Virtual environments as a tool for people with acquired brain injury

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Doctoral thesis

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”Di har sina idéer, tanterna...”

Greta Wallergård

Abstract

People with acquired brain injury (ABI) often have problems leading an independent life due to impaired cognitive abilities. One way to address this is to let the patients practise activities of daily living as part of their rehabilitation process. However, some everyday activities can be difficult, inconvenient or risky to practise. The demands of the environment can also have an impact on the independence of an individual with ABI. Today, the involvement of people with ABI in the design of public space in minimal. Scarcely any regard is taken to this population when planning a new public transport system, for example. Accordingly, there is a need for development of methodology that can facilitate life for people with ABI. Virtual reality (VR) technology has shown great potential for various applications such as training, learning, visualisation and design. The objectives of the research presented in this doctoral thesis were to: 1) investigate how VR training can be used as a rehabilitation tool by people with ABI, and 2) explore if and how VR can be used to elicit knowledge about public transport accessibility for people with ABI.

The first research objective was investigated in four studies in which 60 able-bodied people with little or no experience of 3D computer graphics and 12 people with traumatic brain injury (TBI) participated. Case study methodology was applied, using observations, interviews and think-aloud protocols to collect data. One of the studies also used quantitative data and statistics. So called desktop VR (i.e. a standard monitor and regular input devices) was used. Three virtual environments were used: a kitchen, a cash dispenser and a hospital environment. In general, the results of the four studies suggest that VR has great potential as a training tool for people with ABI. However, the results also highlighted the importance of an optimised interface between the user and the VR system; seemingly small usability problems can create significant difficulties for a person with ABI. In the first study, a comparison was carried out between a joystick and a special keyboard for navigation in virtual training environments. There were two versions of each input device: one with two degrees of freedom and one with three. The keyboard was found to be more suitable for navigation tasks in which the user wants to give the viewpoint a more advantageous position and orientation for carrying out a specific task. No statistically significant differences between two and three degrees of freedom could be found. Nevertheless, the third degree of freedom, which made it possible to also move sideways, seemed to facilitate the navigation in some situations. The aim of the second study was to evaluate a method for interaction with virtual objects and to compare mouse and touch screen as input device for this purpose. The data showed no difference in performance between the mouse and touch screen subjects. Several touch screen subjects tended to imitate the way things are done in real life, however. This suggests that the touch screen is a more suitable input device in this context since the virtual activity resembles the real world activity. The third study investigated if and how five subjects with ABI could transfer route knowledge from a virtual hospital environment to the real world. They managed to walk a route they had only practised in a virtual environment, which suggests that VR-based route training can be a feasible complement to conventional route training. The aim of the fourth study was to develop and evaluate a virtual cash dispenser that can be used as a training tool by people with ABI. Seven people with ABI practised withdrawing money from the virtual cash dispenser. In general, they learned how to use the virtual cash dispenser. However, some usability problems, mainly related to interaction with virtual objects were noted. Another result, which could also be

observed in the second study, was that unclear or non-existing feedback from the VR application was the cause of several of these problems.

The second research objective was addressed in two studies in which eleven people with ABI and four occupational therapists participated. Once again, case study methodology was used. Data was collected through observations, think-aloud protocols and interviews. Both studies used a virtual environment in which a complete bus trip could be performed. The first study evaluated a suggested VR methodology for enabling people with cognitive disabilities to communicate their knowledge and experiences of public transport systems. The users interacted with the VR system by verbally describing their actions to the person controlling the VR system and/or pointing with a laser pointer while seated in front of three screens on which the virtual environment was projected. Seven people with stroke were filmed as they made a virtual bus trip and were then asked to think aloud about their experience while watching the video material. Despite some initial difficulties, the subjects managed to communicate their intentions, some by combining verbalisations and pointing with the laser pointer in a very efficient manner. They were engaged in the virtual bus trip and made comments on the experience, including comments on emotional aspects. Interestingly, the subjects' verbal descriptions of what they wanted to do revealed in part aspects of how they reasoned when taking the bus trip. The results suggested that the VR methodology can be a feasible tool for people with cognitive disabilities but also revealed several issues in need of improvement. The second study investigated if and how the VR methodology can be used to elicit knowledge from occupational therapists and people with ABI about public transport accessibility for the latter population. Four people with ABI made a virtual bus trip and afterwards were asked to think aloud about their experience while watching the video material from the bus trip. Four occupational therapists with experience of working with people with ABI performed the virtual bus trip while at the same time thinking aloud about public transport accessibility for people with ABI. Afterwards they watched the video material from the virtual bus trip of one of the subjects with ABI while once again thinking aloud about public transport accessibility. In general, both subject groups handled the VR methodology. The most relevant knowledge from the subjects with ABI was related to concrete accessibility problems, emotional aspects and strategies. The direct observations of the ABI subjects making the virtual bus trip led to the identification of some problems but revealed very little about what caused them. Instead, the cause of the problems came to light through the ABI subjects' verbalisations, which demonstrates the importance of not only making observations but also paying attention to the participant's subjective experience. The most relevant knowledge from the occupational therapists concerned the concrete accessibility problems and suggested solutions. Both think aloud sessions elicited unique knowledge from the occupational therapists and should therefore be part of the VR methodology in order to cover as many aspects as possible of public transport accessibility for people with ABI. Overall, the results suggested that the concept of first carrying out actions in a virtual environment and then reflecting over these actions seems to be a very good way of eliciting knowledge about public transport accessibility for people with ABI. The elicited knowledge from people with ABI and occupational therapists seems to illuminate, in part, different aspects of public transport accessibility and hence is complementary.

Sammanfattning

Personer med förvärvad hjärnskada har ofta problem att leva ett självständigt liv till följd av nedsatt kognitiv förmåga. Ett sätt att motverka detta är att låta träning av dagliga aktiviteter ingå i patientens rehabilitering. Det kan dock vara svårt, obekvämt eller riskabelt att träna vissa aktiviteter. Även de krav som miljön ställer på en individ med förvärvad hjärnskada påverkar dennes förmåga att vara självständig. I dagsläget involveras personer med förvärvad hjärnskada i minimal utsträckning vid planering av offentliga miljöer: Denna grupp beaktas i princip inte alls vid planering av t ex nya kollektivtrafiksystem. Det finns följaktligen ett klart behov av utveckling av metodik som kan göra vardagen lättare för personer med förvärvad hjärnskada. Virtual reality-teknik (VR) har visat stor potential för olika tillämpningar såsom träning, lärande, visualisering och design. Syftet med denna avhandling var att 1) undersöka hur VR kan användas som ett rehabiliteringsverktyg av personer med förvärvad hjärnskada och 2) utforska om och hur VR kan användas för att få fram kunskap om tillgänglighet i kollektivtrafiken för personer med förvärvad hjärnskada.

Det första syftet adresserades i fyra studier i vilka 60 friska personer med lite eller ingen erfarenhet av 3D-datorgrafik samt 12 personer med förvärvad hjärnskada deltog. Fallstudiemetodik användes i kombination med observationer, intervjuer och tänka-högt-protokoll för datainsamling. I en av studierna användes dessutom kvantitativa data och statistik. Desktop VR, dvs. VR-teknik baserad på en vanlig standardmonitor och reguljära styrdon, användes. Tre virtuella miljöer användes: ett kök, en bankomat samt en sjukhusmiljö. Rent generellt så tyder resultaten från de fyra studierna på att VR har stor potential som träningsverktyg i rehabilitering för personer med förvärvad hjärnskada. Resultaten belyste även hur viktigt det är att optimera användargränssnittet. Även till synes små användbarhetsproblem kan orsaka stora svårigheter för individer med förvärvad hjärnskada. I den första studien jämfördes en joystick med ett specialanpassat tangentbord för navigering i virtuella träningsmiljöer. Varje styrdon fanns i två varianter: en med två frihetsgrader och en med tre. Tangentbordet fanns vara lämpligast för navigering där användaren vill ge vyn en mer fördelaktig position och riktning för att kunna genomföra en viss uppgift. Inga statistiskt signifikanta skillnader mellan två och tre frihetsgrader fanns. Ändå verkade det finnas situationer i vilka den tredje frihetsgraden, som gjorde det möjligt att även flytta vyn sidledes, underlättade navigeringen. Målet med den andra studien var att utvärdera en metod för interaktion med virtuella objekt samt att jämföra mus och pekskärm som styrdon för detta syfte. Resultaten påvisade inga skillnader i prestation mellan mus-och pekskärmsgruppen. Flera pekskärmsanvändare tenderade dock att härma hur man göra saker och ting i verkligheten. Detta antyder att pekskärmen är ett mer lämpligt styrdon i detta sammanhang eftersom den virtuella aktiviteten liknar den verkliga aktiviteten. Den tredje studien undersökte om och hur fem testpersoner med förvärvad hjärnskada kunde överföra kunskap om en rutt från en virtuell miljö till motsvarande verkliga miljö. De lyckade att gå en rutt de bara hade tränat på i en virtuell miljö vilket tyder på att denna typ av träning kan vara ett tänkbart komplement till konventionell rutt-träning. Den fjärde studien syftade till att utveckla och utvärdera en virtuell bankomat som kan användas i träningssyfte av personer med förvärvad hjärnskada. Sju personer med förvärvad hjärnskada tränade på att göra uttag med den virtuella bankomaten och lyckades lära sig att använda den. En del användbarhetsproblem, i huvudsak relaterade till interaktion med virtuella objekt, kunde dock observeras. Ett annat resultat, som kom fram även i den andra studien, var att otydlig

eller obefintlig återkoppling från VR-applikationen var orsak till flera av dessa användbarhetsproblem.

