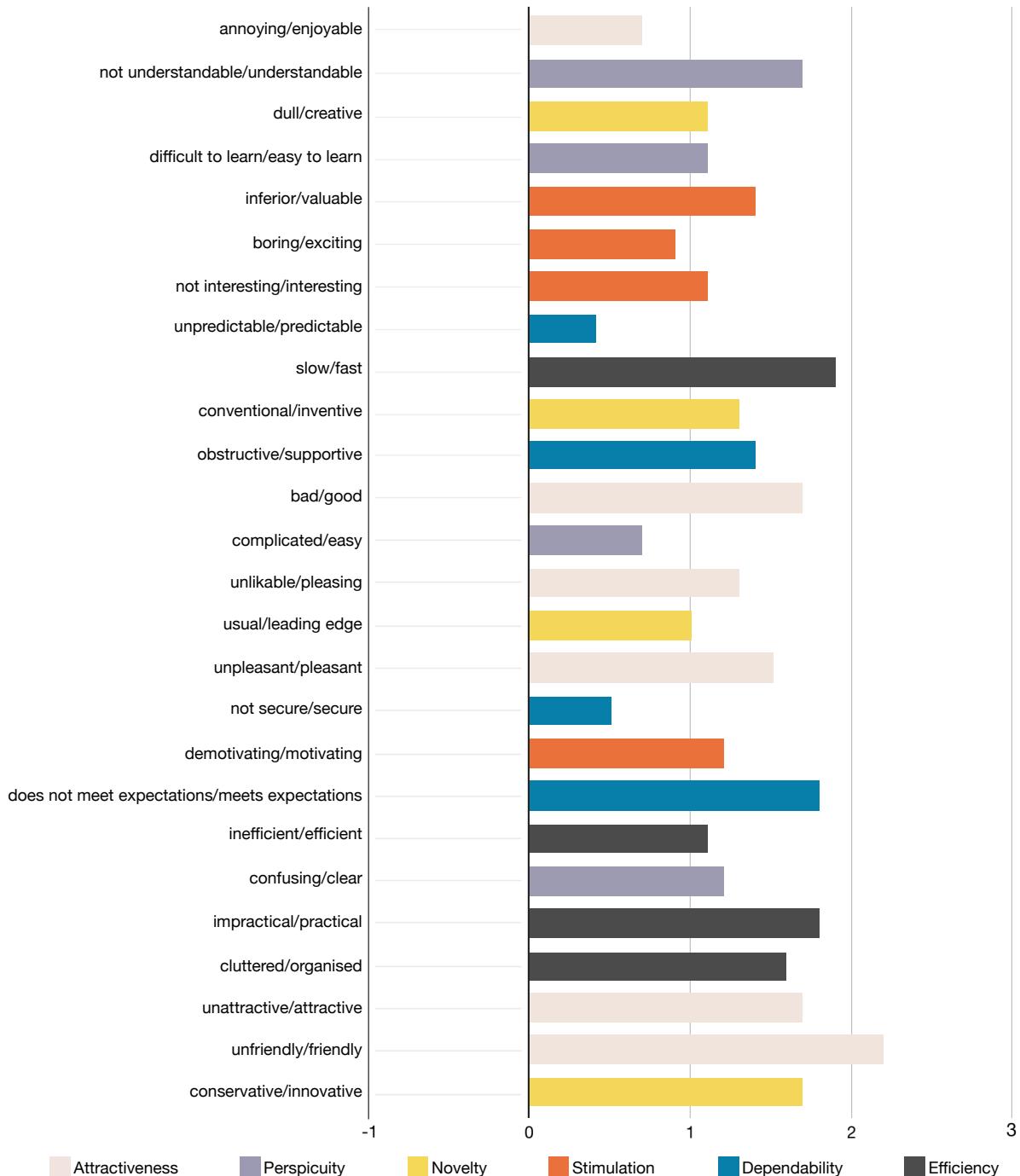


Figure 5.4: Mean values for all the 26 items of the User Experience Questionnaire. The different colours indicate the scale that each items corresponds to.

Observations

As can be seen in Table 5.1, the majority of errors that occurred during the interaction with the VA were due to participants phrasing the queries incorrectly. These were caused either due to participants not knowing how to appropriately structure the query so that it could be recognised by the VA, or overestimating the VA's capabilities, and either resulted in participants failing to complete the task, or inserting incorrect information to the system. Such errors occurred often when participants were trying to include several pieces of information in one query. For instance, some of the tasks required the participants to retrieve information about two separate things (e.g. find out whether the bus or the train was the fastest means to a specific destination). Several participants attempted to retrieve all required information with one query, which resulted in the VA being unable to process the query altogether, or responding only to one aspect of the query⁴. Similarly, in tasks involving inputting multiple pieces of information (e.g. creating a calendar event), the majority of attempts made by the participants to complete the task with only one utterance resulted in errors (failed attempts or incorrect information input). This was made difficult for some participants due to the VA's limited time window for user input:

"The question and response tasks I found more challenging. Trying to phrase the question, and searching of the right words quickly enough is a problem for me." (P9)

An interesting observation is that, in most cases, participants were able to quickly learn from their errors, effectively adjusting their queries so that they could be processed by the VA. As shown in Table 5.1, the number of total errors (unsuccessful attempts) are significantly higher than the number of failed tasks, indicating that the majority of tasks were completed successfully after, at most, two unsuccessful attempts. Additionally, all of the participants who encountered difficulties in tasks requiring the retrieval of two pieces of information, or inserting several pieces of information, were able to successfully complete similar subsequent tasks without any errors.

The importance of knowing how to phrase the query was also apparent in the "unknown" task included in T2. None of the participants reported being aware of the existence of that feature, or knowing which was the correct phrase. Out of the 15 participants, only three managed to complete this task (all three used the correct phrasing in their first attempt). Out of the remaining 12 participants, eight failed to complete the task (three unsuccessful attempts), while four completed the task incorrectly (set a reminder instead). All of the participants were able to carry out the task successfully after being instructed how to do it. Another task that appeared to be particularly challenging due to participants not knowing how to phrase the query, was the one that required the creation of a note. Specifically, four participants failed to complete this task (three unsuccessful attempts) and two completed the task incorrectly (created a note with

⁴Carrying out such tasks with a single utterance was supported by the VA, but required to be structured in a specific way.

the wrong information), with a total of 18 phrasing errors occurring in the execution of this task.

The number of tasks completed incorrectly was higher in T2 (Table 5.1). This was likely due to the higher number of tasks in this set requiring the input of information. Recovering from such errors appeared to be especially problematic, with many participants ($n=7$) not realising that the incorrect information had been inserted. Three participants (P1, P6, P10) attempted to edit the inserted information but failed to do so, thus deciding to repeat the task from the beginning. In the case of calendar events and notes, this resulted in multiple entities being inserted to the system, half of which containing incorrect information.

Memory deficits of participants seemed to have an impact in the execution of some tasks. Specifically, five participants had difficulty memorising the trigger phrase used to initiate the interaction with the VA ("Hey/OK Google"), with two of them associating that difficulty with being used to interact with a different VA (Alexa). Two participants had to write the trigger phrase down in order to be able to recall it successfully for each task. Another way in which poor memory performance hindered the interaction with the VA was in tasks that required the memorisation of the VA's response (T3). This was especially challenging when the response included a list of items, based on which the participant had to perform a follow-up query (e.g. restaurant task), with five participants having to the task to listen the response for a second time. Also, one participant (P11) had to write down the VA's responses in order to be able to perform the follow-up question and complete the tasks.

Apart from the above issues that were observed in several participants, other difficulties were identified which were limited to participants with certain difficulties. Specifically, P1, who had reported having a sensitivity to noises and loud sounds as a result of the ABI, found the VA's responses annoying when containing a lot of information, and described the device as "very talky".

No significant increase in user errors was for P1 through the study, who had reported difficulties in speech when tired. Specifically, the number of total errors (4) in the third set of tasks (T3, which was the last set the participant completed in the study) were below the average (mean=4.53). Moreover, no changes in the participant's speech were observed as the study progressed. P14, however, (the second participant who reported speech difficulties) had an increased number of errors in the last set of tasks (6 in T3, 1.47 above the average). The participant reported that he had gotten tired towards the end of the study and associated the increase in errors to his speech impairment which becomes more prominent when he is tired. Regarding the participants with Scottish accent, P3 had less speech recognition errors than the participants' average in T1 (0 errors, mean=0.80) and more than the average in T2 (2 errors, mean=1.13) and in T3 (3 errors, mean=1.67). However, it was not clear if any of these errors occurred specifically due to the participant's accent. No speech recognition errors were observed for P9.

5.2.4 Discussion

The results of this study confirm the findings of the previous Chapters regarding the positive opinion people with ABI have about Voice Assistants. The positive values in the Attractiveness, Efficiency and Novelty scales of the User Experience Questionnaire (Figure 5.3) reaffirm the conclusion that people with ABI generally view VAs as a helpful technology with several advantages, despite potential challenges in interaction. In some of the items of the UEQ, however, the mean score of responses was particularly low, indicating the existence of different obstacles that can affect the usability of VAs. Apart from security concerns which, as discussed in Chapter 4, should not hinder efficient use, several participants in this study evaluated VAs as unpredictable, annoying and complicated. The difficulties that occurred during the interaction with the VAs which led participants to respond in that manner, as well as potential solutions, are discussed in this section.

Section 4.4 described speech recognition as one of the factors affecting the usability of VAs. This study identified a subcategory of errors related to speech recognition that occurred due to participants using incorrect phrasing in their queries. These errors were more prevalent than errors due to the VA's inability to correctly parse the users' utterances, and led more often to unsuccessful task completion and to the input of incorrect information. These errors occurred significantly more often in the second and third sets of tasks (T2 & T3) which were described by participants as more demanding in terms of workload. However, the lack of significant correlation between the workload of the tasks and the number of errors in each task suggests that these errors did not occur more often due to the increased workload. Observation of the participants' interaction with the VAs showed that incorrect phrasing errors were usually the result of participants not structuring their queries efficiently, not using the appropriate keywords, including too much information in their queries (attempting to complete the task "in one go"), or not being aware of the limitations in the VA's capabilities. Therefore, phrasing errors were more frequent in T2 and T3 likely due to the inclusion of more advanced tasks which the participants were not familiar with (tasks that were not among the most commonly used ones described in Sections 2.4.3 and 4.3.3), or due to the longer and richer interactions that these tasks required. The total number of tasks completed incorrectly was highest in T2, as more of the tasks required user input. As discussed in the previous Chapter, this issue becomes especially important for people with memory difficulties who can be led to follow an incorrect prompt or reminder, after having inserted the wrong information due to phrasing errors. Additionally, editing information that has already been inserted in the system was found to be particularly challenging. Therefore, ensuring that the correct information is input is essential. Potential solutions to this issue would be to provide additional confirmation dialogues, or to restructure the interaction into smaller, simple steps. However, this could reduce the speed of task completion [230], and therefore compromise satisfaction and usability [56]. According to the findings of this study, another way

that the frequency of errors due to incorrect phrasing can be reduced is through experience and learning, which is discussed later in this section. These options will be examined further in the next chapter.

The fact that there was no significant correlation between the number of speech recognition errors and how participants responded in the UEQ confirms the findings of Myers and Weber [150] that such errors are not the biggest threat for the UX of VAs. Contrarily, there was a significant negative correlation between the perceived total workload of the tasks and the responses in several of the scales of the UEQ scales, including Efficiency and Perspicuity. This suggests that the way people with ABI evaluate the usability of VAs depends on how demanding they find the interaction with them (also found in the study by Kiseleva et. al [101]). Moreover, the total workload of tasks in T2 and T3 was significantly higher than in T1. The tasks in these two sets were more complex than those in T1, as they required the answer to more than a simple question to be completed successfully. Given the negative correlation between the workload of these tasks and the answers to the UEQ questions, it can be argued that the UX of VAs while carrying out these tasks was worse than that of the simpler tasks of the first set (T1), which is likely to be one of the reasons why users generally prefer to use VAs for such simpler tasks, as found in Chapter 4 and in related literature [6, 55]. Chapter 3 identified simplicity as one of the characteristics that a technological aid should have in order to be used efficiently by people with ABI. Moreover, the complexity of interaction was also identified in Chapter 4 as one of the factors that can impact the usability of VAs. Therefore, to determine how the latter can be improved, it is essential to examine ways that the interaction with the VAs can be simplified, by reducing its workload.