Det andra syftet adresserades i två studier i vilka 11 personer med förvärvad hjärnskada samt fyra arbetsterapeuter deltog. Återigen användes fallstudiemetodik i kombination med observationer, tänka-högt-protokoll och intervjuer för datainsamling. I båda studierna användes en virtuell miljö i vilken det var möjligt att genomföra en hel bussresa. Den första studien utvärderade ett förslag till VR-metodik för att göra det möjligt för personer med kognitiva funktionshinder att kommunicera sin kunskap om och sina erfarenheter av kollektivtrafik. Användarna interagerade med VR-systemet genom att verbalt beskriva sina handlingar för personen som kontrollerade VR-systemet och/eller peka med en laserpekare. De satt på en stol framför tre skärmar på vilka den virtuella miljön projicerades. Sju personer med stroke genomförde en virtuell bussresa och blev samtidigt filmade. Efteråt fick de tänka högt om sin upplevelse samtidigt som de tittade på videomaterialet. Trots inledande svårigheter så lyckades testpersonerna kommunicera vad de ville göra, några av dem genom att kombinera verbala beskrivningar med pekande med laserpekaren på ett väldigt effektivt sätt. De var engagerade i den virtuella bussresan och kommenterade upplevelsen, även med avseende på känslomässiga aspekter. Ett intressant resultat var att testpersonernas muntliga beskrivningar av vad de ville göra till viss del synliggjorde hur de resonerade för att genomföra bussresan. Resultaten tydde på att VR-metodiken kan vara ett möjligt verktyg för personer med kognitiva funktionshinder men visade också på flera aspekter i behov av förbättring. Den andra studien undersökte om och hur VR-metodiken kan användas av arbetsterapeuter och personer med förvärvad hjärnskada för att ta fram kunskap om tillgänglighet i kollektivtrafiken för den sistnämnda gruppen. Fyra personer med förvärvad hjärnskada genomförde en virtuell bussresa och fick sedan tänka högt om sin upplevelse medan de tittade på det inspelade videomaterialet från bussresan. Fyra arbetsterapeuter med erfarenhet av att jobba med personer med förvärvad hjärnskada genomförde samma virtuella bussresa och tänkte samtidigt högt om tillgänglighet i kollektivtrafiken för denna grupp. Efteråt fick de titta på det inspelade videomaterialet från en av testpersonerna med förvärvad hjärnskada medan de återigen tänkte högt om tillgänglighet i kollektivtrafiken. Överlag klarade alla försökspersonerna av att hantera VR-metodiken. Den mest relevanta kunskapen från personerna med förvärvad hjärnskada handlade om konkreta tillgänglighetsproblem, känslomässiga aspekter och strategier. Observationerna av hur personerna med förvärvad hjärnskada genomförde den virtuella bussresan ledde till att en del problem framkom men avslöjade väldigt lite om vad som orsakade dem. De bakomliggande orsakerna kom istället fram genom de kommentarer som personerna med förvärvad hjärnskada gjorde vilket visar hur viktigt det är att inte bara göra observationer utan även lyssna på användarens subjektiva upplevelse. Den mest relevanta kunskapen från arbetsterapeuterna handlade om konkreta tillgänglighetsproblem och förbättringsförslag. Vid båda tänka-högt-sessionerna kom det fram unik kunskap från arbetsterapeuterna och de bör därför båda vara del av VR-metodiken för att täcka så många aspekter som möjligt av tillgänglighet i kollektivtrafiken för personer med förvärvad hjärnskada. Sammantaget pekar resultaten på att görande i en virtuell miljö i kombination med reflekterande över detta görande kan vara ett bra sätt att ta fram kunskap om tillgänglighet i kollektivtrafiken för personer med kognitiva funktionshinder. Kunskapen som kom fram från de två grupperna verkar delvis belysa olika aspekter av tillgänglighet i kollektivtrafiken och kompletterar varandra.

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Other work by the respondent

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Lindén, A., Davies, R. C., Boschian, K., Minör, U., Olsson, R., Sonesson, B., Wallergård, M., & Johansson, G. (2000). Special considerations for navigation and interaction in virtual environments for people with brain injury. *Proceedings of the 3rd international conference on disability, Virtual Reality and associated technologies,* 287-296.

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List of included papers

I. **Initial usability testing of navigation and interaction methods in virtual environments – developing usable interfaces for brain injury rehabilitation**
Wallergård, M., Lindén, A., Davies, R.C., Boschian, K., Minör, U., Sonesson, B., & Johansson, G. (2007). *Presence: Teleoperators & Virtual Environments, 16*(1), 16-44.

Wallergård and Lindén were responsible for the execution of the first experiment, the analysis of the data, and for writing the article. Davies implemented the virtual environment that was used in the two experiments, performed the second experiment and also made the initial analysis of the quantitative data. All authors participated in the design of the experiments, and the discussion of the results.

II. **Investigating Virtual Reality training for brain injury rehabilitation**
Wallergård, M., Lindén, A., Boschian, K., & Johansson, G. Submitted to *Journal of NeuroEngineering and Rehabilitation*.

Wallergård and Lindén executed the two experiments and performed the data analysis. Wallergård and student Elin Löfgren developed the two virtual environments. All authors participated in the design of the experiments and the discussion of the results and Wallergård was responsible for writing the article.

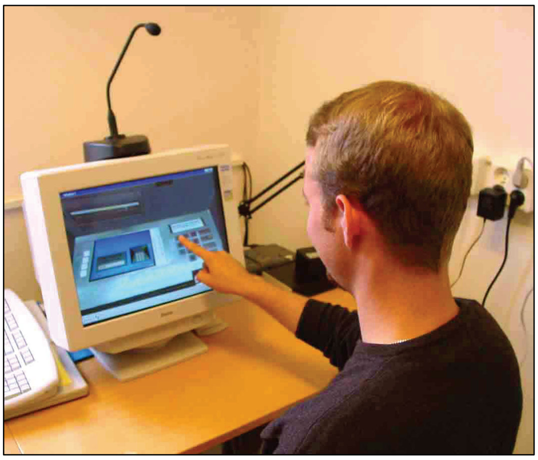
III. **A suggested Virtual Reality methodology allowing people with cognitive disabilities to communicate their knowledge and experiences of public transport systems**
Wallergård, M., Eriksson J., & Johansson, G. A revised version of this paper has been accepted for publication in *Technology and Disability*.

Wallergård and Johansson planned the experiment, reflected on the results and wrote the article. Wallergård developed the virtual environment and executed the experiment. Eriksson assisted in the set-up and execution of the experiment.

IV. **A virtual reality methodology for eliciting knowledge about public transport accessibility for people with acquired brain injury**
Wallergård, M., Eriksson J., & Johansson, G. Submitted to *Disability and Rehabilitation.*

Wallergård and Johansson planned the experiment, reflected on the results and wrote the article. Wallergård developed the virtual environment and executed the experiment. Eriksson assisted in the set-up of the VR equipment and the execution of the experiment.

1 INTRODUCTION



Wednesday 10 a.m.: *Johan cannot believe his eyes when the cash dispenser on the computer screen confiscates his bank card and tells him to visit the bank office. He entered the right code, didn't he? Even three times in a row! Johan leans back in the chair and scratches his head. The scar from his motor cycle accident eight months ago still itches a lot.*

"Would you like to try again?"

The computer-animated woman who just appeared on the computer screen is communicating with Johan through speech and a speech bubble.

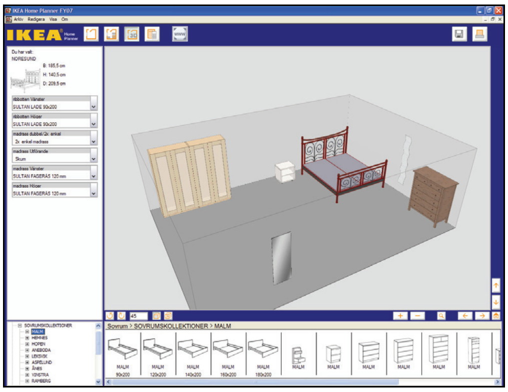
"And maybe this time you would like me to help you."

Johan pushes the Yes button on the touch screen. The virtual cash dispenser on the computer screen restarts and Johan begins another money withdrawal assisted by Lena, the virtual training coach.

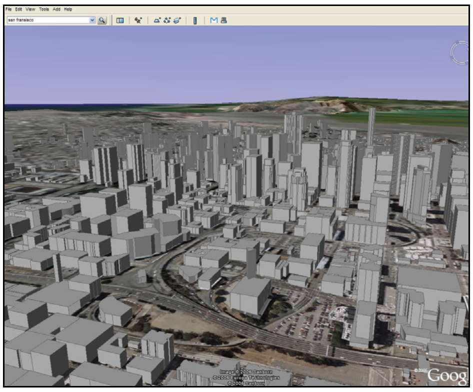
Friday 14 p.m.: *Some time ago Johan joined* BrainPower, *a stake holder organisation for people with acquired brain injury. He has been invited to the transport system authorities of Lund municipality to discuss the latest proposal for new bus stops. Right now he is in the visualisation room with Gunilla and Lars who are responsible for the project. The central part of Lund can be seen on three big screens around them. Johan points at a bus stop in a corner of the main square: "Let's go there!" Lars makes the company move over the square by pulling a joystick. Johan scans the bus stop but does not find what he is searching for: "Hmm…. Which bus line is it? There comes a bus. Ah, number one!"*

Forty-five minutes later the meeting in the visualisation room is over. Johan has performed a complete bus trip in the virtual environment. Gunilla has been taking notes, which she now will summarise in a document that will be discussed the next time the transport system authorities of Lund municipality hold a meeting.

These two scenarios illustrate how virtual reality technology (VR) can be used by people with acquired brain injury (ABI) and this thesis presents the results of research on how to realise them. VR is gradually becoming a natural part of everyday life. We design our homes with *IKEA Home Planner* (Fig. 1a). We plan our holiday trips using *Google Earth* (Fig. 1b) and we build parts of our social lives in virtual communities like *CyberTown* and *Second Life* (Fig. 1c). We play golf and tennis with our *Nintendo Wii* (Fig. 1d). Can this technology be used by people with ABI due to a car accident or stroke, for example? How must it be designed in order to make it possible for this population to use it?



(a) IKEA Home Planner



(b) Google Earth

(c) Second Life

(d) Nintendo Wii. Picture reproduced from the Nintendo webpage.

Figure 1. Examples of everyday VR technology

1.1 Research objectives

The objectives of the research presented in this thesis were to:

1. Investigate how VR training can be used as a rehabilitation tool by people with acquired brain injury.
2. Explore if and how VR can be used to elicit knowledge about public transport accessibility for people with acquired brain injury.

2 THEORETICAL OVERVIEW

The purpose of this chapter is to give the reader an overview of knowledge relevant for this thesis. It starts with a description of acquired brain injury (ABI) and its consequences. Then follows a section concerned with the user interface, the junction between man and technology. The chapter concludes with an overview of VR technology and research.

2.1 Acquired brain injury

Acquired brain injury (ABI) is damage to the brain after birth and can result from traumatic or non-traumatic brain injury. Traumatic brain injury (TBI) occurs when the brain is exposed to sudden trauma such as in a traffic accident or an assault, whereas non-traumatic brain injury is the result of stroke, brain tumour or poisoning, for example. The incidence of TBI in Sweden has been calculated to 259 individuals per 100 000 inhabitants per year (Kleiven, Peloso, & Holst, 2003) and the incidence of stroke in Sweden is approximately the same: 300 people per 100 000 inhabitants per year (Riksstroke, 2001).

2.1.1 Cognitive effects of acquired brain injury

Memory disturbances have been found to be one of the most common deficits following both stroke (Hochstenbach, Mulder, Van Limbeek, Donders, & Schoonderwaldt, 1998) and TBI (Ponsford, Olver, & Curran, 1995), and include difficulties learning new information, retaining it and thereafter accessing it. Slowness in information processing is another common problem both for TBI (McKinlay & Watkiss, 1999) and stroke victims (Hochstenback et al., 1998). Van Zomeren and Brouwer (1990) have found that this slowness leads to impaired divided attention, which makes it hard for the patient to do several things at the same time.

Hemispatial neglect is a relatively common symptom in both stroke (Appelros, Karlsson, Seiger, & Nydevik, 2002) and TBI patients (McKenna, Cooke, Fleming, Jefferson, & Ogden, 2006). It is characterised by a deficit in attention to one side of space. A patient with hemispatial neglect behaves as if a particular region of sensory space does not exist. The most common type is left-sided hemispatial neglect, which is the result of brain injury in the right hemisphere of the brain. If a person with this type of neglect is shown a drawing and asked to reproduce it, the drawing will lack many of the details on the left side (Fig. 2).

Stroke often results in aphasia (Engelter et al., 2006), which includes a number of symptoms that are usually divided into expressive and receptive. Expressive aphasia symptoms concern a person's ability to speak and write, and might, for example, cause the person to say "chair" when he wants to say "table". Receptive aphasia symptoms concern a person's ability to understand speech and to read, and can make it difficult for the person to recognise letters, for example. Aphasia is a relatively rare deficit in people with TBI but general communication difficulties are nevertheless fairly common in this group (McKinlay & Watkiss, 1999).

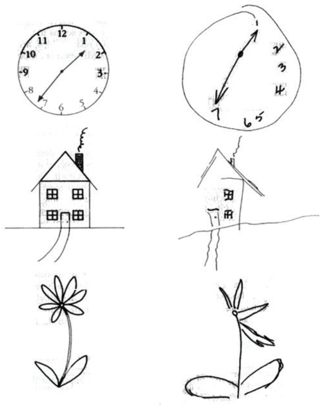


Figure 2. An example of left-sided hemispatial neglect. Picture reproduced from *Neuroscience: Exploring the Brain*, (Bear, Connors, & Paradiso, 2001).

A neurological condition sometimes accompanying aphasia is apraxia, which is very common in stroke (Lindén, Skoog, Fagerberg, Steen, & Blomstrand, 2004) but has also been observed in TBI patients (Hillier, Sharpe, & Metzer, 1997). Apraxia is characterised by loss of the ability to execute learned movements, despite having the desire and the physical ability to perform them. A person with this neurological condition might have difficulties using a pair of scissors, for example, even though he knows what scissors are and what to do with them. The problem is that he cannot find the right motor program for the activity of using a pair of scissors.

Many TBI (McKinlay & Watkiss, 1999) and stroke patients (Stephens et al., 2004) experience problems with higher cognitive processes such as planning, initiation, and abstract thinking, which are controlled by the so-called executive system. Deficits in executive function can make it hard for the patient to be flexible when conditions change and to move from one task to another.

Sometimes people with brain injury are unaware of their impairments, especially in the early stages of brain damage. This condition is called anosognosia and is common in both TBI (Fleming, Strong, & Ashton, 1996) and stroke patients (Jehkonen, Laihosalo, & Kettunen, 2006).

According to Katz (1998), decreased cognitive ability is of great importance for people's daily living and their autonomy, and there is evidence that neuropsychological factors are more important determinants of functional outcome after stroke than physical disability (e.g. Patel, Coshall, Rudd, & Wolfe, 2002). Therefore, good rehabilitation is of outmost importance for people with brain injury to reduce disabilities while gaining independence and good quality of life.

2.1.2 Cognitive rehabilitation

Cognitive rehabilitation refers to a variety of intervention strategies or techniques that strive to help patients reduce or cope with cognitive deficits caused by brain injury. According to Mateer and Rasking (1999), most rehabilitation efforts take one of three forms: environmental modifications, compensatory approaches and direct interventions. Environmental modifications are rehabilitative approaches that focus on changing factors outside the brain injured patient, such as reminders that provide oral or written cues. In contrast to environmental modifications, compensatory approaches target compensatory skills and behaviours in the patient. The patient could, for example, be trained to independently record in and refer to an electronic organiser. Direct interventions strive to improve underlying cognitive skills, such as attention, memory and problem solving. The latter category also includes training of behaviours, skills and instrumental activities of daily living. Instrumental activities of daily living (IADL) embrace the tasks necessary for taking care of one's home and for being independent in the community (McNeny, 1999). Examples of IADLs are cooking, shopping, using a cash dispenser, and taking the bus.

Independent of what rehabilitation approach is used, the cognitive rehabilitation process starts with a neuropsychological assessment, usually performed by a neuropsychologist. The goal of the assessment is to achieve detailed and comprehensive information about the patient's cognitive capabilities. A wide range of neuropsychological tests and batteries are available, for example the *Benton Visual Retention Test* (Youngjohn, Larrabee, & Crook, 1993), which assesses visual perception, visual memory, and visuo-constructive abilities, and the *Wisconsin Card Sorting Test* (Heaton, Chelune, Talley, Kay, & Curtis, 1993), designed to assess executive function. Once the neuropsychological assessment is completed, it is used as a basis for the formation of a rehabilitation plan, which describes the goals of rehabilitation and when they should be achieved. The patient often takes an active part in the drawing up of the plan, and when necessary relatives can also participate. Cognitive rehabilitation is interdisciplinary by nature and many professions usually collaborate in the rehabilitation team. For example, at the Department of Rehabilitation at Lund University Hospital (The Department of Rehabilitation, 2007) a team usually consists of a physician, neuropsychologist, occupational therapist, physical therapist and nurse.

2.2 The user interface

The medium through which a user interacts with a machine, a computer program or another complex system is called the user interface. The user interface provides means for the user to control the system by providing input and allows the system to inform the user by giving output. For a person with cognitive disabilities, due to ABI, an awkward user interface is likely to create great difficulties. This chapter will present aspects regarding user interfaces that have been central during the work on this thesis.

2.2.1 Mental models

According to Norman (1988), the quality of a user interface is strongly tied to the mental model it provides to the user. The designer of a system has a mental model of how the system is supposed to work. The user also has a mental model of how the system works, developed by interpreting the perceptible structure of the system called the system image, i.e. the user interface, its behaviour and the documentation (Fig. 3). If the system image does not communicate the designer's mental model in an appropriate manner, the user might build an incorrect mental model and cannot handle the system in a good way. A classical attempt to help the user build an adequate mental model is the desktop metaphor used by most contemporary operative systems, such as *MS Windows XP* and *MacOS*. Well-known concepts and objects such as desktop, trash can and folders are used to communicate the computer's inner functionality through the user interface.

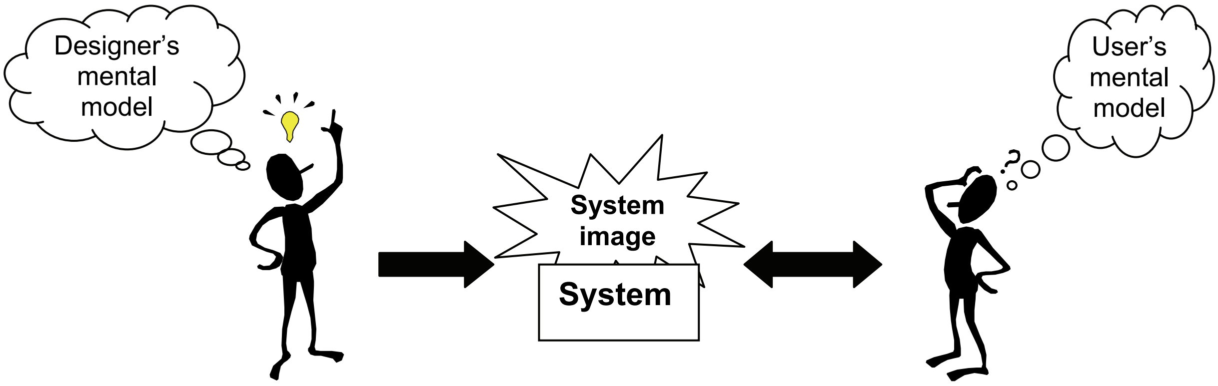
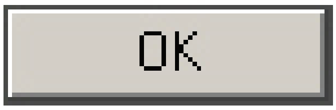


Figure 3. The design model, the system image and the user model (Norman, 1988)

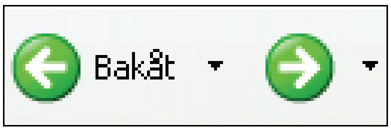
2.2.2 Visibility, affordance, mapping and feedback

Norman (1988) also states that the user can be offered a good mental model by considering four properties he calls visibility, affordance, mapping and feedback, which are described in Figure 4.

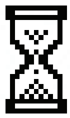
(a) Visibility: what the user can and cannot see in an interface. The interface of the *Google* search engine is designed to present a minimum of information to the user.



(b) Affordance: the perceived and actual properties of an object. Computer interface buttons look three-dimensional and hence signal that they can be pressed.



(c) Mapping: the relationship between a control and its effect. In most web browsers the back button points to the left due to the convention of time progressing to the right.



(d) Feedback: the information the system gives to the user regarding actions performed and the results. The hourglass icon in *MS Windows* signals that the system is processing a request from the user.

Figure 4. Visibility, affordance, mapping and feedback

What visibility, affordance, mapping and feedback have in common is that they rely on the fact that people recognise information far more easily than they can recall it from memory (Preece et al., 1994). This principle has become so important for user interface design that Norman (1988) has suggested the dichotomy of "knowledge in the world" (recognition) and "knowledge in the head" (recall). This dichotomy can be demonstrated by comparing the two word processors *Word* and *LaTeX*. With the former, the user can choose between different commands from menus, whereas the latter requires the user to enter memorised commands.

2.2.3 Direct manipulation and interface metaphors

Computer systems that replace complex command syntax with the ability to directly interact with the object of interest are usually referred to as direct manipulation systems (Shneiderman, 1998). For example, in *MS Windows* it is possible to move a file by simply dragging it to its new place.

Direct manipulation systems often use interface metaphors, such as the desktop and the trash can, which has proved to be a very successful approach. The idea is to use familiar objects or concepts to make it easier for the user to understand computer domain concepts. The problem with interface metaphors, on the other hand, is that they say too much and too little at the same time (Löwgren, 1993). They say too much since they can activate too much background knowledge. For example, a novice user might be confused by the desktop metaphor when he does not find any lockable desk drawers for storing private documents. Metaphors can also say too little in the sense that they do not help the user to find services that are particular for the computer system. For example, telling a user that a word processor is like a typewriter might make it hard for him to understand the "find and replace" function.

2.2.4 Cognitive load theory

Cognitive load theory has considerable implications for the design of VR applications for people with ABI. It was originally developed for use in instructional psychology (Sweller, 1994) but has also proven very useful for the design of user interfaces (Chalmers, 2003). Cognitive load can be casually defined as the "mental energy" required to process a given amount of information, in this case the information presented by a user interface. A basic distinction can be made between intrinsic and extraneous cognitive load. The intrinsic cognitive load is determined by the difficulty level of the content, whereas the extraneous cognitive load is due to the way in which the information is presented to the user. If the total cognitive load (i.e. the sum of intrinsic and extraneous cognitive load) exceeds the user's mental resources he may fail to solve the task (Fig. 5). In this thesis, designing VR user interfaces that do not put too much extraneous cognitive load on the user has been a crucial matter.

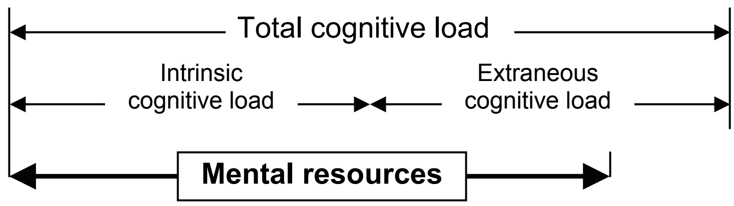


Figure 5. The total cognitive load exceeds the mental resources of the user

2.2.5 Approaches to user interface design

In the 70s and early 80s, most work on user interfaces was based on the idea that general knowledge from psychology research should assist developers in designing usable systems (Löwgren, 1993). This theory-based design approach proved problematic for several reasons. Above all, it turned out to be very difficult to produce general descriptions of humans interacting with systems, which could be used for guidelines and evaluation in the development process (Carrol, 1993).

The concept of user-centred design has gained a lot of attention during the latest decade, but has in fact been promoted since the late 70s by John Gould and Clayton Lewis (Gould & Lewis, 1985). They suggest that user-centred design should be based on three principles:

1. *Early focus on users and tasks.* First of all, the designer must understand the characteristics of the users and the tasks they are to perform.
2. *Empirical measurement.* Early in the design process, the system should be evaluated on users, using simulations and prototypes.
3. *Iterative design.* The design process should be a cycle of design, evaluation and redesign, repeated as often as necessary (Fig. 6).