One way that the workload of VA tasks can be reduced is by decreasing memory demand [161]. This study identified some aspects of interaction where high memory demand became an obstacle to usability. Specifically, participants had difficulties being able to remember the VA's response, when it consisted of a list of items (e.g. list of nearby supermarkets, from which the participant had to choose one and ask for its opening times), often resulting in unsuccessful task completion. This confirms the findings of Study 4, indicating that the fast and non-visual interaction of VAs can make conveyed information harder to memorise. The number of items in the list contained in the VA's response was inconsistent throughout the different tasks (it depended on the source of the information), but typically ranged from three to five items. However, a smaller number of items in the list did not improve task completion in participants with severe memory issues; for instance, P11 had to write down the VA's responses to be able to use them in subsequent tasks, regardless of their length. What did seem to make processing of the response easier was the user's familiarity with the information, e.g. when they knew one of the results in the list of nearby restaurants (T3), participants reported it was easy to remember it for the follow up question. Some of the use cases of VAs presented in Table 4.3 could require the conveying

of information consisting of several items, such as the day's tasks (organisation) or a list of reminders or prompts (memory and rehabilitation). It is, therefore, important to create efficient ways to minimise the memory load when presenting information in these situations, such as using repetition to increase familiarity, or adjusting the amount of information in each response based on the context of use (see Section 3.4 about personalisation and adaptivity). Different methods to achieve this will be examined in the next chapter.

Memory demand in VA interaction can also refer to having to remember the required keywords, phrases or ways to structure the query which, according to the findings of this study, can be challenging for users with poor memory performance (e.g. not being able to remember the trigger phrase). As discussed above, not being able to use the correct phrasing can compromise successful task completion, and hence have a negative impact on the usability of VAs. Although experience interacting with the VAs and appropriate training could reduce the frequency of this issue (discussed below), it is essential to consider different methods to support users in remembering certain keywords, phrases or sentence structures required to use a VA application efficiently (will be examined in Chapter 6).

Apart from memory demand, another aspect of the interaction that, in some cases, seemed to increase its complexity and lead to errors was the perceived flexibility of the VA's Conversational User Interface. As discussed in Section 2.4.3, the human-like presentation of VAs and their CUI can increase user satisfaction and frequency of use, but can also create a gap between the users' expectations and the device's capabilities [29, 54, 119]. Overestimating the VAs capabilities was observed in several occasions in this study, where participants tried to include several pieces of information in a single query. Besides being a cause for speech-recognition errors and often resulting in unsuccessful task completion, this approach seemed to increase the mental demand of the interaction, with participants describing it as overwhelming. As mentioned above regarding methods to increase user errors, a potential solution to this issue would be to enforce a more structured interaction, where users would be able to provide limited amount of information in each step. This, however, can increase the task completion time and, as discussed, possibly compromise the UX. Potential solutions to this issue will also be examined in the next Chapter.

Another aspect of the interaction that was identified as a factor that can impact usability in Chapter 4 was timing, i.e. the limited time window that VAs give users to complete their queries. In this study, however, did not seem to significantly affect task completion. As can be seen in Figure 5.2, the perceived temporal demand of all three sets of tasks was rather low. Moreover, the observation analysis identified only two occasions across all 15 participants where timing errors occurred, during the execution of the tasks. In the next paragraphs it is argued that the frequency timing errors can be reduced through training and experience, or by providing the appropriate support to help users know what to say before they initiate the interaction (examined in Chapter 6).

The findings of this study showed that participants who used VAs more frequently had fewer errors during interaction Table 5.2, and their subjective evaluation of the workload of the tasks was generally lower compared to participants who used VAs less frequently (Table 5.3). Additionally, frequent users of VAs evaluated their experience interacting with VAs more positively than infrequent users in 5 out of the 6 scales of the UEQ (Table 5.4). These results are in agreement with findings from the studies by Myers et. al [151] and Dubiel *et al.* [55], which showed that experience in using VAs can lead to improved user satisfaction. However, the differences between frequent and infrequent users in those three aspects (user errors, workload and UEQ scales) was not statistically significant, and the number failed tasks was not lower for frequent users (Table 5.2). Moreover, most participants (12 out of 15) failed to complete the "unknown" task in T1, and had difficulty completing the note-taking task in T2, regardless of how experienced they were with using VAs. Furthermore, all of the participants were able to successfully complete failed tasks after being instructed how to do so. The above findings suggest that, even though experience and higher frequency of use can improve UX, it does not necessarily help with the successful completion of unknown tasks, and therefore, proper training and support is essential for all people with ABI in order to ensure efficient use of VA applications.

As discussed in Chapters 2 and 4, however, learning how to use a new technology and discovering new VA features can be especially problematic for people with ABI, due to certain obstacles induced by cognitive impairments. Therefore, in order to improve the usability of VA applications, it is essential to examine ways to support users in learning how to use them and to facilitate the discovery of unknown features. Corbett and Weber [36] presented three different methods to improve the learnability of a VUI: 1) The "learn as-you-go" method, referring to a virtual tutor that provides helpful messages in certain parts of the UI, explaining its functionality; 2) the "Discovery Based Learning", which involves the prompting and encouragement of users to discover functionality on their own, and 3) the "Contextualised Help", where users can ask "What can I say here", while performing a certain task to receive appropriate guidance from the VA. Although these methods could provide potential solutions to the difficulties associated with learning how to use VA applications and features in people with ABI, they relied, to a certain extent, on the use of visual feedback, and were not targeted to users with cognitive impairments. Chapter 6 will examine the applicability of these methods to VA applications for people with ABI, as well as explore other solutions to support learning.

5.3 Conclusions

Study 5 examined the interaction of 15 brain injury survivors with a Voice Assistant (Google Home) in a wide variety of tasks grouped in three sets. For the first set of tasks (T1) the participants were asked to acquire some information from the VA with a single query (e.g. ask for the

weather), for the second set (T2) they were required to insert some information to the system (e.g. create a calendar event), and for the third set (T3) they were required to retrieve some information from the VA, and perform a follow up query based on the response (e.g. discover nearby restaurants and ask the address of one included in the response).

The total number of user errors and failed tasks, as well as the subjective workload were higher in the second and third sets of tasks compared to the first, but no significant differences were found between T2 and T3. Errors which occurred due to participants using incorrect phrasing were generally more prominent than speech recognition errors, leading more often to unsuccessful task completion. The number of total errors, as well as the total workload in all three sets of tasks was generally lower in participants who reported using VAs more frequently, however, there were no statistically significant differences between the two groups of participants. Moreover, the majority of participants had difficulties in completing tasks that required the use of features they were unfamiliar with, regardless of their experience with VAs. The Chapter discussed the importance of minimising user errors to increase successful task completion, and discussed potential ways that this can be achieved, such as using confirmation dialogues.

The Study results showed a strong association between how participants evaluated the UX of the VA, and how cognitively demanding they perceived the tasks to be, indicating that, in order to improve the usability of VAs for people with ABI it is essential to reduce the complexity of the interaction. Different methods through which that can be achieved were discussed. These included adjusting the amount of conveyed information in the VA's responses to minimise memory load, and providing a more structured interaction where the input of information will be done in smaller chunks.

Finally, the findings of the study showed the importance of training and experience to improve the usability of VAs for people with ABI, by increasing the efficiency of use and reducing the occurrence of different obstacles to successful task completion. The different challenges associated with learning, as well as potential methods to approach this issue were discussed.

By examining and identifying the different issues that can occur during the interaction with VAs, as well as how these can hinder successful task completion and impact how people with ABI evaluate the usability of VAs, this chapter addressed the second research question of the thesis:

RQ2: Which are the factors that affect the usability of Voice Assistants when used by people with cognitive impairments due to ABI?

Moreover, by identifying the different challenges that can emerge when people with ABI interact with a VA to perform a wide variety of tasks, and by introducing potential solutions to overcome them, the chapter set the groundwork for providing an answer to the third research question:

RQ3: How can the usability of Voice Assistants be improved for people with ABI, through the design of the Conversational User Interface?

Chapter 6 will aim to gather the additional information required to determine the most suitable ways to design the CUI of VAs, in order to minimise the impact of the identified factors on their usability for people with ABI.

Chapter 6

Exploring the Design of a VA-based Prompting System

6.1 Introduction

The previous Chapters investigated how cognitive impairments caused by a brain injury can affect the use of Assistive Technologies. Chapters 4 and 5 specifically investigated the impact of these on the use of Voice Assistants, and determined how factors such as memory load, complexity of interaction, lack of initiation and changes in cognitive performance can limit their usability. Moreover, these chapters identified different aspects of the functioning of VAs that can affect their User Experience and efficacy as cognitive aids for people with ABI, such as their lack of portability and problematic speech recognition.

Additionally, Chapters 3, 4 and 5 showed that the usability of VAs for people with ABI can be improved by designing applications so that they employ certain characteristics (Table 3.5), and by adjusting their VUI to minimise mental workload and input errors. Furthermore, Chapter 5 concluded that the usability and overall UX of VAs can be improved through experience and learning, presented certain methods for improving the technology's learnability and discussed the associated learning challenges in people with ABI.

The objective of this Chapter is to assess the efficacy and applicability of the different design solutions to the above usability barriers, as well as look for unidentified methods to increase the usability of VAs in people with ABI. This is accomplished through the evaluation of the design of a prototype VA-based prompting system, which aims to increase the independence of people with cognitive impairments due to ABI. The VUI of the prototype was evaluated through an Expert Review [153] study (Study 6) with eight experts in the fields of Human-Computer Interaction (HCI) ($n=4$) and brain injury rehabilitation ($n=4$). The participants were presented

with the different aspects of the system's interface and provided their feedback on its design. The prototype, called Mindframe, encompasses several of the identified use cases of VAs listed in Table 4.3 related to the support of cognitive functions and the aid of the rehabilitation process.

This Chapter presents the design of the prototype system, and the results of the expert review study (Study 6). The specific aims of Study 6 were to evaluate the different ways to design the VUI of the prototype system in the following areas: 1) Conveying information to the user, 2) Providing prompts, 3) Enabling users to insert information to the system, 4) Monitoring and assessing the user's activity, and 5) Increasing the system's learnability. The participants' feedback was analysed to determine how the VUI in each area should be designed to reduce the workload of the interaction, minimise user errors, and increase the efficacy of the provided support.

By accomplishing the above, Study 6 aims to address the third research question of the thesis:

RQ3: How can the usability of Voice Assistants be improved for people with ABI?

6.1.1 Chapter Structure

Section 6.2 presents the design of the prototype prompting system (Mindframe). Section 6.3 describes the process of Study 6 and the methods used to acquire and analyse the experts' feedback on the design of the prototype. Section 6.4 presents the results of Study 6, and Section 6.5 discusses how the acquired feedback can be used to inform the design of VA applications for people with ABI. Finally, Section 6.6 summarises the results of Study 6 and describes how they inform the answer to RQ3.

6.2 Prototype Design

6.2.1 Prototype Concept and Development

The professionals interviewed in Study 2 described prompting as the most suitable way to support people with memory difficulties, lack of self awareness and behaviour issues, and reported that it can permanently improve functioning of people with ABI through the formation of routines and habits. The efficacy of prompting was also demonstrated in several of the reviewed studies in Chapter 2 (e.g. [63, 194, 203]). The findings of Study 3 identified specific ways that prompting can support the functioning of people with ABI, namely by increasing the fulfilment of future intentions, by improving task engagement and task completion, by notifying or reminding people of their inappropriate behaviour, by promoting habit formation, and by helping users

follow a specific schedule or plan. In order to provide the latter, a prompting system should be capable of calendar-management functionality, which can also support users with organisation, planning, time management and decision making difficulties (Table 4.3). Moreover, Chapters 3 and 4 found that, by supporting communication between family members/carers and people with ABI, and by acting as a means to provide remote support, a VA-based system can reduce conflicts and increase the sense of self-dependence of the person with ABI. Finally, these two Chapters showed that a VA application can improve the user's initiation and motivation, support their long-term memory and facilitate their rehabilitation process by providing monitoring of their day-to-day activity and completion of tasks.