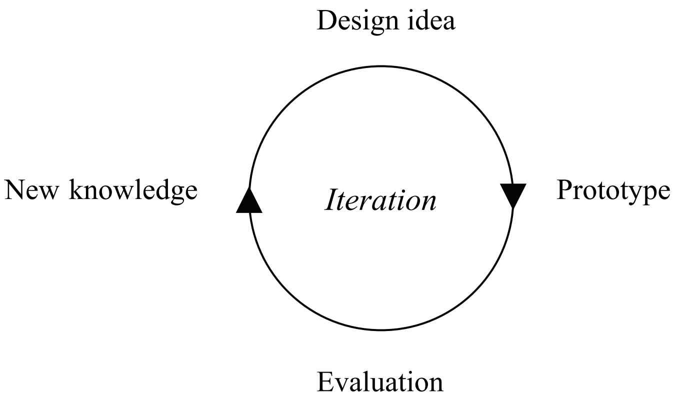


Figure 6. Iterative design: A design idea results in a prototype that is evaluated. The acquired knowledge from the evaluation leads to new design ideas that can be used to produce a new prototype and so on.

There is a wealth of techniques for working with users in the design process (Preece, Rogers, & Sharp, 2002). However, a lot of these techniques are not suitable for people with cognitive disabilities, due to their complexity. For example, a person with communication problems might find it very hard to participate in a brain storming session. This issue is to some extent addressed in the *USERfit Handbook* (Poulson, Ashby, & Richardson, 1996), which provides information regarding user-centred design for assistive technology. In general, very little research has been done to study how people with cognitive disabilities can contribute to a design process. In one of the few studies that has addressed this issue, Moffat, McGrenere, Purves and Klawe (2004) used a participatory design approach to develop a daily planner for people with aphasia. Among other things, the authors proposed a small set of guidelines for participatory design with this population.

2.3 Virtual reality

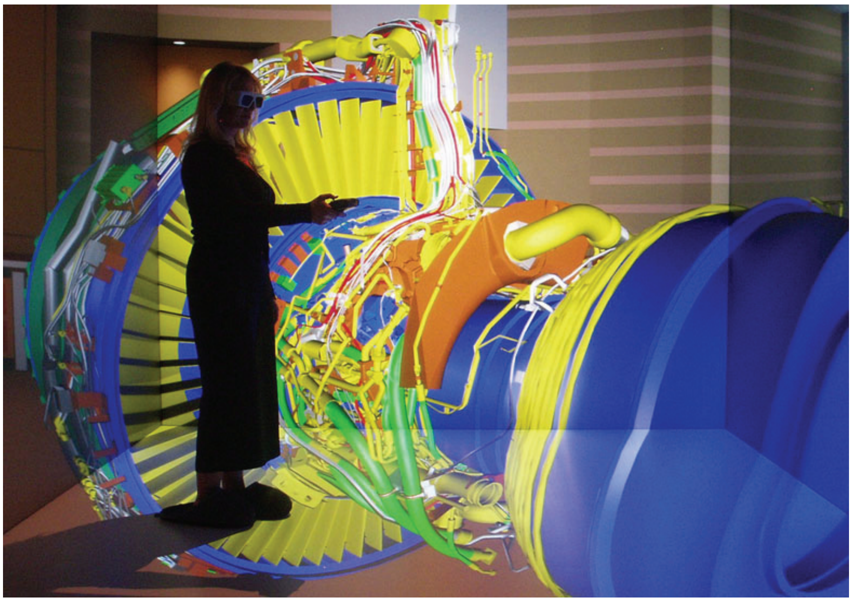
In the beginning of the 1990's the term "virtual reality" became popularised in the mass media. Movies like *The Lawnmower Man* and the non-fiction book *Virtual Reality* (Rheingold, 1992) created enormous expectations on this technology in the public. However, disappointment and ambivalence followed when people realised that the VR technology could not match their expectations. Nevertheless, some people believe that this technology will have a profound impact on human life and activity in the future. Perhaps most notably, Cline (2005) argues that:

- VR will be integrated into daily life and activity and will be used in very human ways.
- The design of virtual environments may be used to extend basic human rights into virtual space, to promote human freedom and well-being, and to promote social stability as we move from one stage in socio-political development to the next.

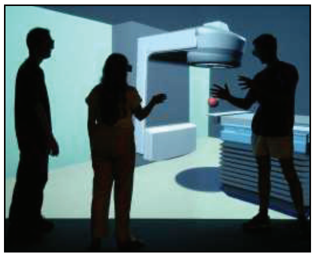
But exactly what is VR? One of the easiest ways to understand what this technology is about is to think of 3D computer games. Many such games let the player experience three-dimensional worlds filled with people, creatures and various objects. The player solves different tasks by moving around in and interacting with the game environment and this is exactly what VR technology can offer. Accordingly, VR can be defined as an "advanced communication interface based on interactive 3D visualisation, able to collect and integrate different inputs and data sets in a single real-like experience" (Riva, Mantovani, & Gaggioli, 2004).

2.3.1 Virtual reality technology

There are several types of VR technology and a basic distinction can be made between immersive and non-immersive VR systems. With an immersive VR system the user is completely, or almost completely, surrounded by the virtual environment. The *EON ICube* (Fig. 7a), is probably one of the most advanced immersive systems that can be purchased today. The virtual environment is projected on three screens and the floor and thus completely encompasses the user. Some less advanced immersive systems, for example the *Fakespace PowerWall* in Figure 7b, use only one large screen to display the virtual environment. These two systems allow several users to interact with the virtual environment at the same time. A head mounted display (Fig. 7c), on the other hand, displays the virtual environment for one single person using two small screens, one for each eye. Immersive VR systems often display the virtual environment in stereo, which means that the user experiences a feeling of depth. This type of display is sometimes referred to as stereoscopic. The computer calculates one picture for each eye and special hardware is used to get the left image to the left eye and the right image to the right eye. One way to do this is with glasses with liquid crystal shutter lenses that close off one eye or the other at the same time as the screen shows alternatively the left or right image.



(a) EON ICube

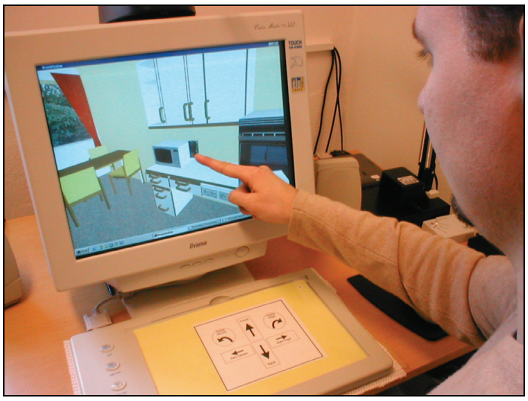


(b) Fakespace PowerWall

(c) A head mounted display

Figure 7. Examples of immersive VR systems

The most common type of non-immersive VR system is a regular desktop computer that shows the virtual environment on a standard monitor (Fig. 8a). A more advanced type of non-immersive system projects an image on a large screen (Fig. 8b). Systems like these can either be classified as immersive or non-immersive depending on how large the virtual environment is in relation to the user and whether stereo is used or not.



(a) Desktop VR: a desktop computer with a standard monitor.

(b) A Fakespace Immersive Workbench.

Figure 8. Examples of non-immersive VR systems

One of the most important components in a VR system is the input device. Input devices can be classified based on the types of events they produce. With a discrete-input device, like a keyboard, the user generates one event at a time, whereas a continuous-input device like a joystick generates a stream of events. Input devices can also be categorised after the degrees of freedom they offer. A degree of freedom is defined as the possibility to move along or rotate around one of the axes in a Cartesian coordinate system. For example, a car can move forwards and backwards and also turn to the left or right, and can therefore be said to have two degrees of freedom. The *Spacemouse* and the *Spaceball* (Figs. 9a and 9b) allow the user to move around or manipulate objects in the virtual environment using six degrees of freedom. They are used by holding their movable part and lifting, pushing, pulling or rotating it, which makes them quite hard to use for inexperienced users. A data glove is a more advanced input device that allows the user to interact with the virtual environment using hand and finger motions. There are two basic types of data gloves: bend-sensing gloves (Fig. 9c) and pinch gloves (Fig. 9d). A bend-sensing glove gives input to the virtual environment by registering the flexion of the user's fingers. A pinch glove is less advanced and only registers if the user puts two or more finger tips together. Data gloves are usually used in combination with a so-called motion tracking system which keeps track of the data glove's position and orientation. There are several tracking technologies available today, such as magnetic and optical tracking. A magnetic tracking system produces a magnetic field that sensors placed on the user's body can pick up and transform to position and orientation information (Fig. 9e). Optical tracking systems, instead, use some form of bearing sensors, such as a camera, to track point-like targets placed on the user. 3D mice are a group of input devices that combine motion tracking with a set of physical device components. *The Wanda* is a handheld 3D mouse that is commonly used in combination with immersive VR systems for both navigation and selection of objects (Fig. 9f). Another handheld 3D mouse is *The Cubic Mouse* (Fig. 9g), which has proven to be a very convenient input device for manipulation of volumetric data (e.g. a 3D object). There are also many input devices primarily designed for 2D computer applications that can be used for virtual environment interaction. For example, a very common navigation technique in many VRML browsers of today uses a regular desktop mouse. Different modes such as walk and pan modes are used to achieve several degrees of freedom. Another example is the joystick which can be an adequate input device for virtual environments in which the user is walking or driving around. There are also devices that allow the user to actually feel a virtual environment through force-feedback in what are referred to as haptic interfaces. Using small motors, a haptic interface simulates the forces our bodies feel when touching virtual objects. The *PHANToM OMNI* lets the user feel the shape, weight and texture of virtual objects through a pen interface (Fig. 9h).

(a) A Spacemouse

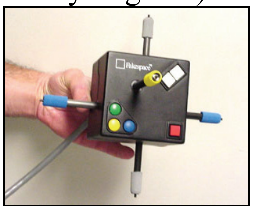
(b) A Spaceball

(c) A bend-sensing glove (VTI Cyberglove)

(d) Pinch gloves

(e) Magnetic tracking equipment

(f) The Wanda



(g) The Cubic Mouse

(h) PHANToM OMNI

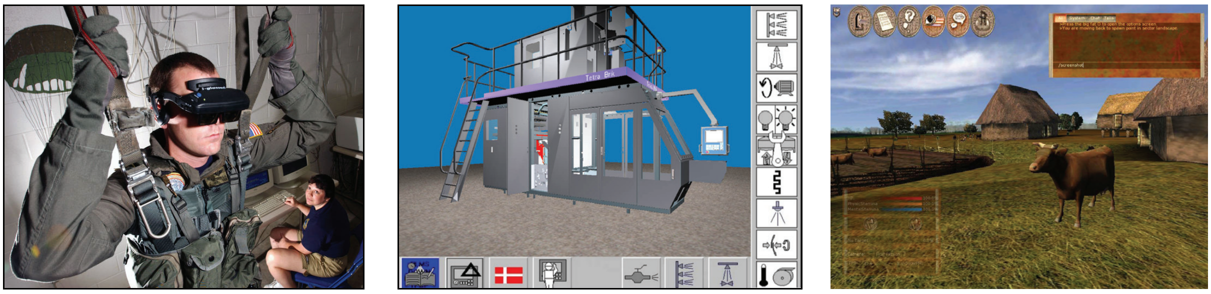
Figure 9. Input devices and equipment for interaction with virtual environments

2.3.2 Application areas for virtual reality

VR technology has shown potential in numerous application areas. One of the oldest and most obvious applications is military training simulators, such as flight simulators, tank simulators and the *VR parachute trainer* used by the U.S. Navy (Fig. 10a). VR is also believed to be part of a totally new paradigm in surgical education and training (Satava, 2006). One of the most successful applications in this area is the *Minimally Invasive Surgical Trainer* (MIST), which uses a haptic interface to simulate minimally surgical interventions.