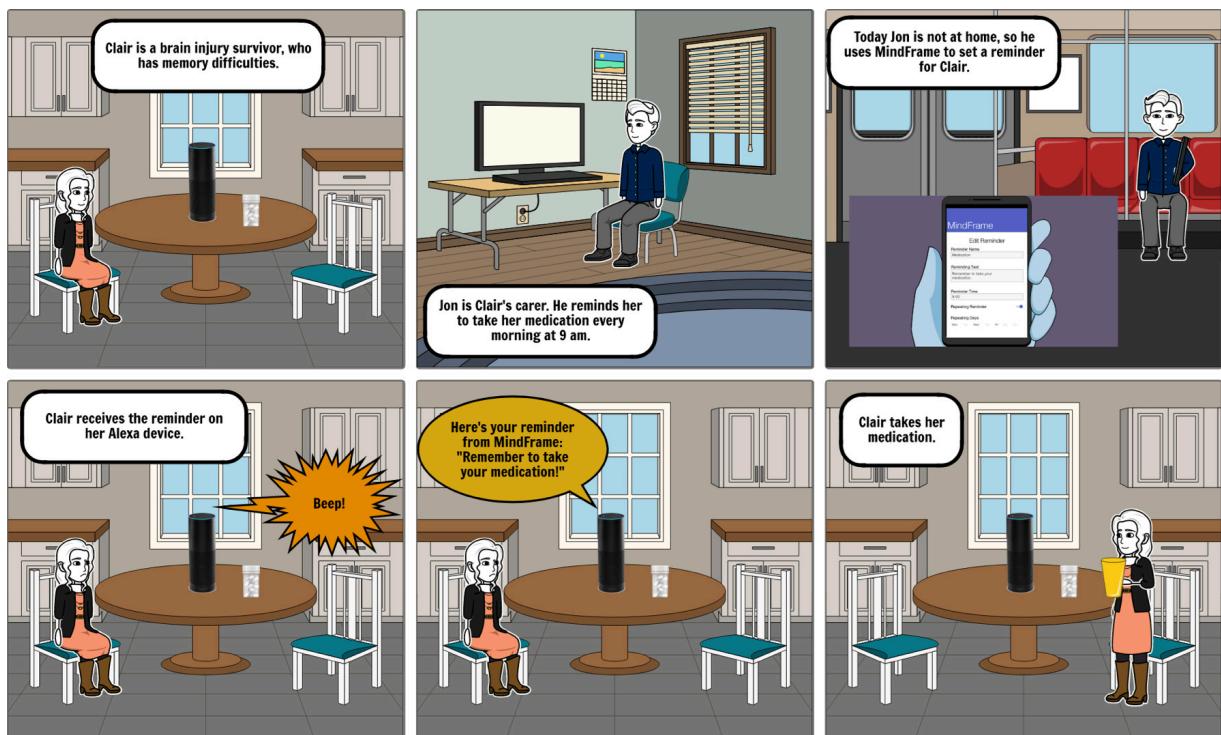


Figure 6.1: Storyboard used to describe the concept of the prototype (Mindframe) to participants of Study 6.

Mindframe, the prototype designed for the purposes of this study, is a multi-functional skill¹ for Amazon's Voice Assistant (Alexa), which encompasses the use cases described above. Specifically, the prototype enables people who provide support to a person with ABI (professional carers, family members, therapists) to schedule prompts through a web or mobile interface (Figure 6.2). The prompts, which are referred to as reminders within the application, are then conveyed to the end user (person with ABI) through a smart speaker (Amazon Echo) in an unsolicited manner, at the programmed time and date (Figure 6.1). Reminders can also be set to repeat on specific days of the week. Besides the day and time of the reminder, the system also enables users to specify the content of the message that is being conveyed to the person with ABI through

¹<https://developer.amazon.com/en-US/alexa/alexa-skills-kit> - Accessed: 11/5/2021

the "text" field. Additionally, each reminder can have a confirmation prompt which is conveyed at a specified time after the initial reminder, to increase its efficiency.

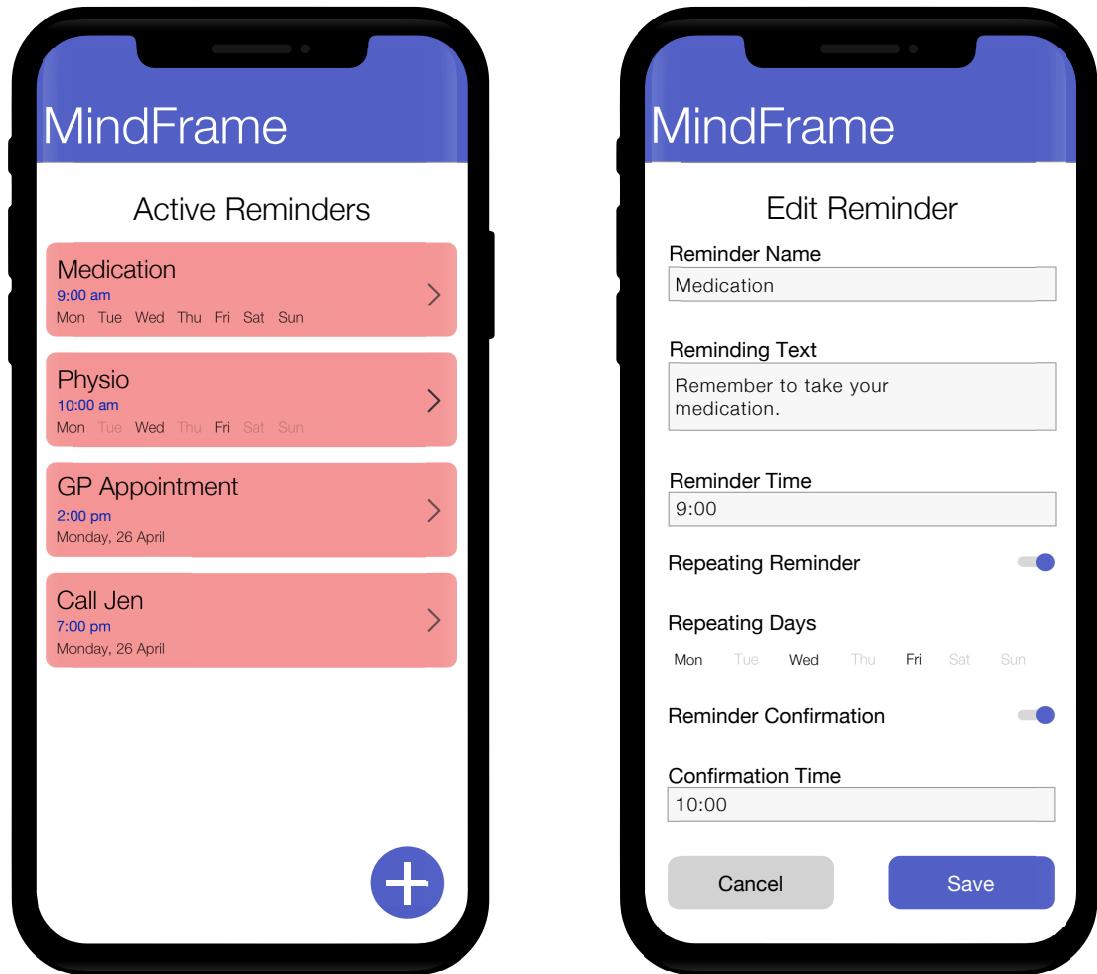


Figure 6.2: Mobile interface used to view (left) and create (right) reminders for the prototype prompting system (Mindframe). This interface is meant to be used by people providing support to the person with ABI.

Besides setting reminders through the web/mobile interface and conveying them to the user through the smart-speaker, Mindframe enables users to use its Voice User Interface to: 1) Receive a list of all the reminders programmed for a specific day; 2) Receive a list of missed or unconfirmed reminders; 3) Create new reminders, and 4) Modify or delete existing reminders.

6.2.2 Development

The "System in the Loop" method [138] was used for the evaluation of the prototype, implementing only the functionality of the system that was needed to collect the required data. The functional parts of the prototype that were developed for this study were built using the Ama-

zon's Alexa developer console². The participants of Study 6 interacted with the skill through the testing simulator provided by the developer's console.

6.3 Study Design

6.3.1 Participants

The participants of this study were experts in the field of Human-Computer Interaction (n=4) and Acquired Brain Injury rehabilitation (n=4). Similarly to Study 2, The study was conducted online due to the restrictions imposed by the COVID-19 pandemic. Including people with ABI as participants in an online study would complicate the recruitment process and would considerably limit the pool of participants to tech-savvy people with higher cognitive functioning. Additionally, it was deemed that experts of HCI and ABI rehabilitation would be able to offer valuable insight on the design of the prototype's speech interface and the usability of different methods to provide the intended support.

The HCI experts (P1-4) were members of the University of Glasgow's Multimodal Interaction Group³. P5 was a research associate at the University of Glasgow's department of Mental Health and Wellbeing, specialising in neuropsychological rehabilitation. P6 and P7 were neuropsychologists, responsible for running and coordinating a service for brain injury survivors in Scotland⁴. P8 was a neurological sight-loss rehabilitation specialist working with brain injury survivors in Glasgow, Scotland⁵.

6.3.2 Study Procedure

The study was conducted online using a videoconferencing software (Zoom). Each session lasted approximately 70 minutes, and commenced with participants filling in a short background questionnaire to indicate their experience with modern technology, Voice Assistants, and Acquired Brain Injury. Then, the purpose of the study was explained, and the concept of the prototype was described to the participants using a storyboard (Figure 6.1). Participants who reported not having professional knowledge of the effects of ABI (P1-4) were given two personas describing the profiles of two potential users of the system. The first persona described a middle-aged stroke survivor with severe memory impairments, attention and concentration difficulties,

²<https://developer.amazon.com/alexa/console/ask?> - Accessed: 11/5/2021

³<http://mig.dcs.gla.ac.uk/> - Accessed: 11/5/2021

⁴<http://www.wdhscp.org.uk/adults-with-disabilities/acquired-brain-injury/bien-group/> - Accessed: 11/5/2021

⁵<https://visibilityscotland.org.uk/our-services/neuro-project/> - Accessed: 11/5/2021

and impaired vision, who is interested in learning how to use speech-operated technologies but faces learning difficulties due to poor memory functioning. The second persona described a younger TBI survivor, with increased irritability and lack of patience, who is often unaware of his own behaviour issues and remains inactive most of the time, unless repeatedly prompted by his parents. The purpose of these personas was to outline some of the most common difficulties in people with ABI which were identified to affect the usability of VAs.

For the main phase of the study, the participants were asked to interact with the prototype to perform four tasks. For each task, a number of different versions of the VUI had been implemented, employing different approaches in the design of the interface. Each task was repeated a certain number of times, enabling participants to interact with the system using the different versions of the VUI. Figure 6.3 shows the layout that was shown to participants through screen sharing, during the execution of the tasks. At the left part of their screen the participants could see a brief description of each task, with a more detailed description given to them verbally. At the right side of their screen the participants could see the picture of an Amazon Echo device (smart speaker), which simulated the actual device running the prototype. When interacting with the system, the light of the device was on, indicating that the device was operational, and there was a "beep" sound playing at the beginning and end of each interaction. After the completion of each task, there was a discussion phase where participants were asked to express their view on the suitability of the different versions of the VUI presented to them, as well as discuss ideas about how the VUI should be designed to increase the usability of the system for that particular task.

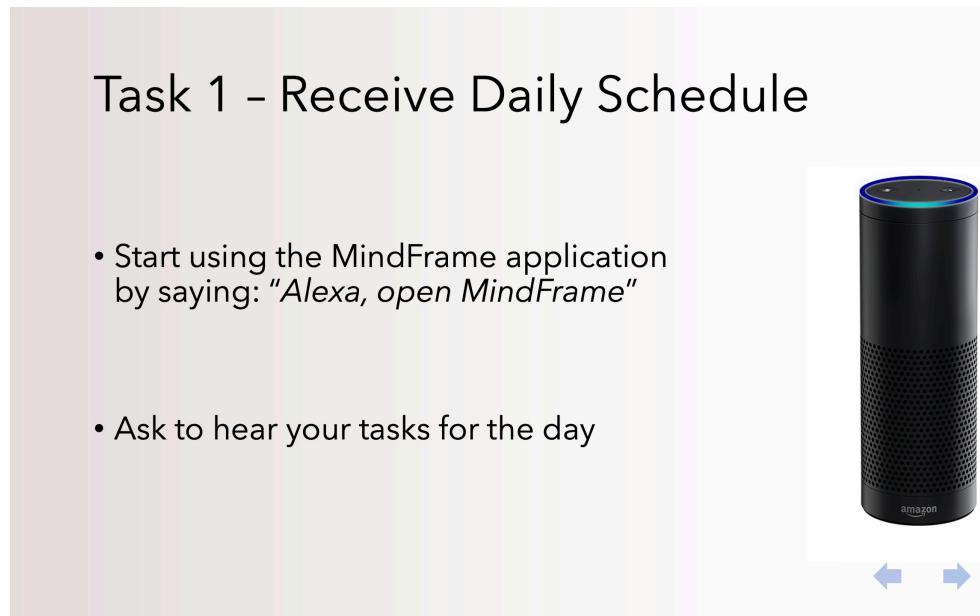


Figure 6.3: Layout shown to participants while performing the different tasks in Study 6. The light at the top of the device is on, indicating that the interaction with the system is ongoing.