VR also offers unique possibilities for operators and technicians who control and survey industrial processes, such as production of chemicals in chemical plants. Traditional 2D computer interfaces have raised interaction to a high level of abstraction, which has resulted in a loss of necessary "feeling" of how the real process works; VR could be one way to achieve intuitive process control again (Möller, 2004). For example, in a collaborative research project, TetraPak and Lund University in Sweden developed a prototype for a VR-based operator user interface for a packaging machine (Khamis, 2002) (Fig. 10b).

Recently, the term "virtual heritage" has emerged, which can be defined as "the utilisation of technology for interpretation, conservation and preservation of natural, cultural and world heritage" (Stone, 1999). Within this new field, numerous virtual environments in which the user can experience historical sites have been developed. *Virtual Annelöv* (Fig. 10c) is a reconstruction of a Swedish Bronze Age settlement in which a role playing game approach is used to let the user experience Bronze Age life (Benigno, 2005).



(a) The VR parachute trainer (b) TetraPak operating panel VR interface (c) Virtual Annelöv

Figure 10. Examples of VR applications

One of the most exciting and promising applications areas for VR technology is training and assessment for people with disabilities. A recent example is Broeren, Rydmark, Björkdahl and Stibrant Sunnerhagen (2007) who got positive results in an explorative study targeting the use of haptic VR for upper extremity assessment and training in people with stroke. Kizony, Katz and Weiss (2003) have developed a unique video capture VR system for physical rehabilitation. The system, which embeds the user's image within a virtual environment so that he/she can interact with animated graphics, has been evaluated with good results. In a study by Magnusson and Rassmus-Gröhn (2005), people with visual impairment successfully explored and learned a route in a virtual haptic-audio traffic environment.

VR is also believed to have the potential to become a usable tool in neuropsychological assessment and cognitive rehabilitation since VR makes it possible to:

- Practise hazardous situations, like crossing the street.
- Practise a certain activity despite motor impairment. In this way, treatment of cognitive skills can take place sooner than with real world training.
- Choose exactly what stimuli are presented to the user, which makes it possible to more strictly control the rehabilitation process than is possible in the real environment.
- Train activities in an independent manner.
- Easily record and measure the user's behaviour.

One area in which traditional methods have shown poor results is memory rehabilitation, possibly due to difficulties in keeping the patient's motivation up when confronting them with a repetitive series of memory training tasks (Wilson, 1997). Accordingly, the gaming factors of VR might be something that speaks in favour for memory assessment and rehabilitation in virtual environments. Brooks, Rose, Potter, Jayawardena and Morling (2004) have shown that desktop VR can be used to test stroke patients' prospective memory ability. Another cognitive process that might be hard to address with traditional methods is executive functioning, i.e. planning, sequencing, abstract thinking, etc. Elkind, Rubin, Rosenthal and Prather (2001) compared the *Wisconsin Card Sorting Test*, a neuropsychological test for assessment of executive function, with a test based on desktop VR called *Look for a Match*. The authors found that the latter measures the same cognitive functions as the former, and suggest that it might be more ecologically valid than the *Wisconsin Card Sorting Test* since it reflects a real-world situation.

Another domain in which VR has shown potential is assessment and rehabilitation of attention processes. Results from a study by Gupta, Knott and Kodgi (2000) suggest that the assessment of hemispatial visual neglect can be made with head mounted display based virtual environments in combination with an eye-tracking system. Similarly, Weiss, Naveh and Katz (2003) have shown that training people with hemispatial visual neglect, using a head mounted display, is a feasible application.

The assessment and rehabilitation of functional skills have also been investigated. Zhang et al. (2003) examined assessment of food preparation skills in a virtual kitchen and managed to prove that the VR method has high construct validity.

There are several things that might make the use of VR for the rehabilitation of people with ABI difficult. It is reasonable to assume that many individuals in this group are extra sensitive to the extraneous cognitive load induced by a user interface. This is a serious threat to the usability of VR applications for this population, especially in the context of neuropsychological assessment and cognitive rehabilitation. Even if the user is able to interact with a VR system at a basic level, the extraneous cognitive effort may distort the targeted assessment and rehabilitation processes (Rizzo, Buckwalter, & van der Zaag, 2002). Moreover, most VR systems only produce visual and auditive stimuli. The absence of other modalities, such as proprioception, might make VR assessment and training less efficient than the real world counterpart. That the VR user interface can make a virtual activity different from the real one has recently been demonstrated in a study in which 50 stroke patients were observed while preparing a hot drink (Edmans et al., 2006). Performing this activity was found to be more difficult in a virtual environment than in the real world. The authors concluded that virtual and real hot drink-making are qualitatively different tasks for people with stroke.

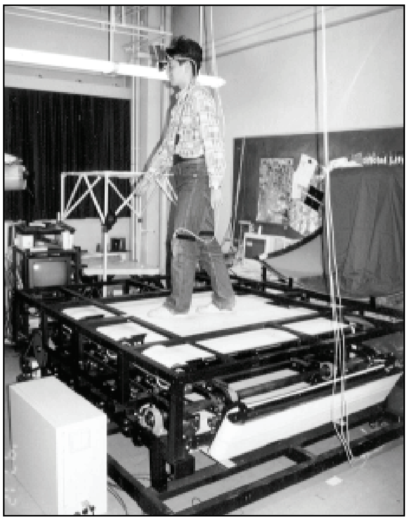
VR has also shown great potential as a tool for involving end-users in design and planning processes. Today hardly anybody questions the necessity of letting the end-users participate in the development process to make products, services and environments accessible and usable for as many people as possible (Preiser & Ostroff, 2001). It might be hard, however, for users to participate in such a process due to difficulties they have to verbalise their knowledge and experiences, or due to the complexity of the design tools (e.g. plan drawings and CAD software). These difficulties are likely to be enhanced in users with cognitive disabilities due to brain injury, for example. One possible solution could be to let the users directly experience what is to be designed or planned in a virtual environment. Several authors have investigated the use of VR for participatory design of work environments, for example Wilson (1999) and Davies et al. (2004). Moreover, VR has proven to be a useful tool for adaptation of workplaces and homes for people with physical disabilities (Eriksson & Johansson, 1996). It has also been suggested that VR can be a feasible tool for involving the public in urban planning (Bailey, Brumm, & Grossardt, 1998; Bucolo, Impey, & Hayes, 2001). That VR can be used to investigate also affective aspects of how the built environment is designed has been shown by Cozens, Neale, Whitaker and Hillier (2003). They used VR to gain knowledge about how people experienced a railway station with regards to crime and fear of crime. Scarcely any research targeting people with cognitive disabilities has been done in this area. Nevertheless, a collaborative project between the University of Teesside and Durham University in the UK is currently investigating the use of VR to allow people with dementia to test outdoor environment designs. So far, the group have presented preliminary results from an experiment in which 38 people with symptoms of mild to moderate dementia performed walks in a virtual version of Middlesbrough town centre (Blackman, van Schaik, & Martyr, 2007). The participants' performance was rated and the virtual environment was redesigned on the basis of this data. The virtual environment was then tested again with subjects with dementia. They performed better in the updated environment and the authors concluded that the VR-based method can be a useful tool in the evaluation of outdoor environments and for identifying improvements for people with dementia.

2.3.3 Interacting with virtual environments

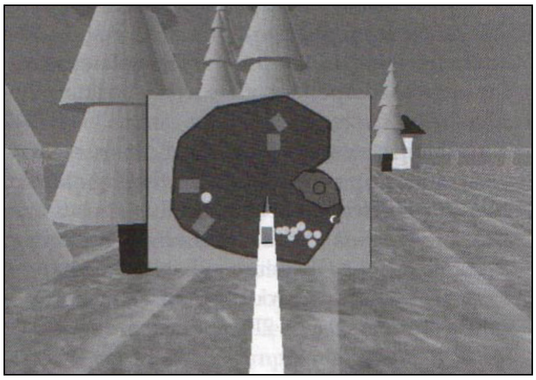
To be able to actually do something in a virtual environment the user must be able to move around, or navigate, in it. Navigation in a virtual environment can have two meanings: a motor meaning called travel, and a cognitive meaning called way-finding (Bowman, Kruijff, LaViola, & Poupyrev, 2001). Travel is the movement of the viewpoint from one location to another, and was investigated in the first study of Paper I. Way-finding can be described as the cognitive process of determining a route through the environment to the desired destination and was targeted in the first study of Paper II. Below, the travel meaning of navigation is described.

Regarding the travel meaning of navigation, Bowman et al. (2001) have defined three categories of travel tasks. In the exploration task the user investigates the surroundings with no special target in mind. The client of an architecture firm, for example, may explore the design of a planned building in a virtual environment. In the search task the user moves to reach a special target location. The above mentioned client might want to move to the front door of the virtual building to evaluate the accessibility for people with physical disabilities. Finally, the maneuvering task is performed when the user wants to position and orientate the viewpoint more advantageously for a specific purpose, such as the client wanting to take a closer look at some detail in the building by moving really close to it.

A number of travel techniques that allow a virtual environment user to perform these three travel tasks have been developed and evaluated. One of several ways to classify these techniques is by real world metaphors (Bowman, Kruijff, LaViola, & Poupyrev, 2005). Physical locomotion techniques mimic, to a greater or lesser degree, different ways of locomotion from the real world. For example, the *Torus Treadmill* (Iwata, 1999) allows the user to move in any direction by walking on the treadmill surface (Fig. 11a). Steering techniques are usually less intuitive but can be fairly easy to handle if well-designed. The most common steering technique is gaze-directed steering, which allows the user to move in the direction toward which he is looking. Target-based techniques allow the user to specify the endpoint, which makes the viewpoint move to the desired location. Figure 11b shows a target-based technique in which the endpoint is selected on a 2D map (Bowman, Johnson, & Hodges, 1999).



(a) The Torus Treadmill
(Iwata, 1999)



(b) Target-based navigation technique
(Bowman et al., 1999)

Figure 11. Examples of travel techniques

Just being able to navigate in the virtual environment is not enough since many VR applications also offer the possibility to manipulate the surroundings, i.e. the virtual objects in the virtual environment. According to Bowman et al. (2001), techniques for interaction with objects should support at least one of three basic tasks: object selection, object positioning and object rotation. A number of techniques for this purpose have been developed and evaluated and just like the travel techniques they can be classified by metaphor. The metaphor-based classification proposed by Poupyrev and Ichikawa (1999) make a basic distinction between egocentric and exocentric techniques. In egocentric interaction, the user interacts with the virtual environment from a first-person view. With exocentric techniques the user instead interacts with the virtual environment from outside of it. The egocentric metaphors can be divided further into virtual pointer metaphors and virtual hand metaphors. Techniques that use a virtual pointer metaphor rely on the fact that pointing is a very intuitive act for humans. The ray-casting technique allows the user to point at virtual objects with a ray that is attached to the user's virtual hand (Fig. 12a). Virtual pointer techniques are generally good for object selection but unsuitable for object positioning (Bowman et al., 2005). Virtual hand techniques allow the user to manipulate objects with a 3D model of a virtual hand that follows the user's real hand via, for example, a data glove (Fig. 12b). These techniques are more suitable for positioning tasks than pointer techniques but are flawed by their inability to offer interaction with objects outside the user's reach. Exocentric techniques are less common but can be very useful for some applications. For example, the world-in-miniature technique provides the user with a miniature handheld version of the virtual environment (Fig. 12c), which enables intuitive interaction with objects in the entire virtual environment.