The four main tasks that the participants were asked to carry out were the following:

Task 1 - Receive the day's schedule.

The findings of Study 5 indicated that conveying a list consisting of multiple pieces of information can be problematic due to the users' inability to process and memorise the contained information. This task aimed to evaluate the different ways to convey such information to the user, by presenting two different designs of the speech interface. The first version of the VUI that the participants interacting with for this task conveyed a list of four items (schedule of the day) as shown in the example below (lists of items in equivalent interactions from the built-in functionality of the VA in Study 5 contained 3 to 5 items):

User: *"Alexa, open Mindframe."*
 System: *"Welcome to Mindframe. What would you like to do?"*
 User: *"What are my tasks for the day?"*
 System: *"Here's your schedule for today: At 9am you have: 'take your medication'. At 10am you have: 'physio'. At 2pm you have: 'doctor's appointment'. At 7pm you have: 'call Jen'. Would you like to do something else?"*

The second version of the VUI presented the items contained in the list one at a time, requiring the user's input before providing the next item:

User: *"What are my tasks for the day?"*
 System: *"Here's your first task for today: At 9am you have: 'take your medication'. Would you like to hear the next one?"*
 User: *"Yes."*
 System: *"At 10am you have: 'physio'. Would you like to hear the next one?"*

Task 2 - Receive a reminder.

The second task required the participants to receive a prompt from the system. Chapters 3 and 4 found that the efficacy of a prompt conveyed by a technological aid can be compromised by the user's memory deficits or lack of motivation, as well as by the technology's lack of portability (in the case of smart speakers). This task aimed to explore how the efficacy of the prompt can be increased, by evaluating the different ways that it can be conveyed to the user, as supported by the functionality of the technology used. First, a reminder was conveyed to the participant in an unsolicited manner, as shown below:

[Device beeps - Light is on]
 System: *"Here's your reminder from Mindframe: Remember to take your medication at 10am."*
[Device beeps - Light is off]

The second method required the participant to actively ask to hear their reminder from the system when the light at the top of the device was on, simulating a situation where the user has missed a notification, as shown in the following example:

[Device light is on]

User: "Alexa, what's my notification?"

System: "You have one reminder from Mindframe: Remember to take your medication at 10am."

[Device light is off]

Task 3 - Create a reminder.

Tasks requiring user input, such as creating reminders/calendar events and making notes, in Study 5 had a higher rate of incorrect completion. The third task of the study aimed to examine different ways that the VUI of a VA could be designed for such a task. Specifically, the task required the participants to create a reminder for a doctor's appointment that had been scheduled on a specific day and time (the next day, at 2pm). The reminder had to be set to go off 2 hours before to the event. The first method to carry out the task required participants to convey all the needed information in a single sentence. The example below shows a successful task completion by one of the participants (P6):

User: "Alexa, ask Mindframe to remind me at 12pm tomorrow that my doctor's appointment is at 2pm."

System: "Sure, I'll remind you tomorrow at 12pm."

Although the "single sentence" method can reduce the interaction time, it was found that it can lead to user errors in Study 5. The second method employed a step-by-step approach, requiring users to insert only one piece of information at a time. This was one of the potential solutions to minimise input errors and mental workload discussed in Section 5.2.4. The following dialogue shows a part of an example interaction with that version of the VUI to create a reminder:

User: "Alexa, open Mindframe."

System: "Sure, welcome to Mindframe. Would you like to listen to your schedule, create a reminder, or do something else?"

User: "Create a reminder."

System: "What is the name of the reminder?"

User: "Doctor's appointment."

System: "What is the day of the reminder?"

User: "Tomorrow."

System: "What is the time of the reminder?"

User: "12pm."

The third version of the VUI that participants were asked to use in order to create a reminder employed the flexible, conversational approach typically characterising agent-based systems [138]. This version was capable of extracting any pieces of information included in an utterance and

ask for the missing ones, allowing users to freely decide how much information to include in a single sentence, as shown in the following example:

User: *"Alexa, open Mindframe."*
 System: *"Sure, welcome to Mindframe. What would you like to do?"*
 User: *"I want to create a reminder for my doctor's appointment."*
 System: *"Sure. When do you want to be reminded?"*
 User: *"Tomorrow at 12pm."*
 System: *"OK, doctor's appointment. I will remind you tomorrow at 12pm."*

In the discussion phase at the end of this task, apart from their feedback on the three different methods, the participants were also asked to express their view on different options regarding confirmations provided by the system to ensure correct information input (a single confirmation with all the inserted fields in the end, separate confirmations after inserting each field, or no confirmation at all).

Task 4 - Edit a reminder.

For the last task the participants were asked to change the time of an existing reminder. Editing information after it has been inserted to the system proved to be particularly problematic in Study 5, often resulting in unsuccessful task completion. This task focused on evaluating different methods to enable users to identify and select the reminder they want to edit, and the part of the reminder they want to change. Similarly to the other three tasks, the participants had to use different versions of the VUI to edit the reminder, with each version employing a different design. The first version involved conveying a list of 4 items (as in Task 1) from which the user had to select the correct one to edit, as shown in the example below:

User: *"Alexa, open Mindframe."*
 System: *"Sure, welcome to Mindframe. What would you like to do?"*
 User: *"I want to change a reminder for tomorrow."*
 System: *"You have four reminders set for tomorrow. At 9am you have: 'physio'. At 12pm you have: 'take your medication'. At 2pm you have: 'doctor's appointment'. At 7pm you have: 'call Jen'. Which one would you like to change?"*
 User: *"The one at 12pm."*
 System: *"What would you like to change in this reminder?"*
 User: *"The time."*
 System: *"What is the new time?"*
 User: *"10am."*
 System: *"OK, I have updated the time of your reminder."*

As with Task 1, the second version of the VUI employed a more structured approach, presenting one option at a time and requiring the user's input before presenting the next one, as follows:

User: *"I want to change a reminder."*
 System: *"When is the reminder you want to change?"*
 User: *"Tomorrow."*
 System: *"You have four reminders set for tomorrow. The first one is: 'take your medication', at 12pm. Is this the reminder you want to change?"*
 User: *"Yes."*
 System: *"What would you like to change in this reminder?"*
 User: *"The time."*

Finally, the third VUI version used for this task enabled participants to edit a reminder using a query consisting of a single sentence. The example below shows a successful task completion by one of the participants (P4):

User: *"Alexa, ask Mindframe to change the time of my medication reminder tomorrow from 12pm to 1pm."*
 System: *"Sure, the time of your reminder has been updated."*

Discussion.

After completing the four tasks, a discussion session followed during which the participants were asked to provide insights on the design of the prototype's VUI, in the following areas:

1. **Confirmations for task completion:** When examining the use of VAs and other cognitive aids in people with ABI, the previous chapters identified several situations where delivered prompts did not result in successful task completion. It was found that this usually occurs due to the user: forgetting the prompt a short time after it is received, not being able to remember the prompt's purpose, or being distracted before completing the task. Also, in the case of smart speakers, the efficacy of the conveyed prompt can be compromised by the device's lack of portability. A set of storyboards similar to the one showed in Figure 6.1 depicting the aforementioned issues was shown to the participants (see Appendix A). Then, the participants were asked to discuss ways in which the prototype could be designed to overcome these issues and increase task completion through confirmation prompts (prompts following the original reminder).
2. **Teaching users how to use the system:** The participants were asked to express their view on what would be the most suitable ways for people with ABI to learn how to effectively use a system like Mindframe.
3. **Monitoring the user's activity:** Besides providing prompts, another way that a tool like

Mindframe could be beneficial for people with ABI would be to monitor the user's daily activity, supporting their long-term memory and facilitating the rehabilitation process. The participants were asked to discuss potential ways that this could be achieved using data acquired through the use of the other features of the prototype, or with the implementation of additional features aiming to gather information about the user's activity.

6.3.3 Data Analysis

The audio of the sessions was recorded and transcribed. The transcribed data were analysed using Deductive Thematic Analysis [23], the framework for which was based on the objectives of the Study and the third research question of the thesis (RQ3). The initial coding of the results was based on which task of the study and which aspect of the interface the participants' responses corresponded to. Specifically, the initial codes were: 1) Receiving the day's schedule; 2) Receiving a reminder; 3) Creating a reminder; 4) Editing a reminder; 5) Confirmation of task completion; 6) Learning how to use the system, and 7) Monitoring. Within these categories, the results were analysed using a set of codes that were based on the discussion points and objectives of the study. These codes were: 1) Comparison between the different versions of the VUI; 2) Difficulties due to cognitive effects of ABI; 3) Design recommendations.

From the thematic analysis, several themes emerged, which are presented below, under their corresponding task-based categories. These themes were: Presentation of lists, and Search functionality (receiving the day's schedule); Priority of missed notifications (receiving a reminder); Length of interaction and security of input, and Supporting multiple versions (creating a reminder); Search functionality (editing a reminder); External help (learning how to use the system). Additionally, the following general themes emerged across the data, which are presented separately: 1) Repetition; 2) Prompting immediate action; 3) Integration with other devices; 4) Trust. The initially generated theme of "Customisation and adaptivity" was rejected, as the need for customisation and adaptivity in assistive technologies has been well established in the previous chapters, and this Study aims to provide more specific conclusions about how to design particular aspects of a VA interface. The initially generated theme of "Notification of system's status" was rejected due to containing a small amount of results. Additionally, the initial general theme named "Features" was rejected for being too broad. The contained data were distributed under the aforementioned task-based categories, signifying specific design recommendations for system features, for every aspect of the interface, forming the sub-themes mentioned above.

The transcribing, coding and the deductive thematic analysis of the data were conducted by the author of this thesis. The next Section presents the results, organised by the related part of the interface (each task of the study corresponded to a particular aspect of the interface), while the broader themes are presented separately at the end of the Section.

This study was approved by the University of Glasgow College of Science and Engineering ethics committee in August 2020.

6.4 Results

6.4.1 Receiving the Day's Schedule

As described above, for the first task participants interacted with the system to receive the schedule of the day in two different ways: through a list of four items, and by hearing one item at a time and being asked before hearing the next one.

Generally participants agreed that the list of four items would be too difficult to process and retain for a user with cognitive difficulties. Some participants (P1, P2, P4) reported that users would be more likely to remember the first and the last item on the list, while others (P5, P8) argued that it would be more challenging to memorise the items at the beginning of the list. P6 (ABI expert) reported that someone with a brain injury would most likely be unable to retain any of the conveyed information:

"There was so many of them. It's really quick. Someone with a brain injury would only get the first item, then would have forgotten it by the time it got to the end." (P6)

The majority of participants (n=5), however, agreed that receiving a list which includes all the reminders set for the day would be beneficial for users regardless of whether they would be able to memorise it, as it would inform them of the number of tasks they have planned and provide an overview of the day's schedule. Moreover, it was reported that if the list is being used for that purpose (i.e. as an overview), receiving a large amount of information will likely be anticipated by the users.

Regarding the second method (listing one item at a time), although it was mentioned that it could make it easier for users to memorise some of the items, most participants reported that it could significantly prolong the interaction and cause frustration.

Presentation of Lists

Participants described various ways to increase the efficiency and memorability of informing users of their daily schedule. One such way was to give emphasis to the first item on the list (or the next upcoming event). This could be done either by separating that particular item from the rest of the list (e.g. providing the first event, then asking if the user wants to hear the rest), or by

repeating it after having recited the entire list:

"An overview would be fine, but then we'd encourage people to ask for the first task of the day, and take it one task at a time. So to give you the list, but re-iterate what your first one is, in some way." (P6)

Another suggested way to make the presented schedule easier to process was to remove items from the list, if they were scheduled for a time before the time of the user's query (i.e. include only the upcoming events). However, even though this solution would reduce the length of the list, participants acknowledged that it would require appropriate management of missed events (this is further discussed below). Participants also reported that the conveyed list would be easier to manage if the events were categorised in groups, allowing the system to present a sub-group of events at a time. This could be done either by grouping events based on their time, e.g. tasks in the morning, afternoon, evening, etc. or by their importance. The latter would require the existence of an additional field in each reminder (priority), which would enable the user to determine whether an event would be presented before, or emphasised more than other events of the same day.

Regardless of the way that the list would be conveyed, however, all participants agreed that it would always be beneficial to inform users of the total number of events of the day (e.g. *"You have 6 tasks planned for today. The first one is..."*). Another piece of information which, according to participants, would be useful to provide every time the user asks for their schedule would be the current time. This should be provided at the end of the interaction, so that the user can know how much time there is until the next task.