(a) The ray-casting technique | (b) The virtual hand technique | (c) The world-in-miniature technique

Figure 12. Examples of techniques for interaction with objects

2.3.4 Presence and immersion

Have you ever seen a movie so captivating that you almost felt like really being there with the main characters? You probably have. This phenomenon is referred to as the diegetic effect in film science (Burch, 1979) and is related to what VR researchers call presence. To date, there is no uniform definition of presence and some VR researchers question if it is a meaningful construct at all (Sadowski & Stanney, 2002). Nevertheless, Slater (1998) suggests that presence includes three aspects:

- The sense of being there in the environment depicted by the virtual environment.
- The extent to which the virtual environment becomes the dominant one – i.e. that participants tend to respond to the events in the virtual environment rather than in the "real world".
- The extent to which the participants, after the virtual environment experience, remember it as having visited a "place" rather than just having seen images generated by a computer.

Despite the intense debate regarding the nature of presence, most VR researchers agree that presence is a complex, multi-dimensional perception, which is the result of the interplay of incoming stimuli and various cognitive processes (Draper, Kaber, & Usher, 1999). Schubert, Friedmann and Regenbrecht (2001) argue that the two cognitive processes involved in the creation of presence are mental model construction and attention allocation. The authors proved their point with a factor analytic study, which indicated that the presence construct is constituted by three factors: 1) spatial presence, which is connected to mental model construction, 2) involvement which is connected to attention allocation and 3) realness. Similar results were achieved in another factor analytic study by Lessiter, Freeman, Keogh and Davidoff (2001), which revealed four factors: sense of physical space, engagement, ecological validity and negative effects. The authors point out that the first three factors are very similar to the three factors identified by Schubert et al. (2001).

Spatial presence and sense of physical space are closely related to the concept of immersion. Slater and Wilbur (1997) define immersion as a description of "the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion to the senses of a human participant". According to this definition immersion is concerned with, for example, the extent to which physical reality is shut out and the visual and colour resolution of a VR display. Witmer and Singer (1998) disagree with Slater's view that immersion is an objective description of the VR technology. They suggest that immersion is a subjective experience, just like presence. In turn, Slater (1998) proposes that the definitions might be different since they address different sorts of immersion: Slater's definition has to do with system immersion while Wither and Singer talk about immersion response. In spite of all the disagreement, it seems that many agree with Witmer and Singer's (1998) view that "both involvement and immersion is necessary for experiencing presence".

Lombard and Ditton (1997) have suggested that there are different types of presence, which can be divided in two main categories: 1) physical presence, which is the sensation of being physically present in the virtual environment and 2) social presence, which refers to the feeling of being and interacting with other actors in the virtual environment, be it computer-controlled characters or remotely located users. When the user experiences physical and social presence simultaneously, a third type of presence can appear: co-presence. It has been defined as "the subjective sense of being together or being co-located with another person in a computer-generated environment" (Schroeder et al., 2001). Shared virtual environments, for example the popular 3D game *Counter Strike*, are an example of media in which co-presence is likely to appear.

2.3.5 Transfer of training from virtual environments

To what extent does a person who practises an activity in a virtual environment, such as one for using a cash dispenser, improve his ability to perform this task in real life? In a pioneering experiment Kozak, Hancock, Arthur and Chrysler (1993) compared the value of VR training, real-world training and no training in the transfer of training to a perceptual-motor task. They found no significant difference between the VR group and the no training group, and concluded that what the subjects in the VR group learned were specific only to the context of VR. The authors suggest that tasks that emphasise cognitive skills may benefit more from VR training. Spatial navigation is an example of such a task, for which several studies have shown a transfer effect from VR training (e.g. Witmer, Bailey, Knerr, & Parsons, 1996). However, a study by Clawson, Miller and Sebrechts (1998) suggests that the learning outcomes of VR route training are specific for the practised route. The participants hesitated more when walking a route in a direction opposite to that of VR training, compared to map training and real world training.

Would it be possible for people with cognitive disabilities to transfer training from a virtual environment to the corresponding real situation? Several studies suggest that this is indeed possible. For example, Mendozzi et al. (2000) found that 20 individuals with learning disabilities improved their ability on a grocery shopping task after VR training. In a similar study by Brooks, Rose, Attree and Ellio-Square (2002), 24 people with learning disabilities practised a food preparation task. Among other things, VR training and real world training were found to be equally beneficial. In a study by Brooks et al. (1999), a woman with amnesia practised route finding in a virtual hospital environment and successfully performed the routes in the corresponding real environment afterwards. Similarly, in the first study of Paper II of this thesis, five people with traumatic brain injury managed to transfer spatial knowledge from a virtual hospital environment to the corresponding real environment.

There is good reason to believe that the fidelity of a training simulator has an impact on the transfer of training. According to Waller, Hunt and Knapp (1998) there are three information domains involved in VR training: the real environment, the virtual training environment and the trainee's mental representation of the environment (Fig. 13). Fidelity is concerned with the quality of the mappings between these three domains and can be divided into environmental fidelity and interface fidelity. Environmental fidelity is determined by the extent to which the variables in the virtual environment resemble those in the depicted real environment. Examples of such variables are pictorial realism and scale agreement. Interface fidelity concerns the degree to which the input and output devices of the training simulator allow the trainee to interact with the virtual environment as he would have done in the real world. For example, an input device based on a walking metaphor is likely to give a higher degree of transfer than a joystick.

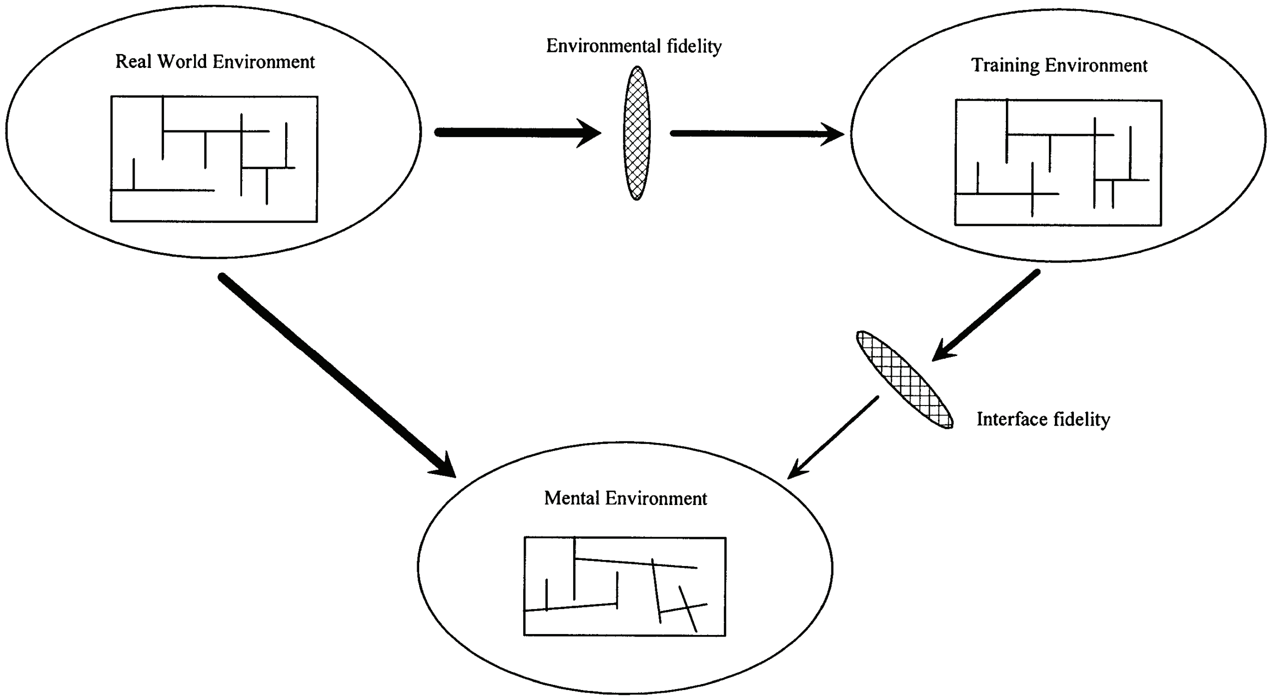


Figure 13. The role of fidelity in VR training (Waller et al., 1998)

2.3.6 Simulator sickness

During the early days of VR, many people who were exposed to virtual environments through a head mounted display (Fig. 7c) reported nausea, dizziness and other unpleasant symptoms. This phenomenon is called simulator sickness or cyber sickness and is believed to be the result of conflicting input to the visual and vestibular senses (Nichols & Patel, 2002). Simulator sickness may induce a number of symptoms that are often divided into three groups: nausea, disorientation and oculomotor symptoms (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Several factors are believed to give raise to simulator sickness. Nichols and Patel (2002) have grouped these factors as: 1) characteristics of the VR technology (e.g. display type), 2) virtual environment design (e.g. navigation speed), 3) task circumstances (e.g. length of period of use), and 4) individual participant characteristics (e.g. motion sickness susceptibility).

Field of view is a spatial property that defines the horizontal and vertical angular dimensions of the display. There is a consensus in the VR literature that a higher field of view results in a higher degree of sickness symptoms (e.g. Duh, Lin, Kenyon, Parker, & Furness, 2002). Flicker in the display is another factor that has been associated with sickness symptoms, especially in wide field of view displays since the peripheral vision is more sensitive to motion than central vision (Pausch, Crea, & Conway, 1992). The effects of stereoscopic displays on simulator sickness are largely unexplored. However, in a study by Ehrlich and Singer (1996), it was found that a stereoscopic head mounted display was more nauseogenic than a monoscopic one.

It has been shown that when virtual environment users have control of their own movements, the severity of sickness symptoms is lower than when users have no control (e.g. Stanney & Hash, 1998). The speed of translational movements in the virtual environment has also been found to significantly affect symptoms of simulator sickness (e.g. So, Lo, & Ho, 2001). Similar results have been found for rotational movements (Lo & So, 2000). The way in which the user is positioned is yet another factor that might affect the risk for simulator sickness: Sitting appears to be the better position in which to reduce simulator sickness symptoms (Regan & Ramsey, 1994). The duration of virtual environment exposure can also increase the probability of simulator sickness (Kennedy, Stanney, & Dunlap, 2000). An individual characteristic that has been associated with increased risk for simulator sickness is motion sickness susceptibility (Hu, Glaser, Hoffman, Stanton, & Gruber, 1996).

Even though VR has been used for training and assessment of people with cognitive disabilities there is very little knowledge about simulator sickness in this population. Pugnetti et al. (1999) found that patients with mild to moderate neurological impairments were not at increased risk of side effects. Similar results were found in a study in which patients with Alzheimer's disease and stroke tried a car simulator (Rizzo, Sheffiel, Stierman, & Dawson, 2003). The neurologically impaired group did not differ from the able-bodied controls regarding sickness symptoms, nor were they more likely to cancel the experiment.

3 METHODOLOGY

This chapter presents an overview of the methodology used in the research on which this thesis is based and a description of the participants. Qualitative as well as quantitative data collection techniques were employed to address the research objectives.