Search Functionality

The majority of participants (n=5) argued that the system should allow users to search for specific items in their schedule, after listing the events of the day. This would enable users to better comprehend and retain certain tasks, improving the usability of this particular function. In particular, the system should allow users to ask about events that they were unable to memorise (e.g. *"What was the second task?"* - P1, or *"you told me the medication was at 9am, but can't remember when the physio was; repeat physio"* - P3), to ask for events at a specific time or period (e.g. *"What do I have before 2pm?"* - P7), or to ask for a specific type of events (e.g. *"remind me what my appointments are."* - P5).

6.4.2 Receiving a Reminder

For the second task participants used the system to receive a reminder in two different ways: through an unsolicited prompt, and by actively asking the system what their notification is, after noticing that the light on the device is on.

Regarding the first method, although participants agreed that it would be beneficial, many ($n=6$) expressed the concern that its successful delivery would depend on the user being within proximity of the device and being able to hear it. It was also argued that the way the prompt is phrased would have an impact on its efficiency (this is discussed later in this Section).

Several concerns were expressed by the participants with regard to the second way of receiving a reminder. Although it was reported that there is no downside in utilising the device's light to indicate the existence of a pending reminder, it was argued that users could fail to notice the light on time. This issue could be exacerbated by potential memory difficulties (forgetting to look at the device) or vision problems:

"For instance, a lot of people have physical challenges, so going to the bathroom takes a lot longer. If somebody's in the bathroom for 10-15 minutes and they miss the notification, they can be really unaware of it. And then they'd come back and not really be looking for the light on the device. That could be quite challenging for some." (P8)

The second concern that participants expressed regarding this method was that, even if they are able to notice the light on the device, some users might not react to it. This could happen either due to being unable to understand/remember what the light signifies, or due to lacking the motivation to initiate the interaction with the system. However, it was reported that the issues that these concerns describe could be overcome with appropriate training:

"I think if people were trained to use it, then yes. One the whole, most of the people we work with could be trained up and actually use it." (P6)

Finally, similarly to when receiving one's schedule, participants argued that it would be valuable to notify users of the current time after conveying a prompt (e.g. *"Remember to take your medication at 10am. The time now is 9:50."*)

Priority of Missed Notifications

In general, participants agreed on the importance of notifying users of missed reminders (i.e. reminders that were delivered by the system, but the user was not able to hear). When discussing the appropriate ways to convey more than one missed reminder, some participants (P2, P3) argued that using a list would not be as problematic as in the first task, since the contained

information would not need to be retained in the long term. Most participants, however, argued that users with cognitive difficulties would still be unable to process the information in the list. Moreover, participants expressed the concern that users could have difficulty distinguishing between missed reminder pertaining to older tasks, and reminders for upcoming tasks. Similarly to the previous task, a proposed way to overcome this issue, according to participants, would be by characterising certain reminders as more important or urgent when created. This would enable the system to determine whether a reminder should be contained in the queue of missed reminders (and for how long), or marked as delivered when conveyed through the first method.

6.4.3 Creating a Reminder

The third task of the study required participants to use the VUI of the prototype to create a reminder using three different methods: via a query consisting of a single sentence, by launching the skill and using the flexible/conversational version of the interface, and by using the structured, step-by-step version of the VUI.

All participants agreed that setting a reminder using the first method would be very challenging for a user with cognitive deficits, mainly due to the high cognitive load of the task, which would require users to combine different pieces of information in one sentence and to find the appropriate way to structure it:

"Giving a precise command and to be able to break it down in such a way is a skill in itself. It's quite high executive functioning. It requires planning, processing, mapping and high communication skills as well." (P8)

Additionally, participants mentioned that this method would be more prone to speech recognition errors.

The participants also agreed that the second method was generally easier and less cognitively demanding compared to the first one. The reported benefits of this method were: giving users more time to think what to say, allowing the information to be input in smaller chunks, and facilitating information recall by providing cues. Some participants (P7, P8), however, expressed concerns regarding the open-ended questions of the interface (e.g. "what would you like to do"), arguing that some users would likely *"ramble and end up making mistakes"* (P8).

Regarding the third method for creating a reminder (step-by-step approach), some participants (P1, P3) mentioned that it could unnecessarily elongate the interaction, potentially causing frustration to the users. ABI experts, however, agreed that it would be very beneficial for some users, such as people with more severe cognitive impairments or with difficulties in the fluidity of speech:

"I think the step-by-step approach will be massively helpful for people with a brain injury because it prompts. For some people, by the time they go to insert the reminder they might have forgotten the required information, so if it asks them every time they can retrieve that information." (P8)

Length of Interaction and Security of Input

When discussing the benefits and disadvantages of the three methods for creating a reminder, the participants often expressed the concern that a longer interaction, which requires a larger number of steps to complete, could frustrate and discourage users, especially those who experience irritability, lack of patience and lack of motivation. This issue would be exacerbated if a task has to be repeated several times (e.g. setting five reminders in a row). However, participants also acknowledged that a slower, more structured VUI can increase the chances of successful task completion and increase the users' confidence in interacting with the system.

A potential method that could decrease input errors, and therefore improve task completion which was discussed in Section 5.2.4, was the use of confirmation dialogues. Participants were asked to provide feedback on two different ways that confirmation dialogues could be applied: 1) multiple confirmations, one after every piece of information that is being input, and 2) a single confirmation dialogue at the end of the interaction. Although it was acknowledged that the former could ensure correct input and allow users to make corrections more easily, participants generally agreed that it could significantly increase frustration. Moreover, according to the HCI experts, it should be presumed that the majority of interactions would be carried out correctly, and that the design should aim to address occasional errors appropriately. Therefore the participants recommended a single confirmation dialogue at the end of the interaction as the most suitable solution, highlighting that, in the case of a negative response from the user (when an error has been detected), the system should offer the option to change a specific field of the reminder, or start from the beginning.

Supporting Multiple Versions

The participants were also asked to provide feedback on the concept of enabling users to choose between the two versions of the VUI (flexible or structured), as well as the possibility for the system to automatically switch between the two modes based on the user's performance.

All participants agreed that it would be beneficial for the system to support both methods, in order to address users with different capabilities or dispositions. Regarding the possibility of the system automatically adjusting the VUI to match the user's performance, it was reported that

this would support users whose cognitive performance can fluctuate from day to day. However, participants argued that changing between the two versions too often would compromise the system's consistency, and that, in the case of people with ABI, it is preferred to use only one method until they learn it well:

"It's better if people learn to do things one way, it should be very consistent. And it can take a long time to get used to it, but it's worth to just keeping on going so that they can iterate through the steps. We have definitely have found that it's just better sticking to one method." (P6)

The participants agreed that, for most people with ABI, the step-by-step version of the VUI should be the default option when starting to use the system. This would allow users to safely learn how to interact with the system, and gain confidence in using it by themselves, before the carer or therapist determines that they are able to use the more flexible mode:

"From a therapist perspective, when you're teaching something to people with a brain injury you usually put things to a most basic setting, and then when you progress you start to go to the advanced setting." (P8)

6.4.4 Editing a Reminder

The fourth task required participants to edit one of the reminders that had already being input in the system, using three different methods: 1) via a single utterance, 2) by using the VUI to select a reminder from a list of results, and 3) through the VUI providing one result at a time and asking for confirmation.

HCI experts (P1, P3 & P4) reported that using the first method to edit a reminder was generally easier and less mentally demanding, when compared to using the same method to create a reminder (second task). The reason for this difference was that, in the case of editing, the user's focus is on one particular piece of information (e.g. time of the reminder). Moreover, the participants argued that this method could be preferred by some users, as it allows for a significantly faster task completion. However, the majority of participants (n=6) described the second method as the most suitable for editing a reminder overall, with regard to mental demand and length of interaction. According to the participants, selecting which reminder to change from a list enables users to efficiently identify the one they want to edit, even though they might not remember some of its details (e.g. the exact time). Moreover, it was argued that using the list in this context would be less problematic than in task 1 (receiving the day's schedule), as the objective of the user is to identify and process only one item in the list, and the retrieved information needs to be retained in the short term (only for the duration of the task).

Participants reported that the interaction length of the third method could vary, depending on

the position of the reminder the user wants to change in the list. Even though this method could reduce the duration and mental demand of the task, if the user is able to identify the sought reminder early, it could significantly increase the number of interactions required to complete the task in the opposite case. Moreover, it was argued that hearing the whole list of events could ensure that the user does not edit the wrong reminder.

Search Functionality

In the implemented methods described above, users were required to search for the reminder they wanted to edit by its day or time (*"When is the reminder you want to change?"*). According to some participants (P5, P7), this could be confusing for users when trying to edit repeating reminders (e.g. replying with *"every day"* to the "when" question). As with task 1, participants argued that providing a more versatile search functionality could improve the usability of the system for this particular task, as it would allow users to identify reminders by their name when the day/time is unknown, or if the reminder is repeating. Moreover, a more flexible way to search, enabling users to include multiple pieces of information in their query (e.g. *"medication tomorrow"*) would return less results, making the conveyed list easier to process.

6.4.5 Confirmation of Task Completion

During the discussion phase of the study, participants were asked to express their view on how task completion can be ensured through confirmation prompts, i.e. prompts about a past reminder delivered some time after the original. One of the options discussed was for the system to repeat the original prompt at regular intervals. Participants agreed that this approach would be beneficial in the case that the user does not hear or forgets the first prompt, or gets distracted before completing the task. However, it was argued that the suitability of this method would depend on the nature and timing of the task the prompt is in relation to. For instance, although it could be useful for the system to repeat a reminder about medication a few minutes after the time they were supposed to be taken, it would not work the same way for a task that would require the user to leave the house at a specific time (e.g. doctor's appointment).

Due to the above issue, participants identified two different purposes in repeating prompts: to remind the user to carry out a task they might have forgotten or neglected, or to simply notify them that they have failed to carry out a task. In order to enable participants to distinguish between the two, it was argued that the phrasing of the confirmation prompt would have to be different than that of the original, and would have to be specified when the prompt is being created.

Finally, participants argued that the system's VUI should enable users to respond to a confirmation prompt to mark it as "completed" or "delivered". This would allow the system to determine when to stop repeating a prompt, and could be accomplished in two ways: 1) By allowing users to unpromptedly notify the system that they have completed a task, or that they have successfully received the reminder (e.g. by saying "*tell Mindframe that I have taken my medication*"), and 2) by phrasing confirmation prompts as questions, expecting a yes or no answer from the user (e.g. "*Have you taken your medication yet?*"

6.4.6 Learning How to Use the System

The next discussion topic was how people with ABI can learn to use a system like Mindframe. The most commonly reported solution was the use of a speech-based tutorial. Participants argued that the tutorial should be automatically activated the first time someone uses the system, describing its capabilities and providing guidance on how to complete supported tasks. It was also argued that it should be designed in a way that provides practical experience, allowing users to complete practice tasks which resemble real-life situations, giving instructions and feedback for every step of the interaction. According to the participants, this would help users understand and memorise the correct way to phrase their sentences and become more confident in interacting with the system:

"[...] It would say 'We're going to set a reminder for today for a GP appointment at 2 o'clock, but you want to walk to the doctor's, so we're going to set it for 12 o'clock today.' And it should give feedback: 'that was good, but wasn't quite right, let's try again'. So allowing a safe learning space." (P8)

Apart from automatically enabling the tutorial the first time the system is used, it was argued that support should always be available through a "help" command. Specifically, participants suggested that, when used, the "help" command should provide users with the following options: 1) Receive an overview of the system's capabilities with example phrases; 2) access the tutorial for a specific task; 3) receive help with the task they are currently trying to complete. Additionally, participants reported that the system should also offer help automatically when errors occur frequently, or when detecting phrases like "*I don't know what to do*". When possible, the help provided through this method should be contextualised, based on keywords contained in the user's query:

"E.g. when it hears 'reminder' it asks directly: 'do you want to set a reminder or edit a reminder?' Not too many options because then it gets complicated. And then you present [users] with keywords that you know your system can process." (P1)

In addition to helping users learn how to use the system, the system's help functionality could

also be utilised for rehabilitation/therapy purposes, to help the person with ABI acquire the skills required to control a system like Mindframe, reducing the involvement of other people:

"If someone is receiving quite intense therapy, every time the OT or the rehabilitation specialist comes out they could open up the training app and practice. Because it could be that the person isn't setting any reminders to begin with, they just use it to receive the reminders. But as a therapist you want that to be progressive, to increase independence. So you'd be going into training mode every time you are there, until you get the person to the point of full control. There could be a couple of scenarios that you can go and do to practice. e.g. setting reminders, cancelling, editing etc. That will remove the third party which is the therapist, family member or carer." (P8)

External Help

Even though the above solutions could provide adequate support for some users, it was argued that they wouldn't be enough for people with more severe memory impairments, or for those who are not "tech savvy". According to participants, in order to enable such users to use the system efficiently, additional help should be provided externally.

One suggested way that this could be achieved was with the use of a reference sheet or leaflet, which can be placed next to the smart speaker, containing a list of example phrases corresponding to the different tasks supported by the system. Specifically, this "reference sheet" should contain instructions on how to: launch the skill, ask for the system's help, and carry out different tasks. Apart from supporting the users' memory, this method could provide an initial guidance that would improve the experience of future interactions:

"That would also help teach them the language to better communicate with the system. It would give them something to work off, which means they would not get the negative experience of putting the effort to trying to learn the system by themselves." (P2)

Additionally, ABI experts (P6, P7 & P8) reported that many people with ABI would require help from other people to be able to learn how to use a system like Mindframe. In most cases, this help would be needed for an initial period, until the users become confident in operating the system on their own. However, in other cases, the need of external support can be continuous.

6.4.7 Monitoring

The final topic that was discussed was how a prompting system like Mindframe could be used to monitor the activity of a person with ABI. According to participants, the data gathered through

such a system that could be associated with the user's activeness is the number of times they use the system to set reminders, as well as the tasks that have been confirmed as completed. That information can be used to provide an overview of the person's activity to therapists or carers, allowing them to assess the user's progress, or to the users themselves, supporting their long-term memory and self-monitoring.

In addition to data associated with creating and receiving prompts, participants also discussed the idea of enabling users to actively input information regarding their daily activity to the system. Participants agreed that the most suitable way to achieve this would be by prompting the users to summarise their activity at the end of the day. According to ABI experts, this recapping process could also help improve memory functioning and provide a sense of self-fulfilment. In order to support users with memory difficulties in this process, participants argued that the system should enquire about specific tasks that had been planned for the day, instead of using open-ended questions (e.g. "Did you do your physio this morning?" instead of "What did you do today?"). However, participants also reported that this would not be suitable for every person, and should therefore be made optional through the system's settings. Finally, participants mentioned potential privacy issues in monitoring the user's activity, highlighting the need to appropriately inform the users on a regular basis that their usage day is being monitored.

6.4.8 General Themes

In addition to feedback referring to specific functions of the prototype, the thematic analysis identified four themes in the participants' responses that can be associated with the design of the system as a whole.

Repetition

Although repetition of information which is not necessary to complete a task can prolong the interaction with the system, participants reported that it can often be beneficial for people with ABI. Specifically, conveying the whole list of reminders set for the day can support the users' memory functioning, and increase their familiarity with their tasks:

"Repetition is the key. The more they repeat things, the easier it is to retain it. So it's a list that should be familiar to that person, or it might not be familiar, but hearing it again generally has a better outcome because it's their list, it's their day. It's not going to take too long to run through that anyway." (P8)

Apart from lists of reminders, participants also often reported that repetition can be beneficial when conveying prompts. Although it was acknowledged that repeatedly receiving the same

prompt could become irritating, ABI experts argued that it could be necessary for some of the users with a tendency to forget or get distracted. However, it was argued that the frequency of repetitions should depend on the urgency of the task, with participants once again discussing the need of characterising certain reminders as more important than others when being created:

"It could be something that you could enter when you're setting the reminder. Based on its alert level, if it's really important it could remind you every ten minutes. But if it's less important it could remind you less frequently." (P5)

Prompting Immediate Action

Participants often expressed the view that reminders should be conveyed in a way that prompts immediate action, in order to be more efficient. Specifically, it was reported that users will be more likely to accept a task, and less likely to forget it, if the message of the prompt contains a description of the upcoming event, and an action that needs to be taken immediately, at the moment that the prompt is being conveyed. Moreover, according to ABI experts, the prompts should be phrased in a short and direct way, to encourage action for people with motivation/initiation issues:

"The reminder should not be just 'you have a physio appointment'. It should be 'you need to book your taxi now to go to your physio appointment'." (P8)

Integration with Other Devices

Participants often stated that the efficacy of a prompting system like Mindframe could be increased if it worked in combination with other devices, in the following ways:

- **Smartphones:** As a back-up method for conveying prompts via push notifications, to ensure delivery; To notify users about reminders create through the VUI, enabling them to confirm that the correct data has been input; To view the reference sheet including the example phrases and voice commands for the system's VUI, increasing its accessibility.
- **Smart devices:** Smart bulbs or TVs can be used to make users aware of a pending reminder (e.g. by flashing or displaying a message respectively); Motion sensors can be used to detect that the user is within proximity of the smart speaker and convey the prompt at the appropriate time.
- **Wearables:** Devices like smartwatches can be used to notify users of a pending notification, or to mark a reminder as "complete" when the user cannot access the smart speaker.

Trust

Finally, participants often discussed the importance of the user's trust towards the system, which can have an impact on whether they would accept the prompt, or choose to interact with the system. ABI experts reported that the speech modality of VAs is generally advantageous in that regard compared to the modalities of other technologies (e.g. text messages on smartphones or sound alarms), as people with ABI find voice messages and prompts reassuring, and are more likely to react to them. However, they also argued that users would be more likely to accept a prompt if the system's tone is polite and personal. Besides adjusting the wording of the prompts, this could also be achieved by including the name of the person who created the prompt, or play voice messages they (carer, family member or therapist) have recorded:

"If it says 'you created this', they might think, 'I'm not sure if I set that right'. Or they might say 'oh Genie [carer] set that so it must be right'." (P7)

6.5 Discussion

Lists of reminders/tasks

Poor memory functioning and information processing were among the identified factors that can affect the usability of VAs in the previous chapters. This issue was prominent in interactions that involved conveying a list of items to the user in Study 5, where lists were found to be problematic due to the users' inability to process or retain the contained information. This Study examined a variety of ways to convey lists of reminders, in different contexts (receiving one's schedule, receiving missed reminders). The participants generally agreed that people with ABI would be unable to memorise all the reminders contained in the list, regardless of its length (only the cases where a list contains at least three items were discussed). However, it was pointed out that the use of lists is less problematic in tasks requiring the identification of a specific item (e.g. when editing an existing reminder), and can be efficient in giving users an overview of their daily schedule. Moreover, participants reported that the user's ability to process a list of reminders can be improved through repetition, as it enables them to familiarise with their pending tasks. This is in agreement with results from Study 5, where participants were more likely to retain the VAs response if it contained information they were already familiar with.

A long list⁶, however, can elongate the interaction and cause frustration. In cases where memorisation of items in a list is required, the following methods were identified from the par-

⁶Amazon's design guidelines for the Alexa VA state that lists should not contain more than four items: <https://developer.amazon.com/en-US/docs/alexa/alexa-design/alexa-conversations.html>- Accessed: 11/5/2021

ticipants' responses, which can improve the user's ability to process the conveyed information:

1. **Emphasising the first item:** This can be appropriate when the list contains upcoming tasks that the user will need to accomplish during the day. In the case that the items in the list are sorted based on the time that they will have to be completed, the first item will correspond to the next task that the user is required to complete. Emphasis on this item can be given by re-iterating it after the list is conveyed.
2. **Priority of items based on importance or urgency:** The length of the conveyed list can be reduced by including only items that are important or urgent. This would require to include an additional component in each reminder, which would enable users to prioritise certain items upon creation. Priority can be given to tasks that require more time to complete (e.g. getting ready for an appointment), or time-critical tasks (e.g. medication). After conveying the list of prioritised reminders, the user should be offered the option to hear the remaining items.
3. **Search functionality:** Providing the ability to search for specific reminders in the list after it is conveyed, can enable users to enquire about items they were unable to memorise or process. Searching by the reminder's time, its position in the list, or by keywords in the reminder's name should be supported.

Prompts and Confirmations

As discussed in chapters 3 and 4, memory difficulties, reduced of motivation and lack of self-awareness can affect the efficiency of conveyed prompts. A solution to this issue discussed in Section 4.2.4 was to provide prompts in an unsolicited manner (i.e. not relying on the user's initiative), a method that has been shown to be efficient in related research [84, 94, 167]. Although participants in this Study reported that unsolicited prompts can be helpful, it was highlighted that they rely on the user being within proximity of the smart speaker. Moreover, participants argued that, for some users, receiving a single prompt would not be enough to ensure task completion.

One of the suggested approaches to increase the efficacy of conveyed prompts was related to adjusting the way it is phrased. In particular, participants reported that prompts should be worded in a direct way that cues immediate action, encouraging users to carry out the corresponding task at the moment the prompt is being conveyed, rather than simply notifying them of an upcoming event. This can decrease the possibility that the prompt is forgotten, or the user is distracted before the task is completed. Additionally, it was argued that users would be more likely to react to a prompt if the name of the person who created it (family member, carer or therapist) is mentioned. This is in agreement with the findings of Chapter 3 (Table 3.5), regarding the trustworthiness of assistive technologies.

Another suggested way to increase the efficiency of a conveyed prompt was through repetition. According to participants, repeating a reminder at regular intervals can improve task completion. This would require enabling users to confirm that they have successfully received the prompt or completed the task, either by phrasing the repeated prompt as a question (expecting a yes/no answer from the user), or by allowing them to unpromptedly notify the system when the task is complete. Finally, it was argued that repetition of prompts should only be used for reminders that have been marked as important or urgent, as they could otherwise become annoying or frustrating. The importance/urgency of a reminder could also be used to determine the frequency of repetition.

Information Input

In Study 5, tasks that required users to input information to the system (such as creating reminders, taking notes or adding calendar events) often resulted in user errors and unsuccessful task completion. From the different methods to input information presented to the participants in this Study, the "single-utterance" approach (including all the required information in a single sentence) was found to be the most cognitively demanding, especially when the query contained multiple pieces of information. Similarly, tasks that required participants to input information through this method in Study 5 often led to user errors.

Contrarily, the other two methods presented were found to be more effective in reducing the task's cognitive demand, facilitating information recall, and minimising the possibility of user errors. Out of these two methods, the more structured/step-by-step approach (requiring the input of one piece of information at a time), was the one that participants recommended should be used for people who are not familiar with VAs, or with more severe cognitive impairments. The flexible/conversational approach was reported to offer the potential of reducing the length of interaction and, therefore, reducing frustration, when used successfully. However, participants recommended that it would be more appropriate for users who are familiar with interacting with VAs, as the ambiguity of cues (open-ended questions) can lead to confusion and input errors. As there were reported advantages in both methods, it was argued that both should be supported, to address users with different abilities. This could be accomplished through a customisation option, which is discussed later in this Section.

Finally, the use of confirmation dialogues was discussed with participants, which, as discussed in Section 5.2.4, can decrease input errors. According to the participants' feedback, offering a single confirmation dialogue after the user has completed the input of all the required information, is adequate to ensure correct input, and would avoid unnecessarily prolonging the interaction. This is in agreement with related literature showing that less confirmation dialogues can increase task completion speed, without compromising task success [230]. As recommended by

the participants, confirmation dialogues should offer the option to start over or change a specific item in the case that the user detects an error in their input.

System Help

Chapters 4 and 5 showed that learning how to use a VA, and discovering unknown functions can be challenging for people with ABI. Pradhan *et al.* argued that speech-based applications should be designed to employ a variety of features that support discoverability, to improve usability for people with disabilities [169]. The results of this Study showed that help can be provided to users of a VA-based system with the following methods:

1. **Tutorial:** A speech-based tutorial should be automatically enabled the first time the system is used to perform a specific task ("learn as-you-go" [36]), and it should be designed to walk users through the completion of training tasks, simulating real-life scenarios. During the execution of these tasks, the system should provide detailed instructions and feedback for every step of the interaction, informing users of how to phrase their input to avoid errors. The users of the system should also be able to access the tutorial whenever needed.
2. **"Help" command:** The system should support the use of a specific word/phrase (e.g. "help"), which can be used at any time during interaction, providing the following options: 1) Giving a description of what the system can be used for, including example sentences for each supported task; 2) Launching the tutorial for a specific function of the system; 3) Providing guidance for the task currently performed by the user ("contextualised help" [36]).
3. **Automatic support:** The system should automatically provide help to support task completion during interaction, when a certain number of consecutive errors are detected, or when the user's input includes phrases like "*I don't know*" or "*I'm not sure*". Additionally, it can automatically provide guidance on how to complete a certain task, when the user performs an unsuccessful query containing keywords that can be associated to that task.