3.1 Qualitative techniques

The majority of the thesis research was carried out using qualitative techniques, mainly observations and interviews but also think-aloud protocols.

Observations based on video recordings were used in all four papers. In the field of human-computer interaction, making observations of users trying to accomplish a task is a very common method for collecting both qualitative and quantitative data. Usually video recordings are preferred to direct observations since the video material can be reviewed repeatedly afterwards. Another advantage with video recordings is that they can be used as the basis for discussions between the subject and researcher. In Papers III and IV, the video recordings were analysed using an observation schedule, which broke down the virtual bus trip into five steps. Each research question had a column in which observations from the virtual bus trip could be written. The columns also had space for the data from the subsequent think-aloud session, which was transcribed using reformulation and concentration. In this way, the recordings from the observations and the think-aloud session could be easily analysed in parallel. Colour coding was then used to create themes within and between the participants. Similar but less elaborate observation protocols were used for the studies of Papers I and II.

Video material was used to elicit data from the participants in Papers II-IV: The subjects with ABI watched the recordings from the trials and simultaneously commented on what they were thinking and feeling while performing the task. This technique is called retrospective think-aloud and is often used in usability testing (e.g. van den Haak, Jong, & Schellens, 2003). Objections concerning its validity has been raised (Russo, 1989) but there is also recent evidence based on eye movement measurements that suggests it can be a valid and reliable source of data (Guan, Lee, Cuddihy, & Ramey, 2006). The major flaw of retrospective think-aloud is that it relies on participants' memory, which could be particularly problematic for individuals with memory impairment. Concurrent think-aloud, in which the participant verbalises his/her thoughts while performing the task, was used in Paper IV to collect data from the occupational therapists. The reason why this technique was not used also for the ABI subjects is that the act of verbalisation has been shown to interfere with task performance (Russo, 1989; van den Haak et al., 2003). There is good reason to believe that this phenomenon could be enhanced in people with ABI.

Interviews were used in all the studies presented in the four papers of this thesis. The interview is a suitable method when the researcher wants to achieve descriptions of a phenomenon from the participant's point of view (Kvale, 1997). Interviews also combine well with observations since these two methods can compensate for one other's weaknesses, thereby increasing validity (Patton, 2002). For example, the observation data enables the researcher to check what is said during the interviews. The interview, on the other hand, enables the researcher to go beyond the participant's external behaviour. The interviews of Papers I and II were structured with a predefined list of questions. The interviews of Papers III and IV were, instead, semi-structured due to the more exploratory character of these two papers. Interview guides with themes were used for these semi-structured interviews.

3.2 Quantitative techniques

The controlled experiment, which was used in the first study of Paper I, is a well established research strategy in the fields of human-computer interaction (Preece et al., 1994) and VR (Stanney, 2002). Usually the investigator manipulates one or a few factors and studies what effect they have on various aspects of user performance. This requires a clear theoretical framework from which the hypothetical cause and effect relationship among variables can be formulated. In Paper I, three performance measures were logged as the user performed the task in the virtual environment: task completion time, travel distance and number of direction changes. The independent variables were type of input device (joystick vs. keyboard) and number of degrees of freedom (two vs. three). A questionnaire was also used in the first study of Paper 1 to gain information about the participants' subjective experience of the task. A five-point Likert scale was used for the five questions of the questionnaire. A between- subjects design was applied since I believed that the learning effects otherwise would bias the experiment. Two way ANOVAs were performed to see if the independent variables had any significant effects on the performance measures and the subjective experience of the subjects.

3.3 Participants

The majority of the research on which this thesis is based (Papers II, III and IV) was conducted using case study methodology (Yin, 2002) since I believed studying specific cases in depth would provide the most rich and useful data for addressing my research objectives. Since the two research areas investigated in this thesis, particularly the one of Papers III and IV, are still relatively new I wanted to assume a holistic approach, which would have been difficult using quantitative methodology. Another reason was that it would have been very difficult to perform quantitative experiments with individuals with ABI. It is hard to procure many enough brain injury patients who have the will, capacity and energy to participate without disturbing their rehabilitation process.

In the studies of Papers II-IV people with cognitive disabilities due to ABI participated. The logics of purposeful sampling were used for selecting participants for the studies of Papers III and IV (Patton, 2002). The idea behind this sampling method is to select information-rich cases for study in depth. The participants of the study of Paper II were instead chosen on the basis of accessibility and available time due to the brain injury patients' limited capacity and energy and collision with rehabilitation procedures. In the study of Paper IV four occupational therapists with experience of working with people with ABI also participated.

The subjects of the study of Paper I were selected using two inclusion criteria: 1) no cognitive disabilities, and 2) no or little experience of 3D computer graphics. The reason I chose able-bodied people was that I wanted to first identify fundamental usability issues. I reasoned that the problems of some people with ABI might be so unique and specific that they would obscure basic usability aspects. The participants were personnel and students from The Department of Rehabilitation at Lund University Hospital.

4 PAPER SUMMARIES

Paper I: Initial usability testing of navigation and interaction methods in virtual environments – developing usable interfaces for brain injury rehabilitation

VR technology has shown great potential as a training tool for medical doctors, soldiers, machine operators and others. It is believed that it can also be a feasible training tool in brain injury rehabilitation. However, people with brain injury are likely to be more sensitive to a flawed VR user interface due to cognitive impairments in one or several areas. Very little research has been done on user interfaces for desktop VR training applications for people with brain injury. The aim of this paper was to do initial usability testing of navigation and interaction methods in virtual environments. Two studies were conducted. Able-bodied people without experience of 3D computer graphics were chosen for participation since we wanted to identify fundamental usability issues. The problems of some people with brain injury might be so unique and specific that they would obscure such basic usability aspects.

The aim of the first study was to find a usable input device for navigation in virtual environments. Four input device configurations were identified in an initial discussion: the *Microsoft Sidewinder* joystick and *IntelliKeys* keyboard, programmed with two and three degrees of freedom each. With two degrees of freedom it was possible to move forwards and backwards and to turn to the left and to the right. Three degrees of freedom were the same but also provided means for sideway movements. These four input device configurations were compared in an experiment, in which sixty adults who met the two inclusion criteria participated. The navigation task was performed in a virtual environment consisting of a kitchen and a corridor. It was performed five times in a row by each subject and was designed to evaluate both fine adjustments of the viewpoint (maneuvering task) and transport of the viewpoint from one location to another (search task). Time, distance and number of direction changes were registered and afterwards the subject filled in a questionnaire consisting of five questions. Three video cameras and a microphone were used to document the experiment.

The results suggested that the keyboard is easier to control than the joystick for the maneuvering task. The keyboard was also slightly easier to control for the search task but was much slower than the joystick, which might make it an inconvenient input device for virtual environments that only involve search navigation. No significant differences could be found between two and three degrees of freedom for the maneuvering task, but the 3rd degree of freedom (sideway movement) seemed to facilitate the subjects' navigation in some situations. Two degrees of freedom were found to be slightly easier to control than three for the search task.

The second study aimed at evaluating a method for interaction with objects and finding a sufficiently usable input device for this purpose. The method for interaction with objects consisted of: 1) A virtual hand used for carrying objects, 2) drag-and-drop used for moving objects, 3) a single click used for activating objects, and 4) the objects being given a proper orientation automatically. Twenty able-bodied adults with no 3D computer graphics experience participated in an experiment. The task was to move four packages in a virtual kitchen environment. The subject performed this task five times in a row and was then interviewed by the test leader. Half of the subjects used a regular mouse for interaction with objects and the other half used a touch screen.

Overall, the method for interaction with objects worked well. The concept of using a virtual hand for carrying objects appeared to be comprehended by the majority of the subjects. However, comments from some subjects during the interview indicated that its visibility and affordance needed to be improved. Also, comments about the somewhat unrealistic behaviour of the objects emerged during the interviews. For example, some subjects pointed out that the objects sometimes changed size. Opening and closing cupboard doors caused some problems, especially for the subjects in the touch screen group who tried to open them with drag-and-drop in a manner that resembled reality. To eliminate these difficulties, the virtual environment should be programmed to allow several interaction styles. In this particular case it should be possible to open the cupboard doors both with a single click and drag-and-drop. No large differences in performance were observed between the mouse group and the touch screen group. However, the actions of the touch screen subjects tended to resemble real life object interaction more than the mouse subjects. This suggests that the touch screen is a more suitable input device in this context since the virtual activity resembles the real world activity.

Paper II: Investigating virtual reality training for brain injury rehabilitation

This paper presents two studies addressing VR training for people with acquired brain injury (ABI).

The purpose of the first study was to investigate the transfer of route knowledge from a virtual to a real environment in five people with ABI. The participants practised a route in a virtual environment using a laptop computer. The test leader demonstrated the route and then the subjects practised it three times in a row. The subject only received help from the test leader if he/she seemed unable to find the way by himself/herself. The training was documented with three video cameras and a microphone. The subject then walked the route in the real environment while being filmed with a video camera. All five subjects managed to transfer spatial knowledge from the virtual environment to the real environment but some difficulties could be observed in four of the subjects. Interestingly, the difficulties appeared in a part of the route that they also had problems with during the VR training. The reason for this could be the way-finding task itself: The mistakes occurred at a difficult part of the route. Another explanation could be that trial-and-error learning did not work well for the subjects. Interestingly, the subjects managed well to walk the route back to the starting point even if they had not practised this in the virtual environment.

The aim of the second study was to develop and evaluate a virtual cash dispenser to be used as a training tool in brain injury rehabilitation. An iterative design process was implemented to develop the virtual environment in three steps. Seven people with traumatic brain injury practised money withdrawals with the virtual cash dispenser on a desktop computer. The training was documented with three video cameras and a microphone. Generally, all subjects managed to learn how to use the virtual cash dispenser. However, some usability problems, mainly connected to moving and rotating the virtual objects, were noted. A large number of these problems appeared to be due to unclear feedback from the VR interface. This seemed to make it particularly difficult for one of the subjects to build a sound mental model of how the interaction worked. Some problems with the touch screen were observed due to insufficient calibration and poor electrical contact between the user and the screen. Except for this, the subjects had no problems handling the touch screen. Three of the subjects tried to physically grab the virtual objects, which seems to suggest that the touch screen elicited behaviour similar to that of the real world activity.

Broadly, the subjects of the two studies had a positive attitude to the VR training.

Paper III: A suggested virtual reality methodology allowing people with cognitive disabilities to communicate their knowledge and experiences of public transport systems

The knowledge and experiences of people with cognitive disabilities are scarcely considered in the planning of public transport systems. The aim of this study was to explore the use of VR technology to allow people with cognitive disabilities to communicate their knowledge and experiences of public transport accessibility. To create a realistic experience, an immersive VR system with three projector screens and surround sound was used. The user could interact with the VR system by providing verbal descriptions of his/her actions and/or pointing with a laser pointer. This method was chosen to make the interaction with the virtual environment as easy as possible, thereby minimising the cognitive load induced by the VR interface.

The VR methodology was evaluated in an experiment in which seven people who had experienced stroke participated. Three of the subjects had no measurable cognitive impairment. The most salient cognitive impairment of the remaining four subjects was in attention, memory, language and spatial ability, respectively. The logic behind this sampling was the assumption that these four cognitive domains have the biggest effect on a person's ability to handle the VR methodology. The task of the subjects was to perform a complete bus trip including a transfer in a virtual environment. Two video cameras and a microphone were used to document the actions, behaviour and verbalisations of the subject. Afterwards, the subject was asked to think aloud about how he/she was thinking and feeling during the virtual bus trip while watching the recorded video material. The test leader also asked questions from an interview guide during the think-aloud session.