Customisation and Adaptivity

According to the findings in Chapter 3, a technological aid should offer customisation and adaptivity, to support users with different levels of impairment, cognitive capabilities and rehabilitation goals. A VA-based prompting system like the one presented in this Study can support the above by: 1) Enabling users to switch between the different versions of the VUI (flexible, step-by-step), when deemed appropriate; 2) Enabling users to prioritise certain prompts, and adjust

the way lists are presented accordingly; 3) Detecting when the user is having difficulty completing a task, and providing suitable guidance; 4) Allowing users to determine the exact content and phrasing of a prompt, as well as its repetition frequency; 5) Offering different options for enabling users to confirm task completion.

Chapter 4 discussed that adaptivity in a system's interface could be used to support changes in the cognitive performance and abilities of a person with ABI. This study examined the solution of automatically switching between the two versions of the voice user interface (flexible/structured). ABI experts argued that this would compromise the consistency of the system, hindering the users' ability to learn how to use the system. It was recommended that a change in the interface should be used when the carer, family member or therapist considers appropriate, or when users have become familiar and fully confident with using the system.

6.6 Conclusion

This Chapter examined different ways to design the voice user interface of a VA-based prompting system for people with ABI. The described Study focused on aspects of the interaction with VAs that had been characterised as problematic in the previous chapters, acquiring the feedback of experts in the fields of HCI and brain injury rehabilitation to determine methods to overcome them.

First, the Chapter described the advantages and challenges of conveying lists of reminders in different contexts, and determined that by prioritising certain items and offering search functionality, they can be more easily processed. Secondly, the Chapter examined different ways to convey prompts, and found that their efficacy can be improved through appropriate phrasing that encourages immediate action, repetition at regular intervals, and by requiring user confirmation. Thirdly, different approaches for inputting information were examined, concluding that breaking down the interaction to smaller steps can improve task completion and minimise user errors. Finally, the Chapter presented different ways to increase the learnability of a VA-based prompting system through user-activated and adaptive guidance, and introduced ways that the system can be customised to support users with different abilities.

By presenting the above, the Chapter addressed the third research question of the thesis:

RQ3: How can the usability of Voice Assistants be improved for people with ABI?

Chapter 7

Conclusions

7.1 Introduction

This thesis made the following statement in its Introduction:

Although Voice Assistants can offer advantages over other external aids in supporting the everyday functioning of people with cognitive impairments due to Acquired Brain Injury, there exist several factors that can affect their usability, and their use with this particular user group has not been thoroughly examined. This thesis presents a set of requirements-capturing studies which examined the impact of the effects of a brain injury on the use of external cognitive aids, investigated how people with Acquired Brain Injury use and interact with Voice Assistants, and explored different methods to improve their usability through the design of their voice user interface. This thesis presents the different situations where the use of Voice Assistants is appropriate and beneficial for people with Acquired Brain Injury, the identified factors that can impact the technology's usability, and a set of design guidelines to increase their efficacy in supporting the functioning and rehabilitation process of brain injury survivors.

In the subsequent chapters, research was presented which supports this statement, addressing the research questions of this thesis. Chapter 3 examined the common cognitive difficulties in people with Acquired Brain Injury, and how these associate with the use of external cognitive aids. It presented a set of areas where technology can be used to benefit people with ABI, and a set of design characteristics that can render technological aids more efficient and acceptable, laying the groundwork for determining how to use and design VAs to better support people with ABI. Chapter 4 further examined how ABI-induced impairments can affect everyday life and impact the use of external aids, investigated how people with ABI use VAs, and identified factors that affect interaction and limit their use. In combination with the results from Chapter 3,

a comprehensive list of ways that VAs can be used to benefit people with ABI was presented. The manner and extent to which the different factors identified in Chapter 4 can affect the usability of VAs, were examined in a wide range of VA-supported tasks in Chapter 5. The Chapter highlighted the key considerations for designing VA applications for people with ABI and discussed potential design solutions to improve their usability. Chapter 6 evaluated the discussed solutions, and further investigated how to improve the usability of VAs, establishing a set of design guidelines for VA applications to support people with ABI. This final chapter summarises the findings of the studies described in this thesis, and discusses how they address the three research questions. Additionally, it summarises the main contributions, discusses limitations of the research work and presents areas for future work.

7.2 Research Questions

7.2.1 Research Question RQ1

What are the use cases of Voice Assistants for users with cognitive impairments due to Acquired Brain Injury?

To answer this question, the studies reported in Chapter 3 investigated the common cognitive effects of ABI, the characteristics of people with ABI who use external aids, and the common methods and objectives of neuropsychological rehabilitation. Moreover, the view of ABI experts on the use and purpose of technological aids was acquired. The studies described in Chapter 4 further examined the impact of the effects of ABI in everyday life, gained feedback from people with ABI on the concept of using VAs as cognitive aids in different contexts, examined how people with ABI use VAs, and looked at how the use of VAs compares to other external aids. By identifying the common injury-induced difficulties in everyday life, the purpose of use of VAs and other external aids, and the objectives of rehabilitation, Chapters 3 and 4 determined the situations where the use of VAs can be beneficial for people with ABI. Additionally, by examining the common difficulties that people with ABI face when using paper-based and electronic cognitive aids, these two chapters identified situations where VAs could provide a more suitable alternative to other aids, or complement their use.

The analysis of the findings showed that Voice Assistants can support the performance of impaired cognitive functions, such as prospective memory and organisation, through the use of reminders, alarms/timers, calendar management and speech-based applications for problem solving strategies. Additionally, they can be used to support behaviour issues and lack of motivation or initiation through timely prompts, facilitate the communication and support between

the person with ABI and their carer or therapist, provide remote support and monitoring, and facilitate the rehabilitation process. Finally, they can be used as training tools to carry out cognitive exercises and improve communication skills. The final list of identified use cases can be seen in Table 7.1.

7.2.2 Research Question RQ2

What are the factors that affect the usability of Voice Assistants when used by people with ABI?

The first step in identifying the factors that can affect the usability of VAs was to investigate the prevalence of the common cognitive effects of ABI, in users of external aids. This was accomplished through the studies described in chapters 3 and 4, which determined the characteristics of potential users of VAs. The impact of the effects of ABI on the use of other external aids was also investigated in these chapters, to determine whether the use of VAs can also be impacted in similar ways. To further investigate their usability, Study 4 (Chapter 4) looked at the common difficulties that people with ABI have when interacting with VAs. Due to the limited range of tasks that participants in Study 4 reported using VAs for, Study 5 (Chapter 5) investigated the interaction of people with ABI with VAs, in a wider spectrum of tasks. The identified factors were: Memory, complexity of interaction, speech recognition, lack of motivation, lack of self-awareness, change in the person's cognitive abilities and performance, learning difficulties, the VAs' lack of portability, and privacy and security concerns. These factors are listed in Table 7.2.

7.2.3 Research Question RQ3

How can the usability of Voice Assistants be improved for people with ABI?

To answer this research question, Study 6 (Chapter 6) acquired feedback from experts in the fields of HCI and brain injury rehabilitation on the design of a prototype VA-based prompting system, aiming to increase the independence of people with ABI. The study assessed the efficacy and applicability of different solutions to the identified usability barriers and looked for new methods to increase the usability of VAs. The study investigated the following areas: 1) How to convey lists of reminders or tasks, so that they can be successfully processed and memorised; 2) How to increase the efficiency of conveyed prompts; 3) How to reduce mental demand and errors during input; 4) How to confirm task completion and successful delivery of prompts; 5) How can users learn to use a speech-based system, and 6) How can the user's activity be monitored.

The participants' feedback on the different solutions that were presented, was used to create a set of design guidelines for improving the usability of a VA-based prompting system. The design guidelines are listed in Table 7.3.

7.3 Contributions

This thesis makes novel contributions which inform about the use of Voice Assistants, and the design of VA-based applications to support the everyday functioning and rehabilitation of people with cognitive impairments due to Acquired Brain Injury. The main contributions are:

1. A set of use-cases describing the situations where Voice Assistants can be used to support people with ABI;
2. A list of identified factors that can affect the usability of Voice Assistants, focused on the cognitive difficulties of people with ABI and the technology's functionality;
3. A set of design guidelines for creating a VA-based prompting system to support the everyday functioning and facilitate the rehabilitation of people with ABI.

7.3.1 Use Cases of Voice Assistants

The results of the studies described in Chapters 3 and 4 were used to determine the use-cases of Voice Assistants for people with ABI, which can be used to inform researchers to further examine the use of VAs in this particular context, clinicians and therapists who aim to use VAs in their practice, as well as people with ABI who want to benefit from the use of VAs, and are presented in Table 7.1. The identified use-cases show that Voice Assistants can be used in a wide range of contexts, from supporting the performance of impaired cognitive functions, to facilitating the rehabilitation process and the collaboration between the person with ABI and their carers, family members and therapists. For further discussion see Sections 3.4, 4.2.4 and 4.4.

7.3.2 Factors that Affect the Usability of Voice Assistants

The results of the studies described in Chapters 3, 4 and 5 were used to determine the different factors that can hinder the usability of VAs. These factors show that cognitive impairments affecting memory performance, information processing, motivation and self-awareness can prevent people with ABI from using VAs efficiently. Additionally, they present important issues

Targeted Area	Use Cases
Prospective memory	Reminders, alarms and timers to remind users of upcoming tasks and events
Organisation	Calendar management, reminders, speech-based applications for applying problem solving strategies
Long term memory	Note taking, storing autobiographical memories, self monitoring
Inappropriate behaviour	Prompts to notify users when behaving inappropriately, reminders for relevant rehabilitation strategies
Initiation and motivation	Prompts to encourage activity, self-monitoring and rewards
Communication	Speaking practice and exercises, send/receive messages to/from carers, family members, therapists and other ABI survivors
Cognitive training	Speech-based cognitive rehabilitation exercises
Support from carers/family	Convey messages indirectly from carers/family, to reduce conflict and increase sense of self-dependence
Assessment	Monitor task completion and gather data to inform rehabilitation and therapy sessions
Accessibility of external aids	Provide alternative speech-based interaction method for currently used external aids
Efficiency of external aids	Encourage and facilitate use of other external aids

Table 7.1: Use cases of voice assistants for people with cognitive impairments due to ABI.

that designers of VA-based applications need to consider when developing solutions for people with ABI, and identify key areas for HCI researchers examining how to improve the usability of VAs. These factors are presented in Table 7.2. For further discussion see Sections 3.4, 4.2.4, 4.4 and 5.2.4.

7.3.3 Guidelines for Designing a VA-based Prompting System

The feedback provided by experts in the fields of HCI and brain injury rehabilitation was used to create a set of guidelines to design usable VA-based prompting systems for people with ABI. These guidelines suggest ways to convey lists of reminders or tasks so that they can be suc-

Factor	Impact on usability
Memory	Forgetting to use the VA Forgetting to carry out the task after receiving a reminder Unable to remember what a prompt is in reference to Forgetting trigger phrase, required keywords/phrases Forgetting how to structure queries/commands Unable to retain required information during input of single-utterance queries Unable to retain responses consisting of lists of items
Complexity of Interaction	Significant association between cognitive difficulties and perceived mental demand Subjective workload affects evaluation of user experience User errors are more often in tasks with longer interactions Input errors are more often in long, single-utterance commands Editing information that has already been inserted is challenging Users prefer to use visual interaction for more complex tasks
Speech Recognition	Can cause frustration Can result in input of incorrect information Common, but does not prevent people with ABI from using VAs Frequency of speech recognition errors can decrease over time Errors due to incorrect phrasing (not knowing how to structure query) are more frequent, but can be prevented with training Single-utterance input is more prone to S.R. errors Speech difficulties can improve over time Users with mild speech impairments can also benefit from VAs
Lack of Motivation/ Self Awareness	Not reacting to prompts/notifications Not initiating interaction with system Not recognising the system's benefit Not realising the need for provided support
Change in Abilities	Cognitive functioning can improve during recovery Cognitive performance can fluctuate due to fatigue
Learning Difficulties	Inability to search new features Forgetting how to use them after a certain period Experience does not help with successful completion of unknown tasks
Lack of Portability	Inability to use outside the house (smart speakers) Missing prompts when not in proximity of speaker
Privacy and Security	Security concerns exist, but would not prevent sharing of personal information if adequately informed about data usage Privacy issues when used in front of others

Table 7.2: Factors affecting the usability of Voice Assistants for people with Acquired Brain Injury.

cessfully processed by the users, ways to increase the efficiency of conveyed prompts, ways to minimise workload and errors during user input, and ways to improve the learnability of VA-based systems. The guidelines are presented in Table 7.3. For further discussion see Section 6.5.

7.4 Limitations and Future Work

This section discusses the limitations of the research work described in this thesis, and provides suggestions for future work.

7.4.1 Use-Cases and Usability of Voice Assistants

As was described in Chapter 2, there is a very wide range of possible cognitive impairments that can result from a brain injury, which can differ significantly from one individual to another. This thesis aimed to conduct a thorough investigation of these impairments, by utilising the broad and cumulative experience of experts in ABI rehabilitation. The use-cases and usability factors of VAs identified in this thesis, however, were based on the most common effects of ABI, as reported by the professionals in study 2, and on data acquired from a limited number of people with ABI in studies 1, 3, 4 and 5. Therefore, the lists of use-cases and usability factors can be expanded, by examining the impact of less common ABI effects on everyday life and the use of technology, and by investigating the use of VAs using a larger number of people with ABI.

Similarly, Study 5 investigated the use of VAs with a limited number of people with ABI. Although the experience of using VAs differed among participants, the majority reported being familiar with other technologies (e.g. smartphones). Therefore, examining the use of VAs with a larger number of people with ABI who are less "tech-savvy", could reveal issues that were not identified in this thesis, expanding the list of factors that can affect the technology's usability.

Finally, although the design of the prototype used in study 6 covers several of the identified use-cases, the usability of VAs in use-cases addressing areas such as communication, cognitive training and behaviour was not examined. Evaluating the design of VA-based systems aiming to address these use-cases could lead to different, or additional design guidelines for improving their usability.

Lists of reminders/tasks
<ol style="list-style-type: none"> 1. Memorisation of list items should not be expected, regardless of the list's size. 2. Can be useful for providing an overview of daily tasks/schedule. 3. First item should be emphasised/re-iterated (in the case of upcoming tasks). 4. Items on the list should be prioritised based on their importance, or execution time (for tasks). 5. Users should be informed of the current time. 6. Search functionality for specific items should be provided, after the list is conveyed. 7. Easier to process when the user is looking for a specific item on the list (e.g. when changing a reminder). 8. Repetition can cause frustration but is recommended, if the contained items are part of the user's schedule. 9. Easier to process or retain when the user is familiar with the contained information.
Reminding prompts
<ol style="list-style-type: none"> 1. Unsolicited prompts are useful, but depend on user's proximity to the device. 2. Users are unlikely to react to the notification indication of smart speakers (light). 3. Important or urgent missed prompts should be repeated at regular intervals, until user confirmation. 4. Current time should be provided, if relevant. 5. Should be phrased to prompt immediate action.
Confirmation prompts
<ol style="list-style-type: none"> 1. Require different wording than the original prompt. 2. Should allow users to mark prompts as delivered, or tasks as completed by: <ul style="list-style-type: none"> a. Allowing users to unpromptedly notify the system that they have completed a task. b. Being phrased as questions, expecting a yes/no answer from the user. 3. Should be repeated at regular intervals, until user confirmation (where applicable).
Information input
<ol style="list-style-type: none"> 1. Ensuring correct information input is essential in the case of reminders. 2. Single-utterance input is very demanding when containing multiple pieces of information (e.g. creating a reminder) 3. Breaking down input to small steps (one piece of information at a time) can improve information recall and input errors. 4. Open-ended questions (e.g. '<i>what would you like to do</i>') can be confusing and lead to input errors. 5. Confirmation dialogues should be given only once, after input completion, offering the option to start over or change a specific item in the case of an error. 6. Switching between interface modes (e.g. from structured to flexible) should be decided by the carer/therapist.
System help
<ol style="list-style-type: none"> 1. User tutorial should be provided which: <ul style="list-style-type: none"> a. Is automatically enabled the first time the system is used. b. Walks users through the completion of training tasks, giving detailed instructions and feedback for every step. 2. A 'help' command should be available, providing the following options: <ul style="list-style-type: none"> a. Describe of what the system can be used for, providing example queries. b. Launch the tutorial for a specific function. c. Provide guidance for the task currently performed by the user. 3. Help should be given automatically when the system detects consecutive errors, or phrases like '<i>I don't know what to do</i>'.
Monitoring
<ol style="list-style-type: none"> 1. Users should be asked to input their activity, once per day, at a specific time. 2. Users should be asked to confirm the completion of specific activities in their schedule. Open-ended questions should be avoided (e.g. '<i>what did you do today</i>').

Table 7.3: Guidelines for the design of a VA-based prompting system for people with Acquired Brain Injury

7.4.2 Cognitive Functioning of Participants

As shown in previous chapters, the level of cognitive functioning and performance can vary greatly among people with ABI, depending on the severity and the type of injury. In the studies described in this thesis, there was no assessment carried out to determine the cognitive functioning of the participants. However, based on the participants' personal reports and descriptions of their difficulties, as well as observed communication difficulties, it can be inferred that several participants of Study 3 had a more severe injury and more limited cognitive functioning than others. Contrarily, the majority of participants with ABI in Studies 4 and 5 demonstrated higher cognitive functioning, through their ability to become informed about the studies, communicate with the researcher to arrange their participation, use technology to attend the studies remotely, and comprehend the different tasks and questions of the studies (with the exception of two participants whose participation was facilitated by their carer). Moreover, all participants in Study 4 were regular users of Voice Assistants and other types of technology, and participants of Study 5 were able to use VAs to complete all the required tasks.

Based on the above, it can be argued that conclusions regarding the user experience of Voice Assistants for people with Acquired Brain Injury are, to an extend, based on people with ABI with higher cognitive functioning. This can affect the validity of the answer to research question RQ2, as it is likely that the User Experience of Voice Assistants might differ for people with more severe injuries or more limited cognitive functioning. This difference in UX could mean that there are factors that affect the usability of VAs which were not identified in this thesis, or that the importance of the identified factors is not the same for people with lower cognitive functioning.

The above limitation should not affect the answer to research question RQ1 to the same extent. Conclusions about the use cases of VAs for people with ABI are largely based on related literature which examines the most common effects of ABI regardless of severity, as well as on the reports of brain injury experts (Study 2), whose responses were not specific to people with a certain level of cognitive functioning. Similarly, participants in Study 6 (RQ3) were asked to provide their insights on how to improve the UX of VAs for people with cognitive impairments due to ABI in general, and not particularly for people with a specific level of cognitive abilities. However, ABI experts who participated in Study 6 reported that it would require good cognitive performance for a person with ABI to be able to use an application like the presented prototype independently, and that people with more severe deficits would require assistance from others.

Therefore, the guidelines for the design of VA applications presented in this thesis would be better suited to people with ABI with a higher level of cognitive functioning, rather than to people with more severe injuries or more limited cognitive performance. These people are also more likely to be the first adopters of the technology, as they would be able to use the technology

without the help of others.

Future work aiming to examine the relation between the severity of the injury or the level of cognitive performance and the UX of Voice Assistants should focus on the assessment of cognitive functioning. As pointed out in Chapters 2 and 3, the accurate assessment of cognitive performance is a complicated matter and should take into account all aspects of cognitive functions. The Behavioural Assessment of the Dysexecutive Syndrome (BADS) [224], the Dysexecutive Questionnaire [164] and the Prospective and Retrospective Memory Questionnaire (PRMQ) [38] can be useful tools in that process.

Following a thorough assessment of cognitive performance, future work could either examine the differences in usability of VAs between people with ABI with different levels of cognitive performance or severity of injury, or focus on the design of Voice Assistants for ABI survivors with more severe impairments. The findings of this thesis could be correlated with the results in either of these two research approaches to identify potential similarities or differences.

7.4.3 Speech Impairments and Speech Recognition

According to related research examining the usability of VAs, poor speech recognition is a common issue [1, 37, 173]. This issue can be exacerbated by speech and communication difficulties caused by ABI [18]. In Study 4, three participants mentioned having speech difficulties which, as they reported can increase the frequency of speech recognition issues when using a VA. This issue can be exacerbated when the user is tired, which causes the speech difficulties to become more prominent. However, the participants in this study who reported having speech difficulties also reported being satisfied with VAs, and that poor speech recognition, although frustrating, did not prevent them from being able to use VAs efficiently. In Study 5, one participant reported that their speech difficulty caused them to make more errors towards the end of the study, when they were more tired, while for another participant with a similar impediment, fatigue did not seem to have an effect on their performance. Generally, however, the participants in the studies described in this Thesis which involved using a VA demonstrated good communication skills, and the effect of potential speech impairments on the use of VAs was not clear. Moreover, the usability of VAs for people with more severe speech impairments (such as aphasia or dyspraxia of speech) was not examined. Future studies could focus on investigating the usability of VAs in users with severe speech impairments, and correlate the findings with the results in this Thesis. Such an approach would require a thorough assessment of the users' speech difficulties. A systematic comparison between the performance (user errors, number of tasks completed successfully or unsuccessfully) of users with severe speech impairments on tasks such as those in Study 5, as well as their subjective evaluation of the VA's usability could provide useful information regarding the effect of ABI-induced speech impairments on the use of VAs.

Additionally, the participants of Study 5 were all native English speakers. Although some participants had a less common accent than the majority of English speakers (Scottish), the findings of the study regarding the effect of the accent on their performance when using a VA cannot be conclusive. Future work can further examine the extent to which different accents can affect the use of VAs for people with ABI. This would require the inclusion of participants from different English-speaking regions. Such research could also examine the use of VAs in different languages, where accents as well as speech impairments, could have a different effect on the usability of VAs.

7.4.4 Long-term Use of Voice Assistants

Studies 5 and 6 examined the usability of VAs in a simulated environment. Although the tasks were designed to resemble real-life scenarios, the experience of interacting with a VA in everyday life could be different for people with ABI. Moreover, although the design recommendations presented in this thesis can increase the usability of VAs in performing certain tasks, further investigation is needed to evaluate their applicability for people with ABI, and to determine how they could affect their usability in the long term. A logical next step for this work would be to apply the presented guidelines to the design of the prototype prompting system used in Study 6, and examine its use with people with ABI in a real-life setting. This will further inform this thesis' findings about the usability of VAs, and evaluate their efficacy as cognitive, and rehabilitation aids in the long term.

7.4.5 Smart Speakers and Other Devices

This study focused on the use of VAs through smart speakers, investigating how to improve their usability through the design of their voice user interface. As discussed in Chapter 2, apart from smart speakers VAs can also be found embedded in devices with screens. Although there are certain benefits to speech-only interaction for people with ABI, the use of a display could be beneficial as a complementary method for providing feedback to the user. Future work investigating the use of VAs through devices with a screen can expand the findings of this thesis regarding the factors that affect their usability, and the presented design guidelines.

One of the reported ways for improving the efficacy of conveyed prompts in Study 6, was through the use of other devices. Related work has shown promise in the use of wearable devices (such as smartwatches [93]), as prompting aids for people with ABI. Therefore, future work could also examine ways to improve the usability of VAs through the use of wearables devices, as well as other external devices like smart phones and smart electronic devices.

7.4.6 Voice Assistants for People with Dementia

Several of the cognitive impairments caused by an ABI, such as loss of memory, concentration difficulties, or problems with planning and organisation, can also be found in people with dementia [216]. Technology has been used to aid people with dementia in ways similar to those for people with ABI, such as supporting communication, compensating for impaired cognition and facilitating task completion [62, 159]. Therefore, some of the use-cases of VAs for people with ABI identified in this thesis also apply for people with dementia. Future work could investigate the use of VAs for people with dementia, to examine the prevalence of the identified usability barriers, and the applicability of the design guidelines presented in this thesis.

7.5 Conclusion

Voice Assistants can be used to benefit people with Acquired Brain Injury in a variety of ways: by supporting memory impairments, difficulties with organisation, lack of initiation or motivation, and inappropriate behaviour, through the use of calendar management and timely prompts; by supporting communication and collaboration between people with ABI and their carers, family members or therapists; by facilitating the rehabilitation process through assessment, monitoring and cognitive exercises, and by promoting and facilitating use of other external aids. However, cognitive impairments affecting memory function, information processing and self-awareness, and issues associated with the technology's speech recognition, lack of portability and security can prevent people with ABI from using VAs efficiently and effectively. The impact of these issues can be mitigated through techniques that: improve the presentation of conveyed information, so that it can be more easily processed; improve the way prompts are conveyed to increase their efficacy; facilitate information input to reduce errors and improve task completion; provide help and guidance to increase learnability.

Appendix A

An Appendix

The material used in each Study and the collected data can be found in the following address:
<https://www.dropbox.com/sh/hu5713jdw67vz0q/AABDE1m6ZUWNElteMfqiTIVFa?dl=0>
(This is a temporary solution as all data will be moved to the University of Glasgow's Enlightenment system).

For each study, the data comprises of:

- Consent forms, information sheet and advertisement texts used in recruitment
- Questionnaire data
- Transcribed data from interviews and focus groups
- Complementary material used in studies (storyboards, personas, pictures of prototype)
- Code for the implemented prototype
- Output of statistical analyses (SPSS)

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