Overall, the results suggested that the VR methodology is a feasible tool for people with cognitive disabilities but also revealed issues in need of improvement. Generally, the subjects had no difficulties perceiving and understanding the virtual environment but all of them had initial difficulties communicating their intentions. They did not understand what was expected from them and described their actions too comprehensively. However, all except one subject quickly improved. Five subjects combined pointing with the laser pointer with verbalisations in an effective manner, which may have lowered their cognitive load since they did not need to provide precise descriptions of their actions.

Four subjects experienced dizziness during the experiment. The majority of the discomfort occurred when the bus was turning, most likely the result of the bus moving in an unrealistic way.

All subjects showed indications of experiencing both physical and social presence in the virtual environment and all of them displayed a positive attitude to the VR methodology.

Broadly, all subjects managed to think aloud about their experience of the virtual bus trip when seeing the video material in a satisfactory manner. They made comments on problems they had during the virtual bus trip, suggested improvements of the virtual environment and reflected over earlier bus trip experiences. Furthermore, the subjects' verbal descriptions of what they wanted to do occasionally revealed aspects of how they reasoned to perform the bus trip.

Paper IV: A virtual reality methodology for eliciting knowledge about public transport accessibility for people with acquired brain injury

The purpose of this study was to investigate if and how a methodology based on virtual reality technology can be used to elicit the knowledge of occupational therapists and people with acquired brain injury (ABI) regarding public transport accessibility for the latter group.

Two people with stroke and two people with traumatic brain injury participated. They were selected to have their most salient cognitive impairment in attention, memory, language and spatial ability, respectively. They made a virtual bus trip, which started out in the subjects' virtual flat and ended at a café. Before the actual bus trip was initiated, they were asked to perform activities in the flat, such as clearing the dinner table. The purpose of this training, which lasted approximately five minutes, was to give the participants an opportunity to get used to the VR methodology. After the virtual bus trip, they watched the recorded video material from the bus trip while thinking aloud about their experience in the virtual environment. Four occupational therapists, with experience of people with ABI, also participated. They too performed the virtual bus trip, but were asked to think aloud while taking the trip about public transport accessibility for people with ABI. Afterwards, they watched the video material of the ABI subject who was judged to have the most problems using the VR methodology, and were once again asked to think aloud about accessibility aspects. For all eight subjects, the experiment was concluded with a semi-structured interview.

The four subjects with ABI managed to handle the VR methodology sufficiently well but some difficulties communicating their intentions were noted. Moreover, some problems thinking aloud were noted, which suggests that for participants with ABI the think-aloud session after the virtual bus trip should be conducted more like a normal conversation to make it easier for them to share their knowledge. The four occupational therapists had no problems at all handling the VR methodology and overall they managed well to think-aloud while making the virtual bus trip and during the video-based think-aloud session. Nevertheless, the results also indicated that they ought to be able to acquaint themselves with the think-aloud protocol before the virtual bus trip. Think-aloud training in the virtual flat could be one way to do this. Five of the eight subjects experienced some sort of dizziness, which is regarded as a symptom of simulator sickness. This risk for simulator sickness symptoms can be reduced by avoiding fast or jerky movements in the virtual environment and by letting the participant sit on a chair during the virtual bus trip. It can also be a good idea to screen the user for motions sickness before participation. The virtual environment lacked some of the stimuli found in a real public transport system, such as crowds of people and cars, and thus it was occasionally perceived as unrealistic or peculiar by the subjects. Even so, some of them commented that the virtual experience actually felt like taking the bus. The most relevant knowledge from the subjects with ABI was related to concrete accessibility problems, emotional aspects and strategies. The elicited emotional aspects can probably be very useful for a real public transport planning context. If the planners see the anxiety or stress of people with ABI with their own eyes, they may become more aware of the consequences of a poorly planned public transport system and may also be more willing to consider the needs of individuals with cognitive impairments in the planning process. The direct observations of the ABI subjects making the virtual bus trip led to the identification of some problems but revealed very little about what caused them. Instead, the cause of the problems came to light through the ABI subjects' verbalisations, which demonstrates the importance of not only making observations but also listen to the participant's subjective experience. The most relevant knowledge from the occupational therapists concerned concrete accessibility problems and suggested solutions. The fact that a fourth of the utterances proposed solutions is a very positive result since it suggests that the VR methodology encourages occupational therapists' ability to analyse how things can be improved. The occupational therapists were thinking aloud during the virtual bus trip and also while watching the video material of one of the ABI subjects. Both think aloud sessions appeared to elicit unique knowledge and should therefore be part of the VR methodology in order to cover as many aspects as possible of public transport accessibility for people with ABI. In general, all eight subjects displayed a positive attitude to the VR methodology.

Overall, the results suggests that the concept of first carrying out actions in a virtual environment and then reflecting over these actions seems to be a very good way of eliciting knowledge about public transport accessibility for people with ABI. The elicited knowledge from people with ABI and from occupational therapists seems to illuminate, in part, different aspects of public transport accessibility and hence is complementary.

5 DISCUSSION

This chapter discusses the results of the four papers, as well as methodological and ethical issues and future possibilities.

5.1 Does it work and if so how?

In general, the results of the research presented in this thesis suggest that virtual reality (VR) can be used by people with acquired brain injury (ABI) as a training tool in rehabilitation and as a tool for eliciting knowledge about public transport accessibility for this population. But why use VR technology in the first place? Is the real world not enough? There are several motivations for using VR: Hazardous situations can be practised, stimuli can be controlled in a precise manner, environments that do not yet exist can be evaluated, etc. A reason that has emerged clearly during the research on this thesis is that using VR is fun and motivating. Furthermore, even if not investigated in detail here, VR training seems to be time efficient: Many training sessions can be performed in a relatively short time compared to real world training.

However, the experience of a virtual environment will never be as realistic as experiencing the real world, at least not with current VR technology. Usually, only two of the human senses, sight and hearing, are stimulated and the user does not use his/her body as in the real world. In the experiments presented, the users have been sitting down on a chair, interacting with the virtual environment with arm movements. Can this simplified reality, with moderate environmental and interface fidelity (Fig. 13), be of any real use? The results suggest that visual and auditory stimuli and limited body involvement are sufficient, even when delivered by less advanced VR equipment. As for brain injury rehabilitation, the study in Paper II gave further support to the hypothesis that a VR system based on standard desktop computer technology is a plausible training tool. However, this type of equipment is probably not sufficient to let people with ABI and occupational therapists communicate their knowledge and experiences in a planning process. Theory suggests that a more immersive experience, capable of inducing a higher degree of presence in the user, is needed to adequately elicit the user's knowledge of accessibility issues. The immersive VR system used for the studies described in Papers III and IV seemed to be able to create an experience similar to that of a real bus trip, capable of triggering the knowledge of people with ABI as well as occupational therapists. Exactly what degree of immersion is needed for this application remains to be seen, however. It should be noted that the lack of bodily involvement in this immersive VR system may not only be a disadvantage. The absence of proprioceptive and tactical stimuli in the virtual experience may decrease the participant's attention to physical accessibility issues thereby making it easier for him/her to focus on cognitive aspects of accessibility. As already mentioned, the combination of visual and auditive stimuli seems to create a sufficiently persuasive experience, but it is very important to consider how these stimuli are presented to the user. Some of the research results presented here indicate that behavioural realism is very important, perhaps even more important in some cases than pictorial realism. Virtual objects that behaved in unexpected or unrealistic ways seemed to confuse some of the subjects. It is likely that this issue is even more important to consider when the users are people with ABI, since they might have difficulties understanding that unrealistic behaviour in the virtual environment is not their fault but due to non-optimal programming of the VR application.

User interface issues were examined in all four papers. Overall, it seems possible to make user interfaces for VR applications that work sufficiently well for people with ABI. All subjects in the Paper II study became better at handling the VR interface with time. In a rehabilitation context an initial learning period can be allowed: The user interface does not have to be perfectly intuitive from the very beginning. However, the Paper II study also showed that also relatively small user interface details can be crucial for how some individuals in this group can learn how to use the VR technology. This is in line with Lawton's docility hypothesis, which states that individuals with low competence are more vulnerable to environmental demands than those with high competence (Lawton, 1980). Furthermore, it is possible that a non-optimal interface renders the virtual task different from the real world task. Edmans et al. (2006) studied 50 stroke patients who prepared a hot drink in a virtual environment and in a real rehabilitation kitchen. One of their conclusions was that virtual and real hot drink making are qualitatively different tasks for stroke patients. The virtual task appeared to be more difficult and the authors attributed this to user interface and technical problems. Apparently there is a need for more research on how user interfaces should be designed for different types of VR training applications in brain injury rehabilitation.

The purpose of the study presented in Paper I was to do initial usability testing of different ways of interacting with virtual environments. Able-bodied people participated, which gives rise to an important question: How much of the results can actually be generalised to people with ABI? The main reason for studying an able-bodied population was that the problems of people with ABI might be so unique and specific that they would obscure basic usability aspects. Based on my research experiences, I believe the majority of the results presented in Paper I to be relevant also for people with ABI. For example, the keyboard was found to be easier than the joystick and I believe this difference to be even more apparent in the ABI population. Another example was that some aspects of the virtual kitchen were perceived as unrealistic, which created problems. The able-bodied participants seemed to be able to overcome this, but for a user with ABI this can cause greater difficulties.

The VR methodology described in Papers III and IV is to be used in a planning context and this puts different demands on the user interface. It must be much more intuitive to avoid that difficulties using the VR technology are interpreted as accessibility problems. Furthermore, the VR methodology should be possible to use with a minimum of training due to the time constraints of most planning processes. My experiences from Papers I and II told me that this would require a completely different type of user interface. In general, the "talk and point" interaction that was evaluated in Papers III and IV turned out to work very well for all the subjects. Now the attentive reader might ask: If "talk and point" is so easy to use, why was a similar interaction method not used in the VR training studies? There were two reasons for this: First, there is good reason to believe that it is important for the quality of the training that the user directly controls the input device. Second, it would probably be very difficult to implement a VR system for independent training equipped with a "talk and point" interface, at least with the current technology.

5.2 For whom can VR be a feasible tool?

As described in chapter 2.1, the cognitive effects of ABI can be many and diverse. This raises the question of whether the VR technology is a feasible tool for all individuals in this population or not. My experiences from the research with this thesis tell me this is not the case. Individuals with severe cognitive impairments, who are in the beginning of their rehabilitation, might not be able to overcome the extraneous cognitive load induced by the VR tool. For brain injury patients with only light cognitive limitations, VR training might not be relevant since they probably only have very subtle difficulties best trained in the real world. I believe VR training to be relevant mainly for those patients who are in the midst of their rehabilitation and who do not have so severe cognitive limitations that they cannot use the VR technology. A similar line of reasoning holds for the VR methodology described in Papers III and IV: It is probably not a feasible methodology for those with severe cognitive limitations. On the other hand, it could be argued that the VR methodology would not be meaningful for this group anyway since they probably would find it too hard to use public transport.

VR has also shown great potential as a tool for people with learning disabilities, above all for training (e.g. Brooks et al., 2002). There is good reason to believe that VR training can be useful for many other individuals who want to practise some activity to be able to lead a more independent life. For example, elderly people who want to go by bus, but do not dare to, could practise this activity at their own pace as many times as they want. In a similar manner, it is also possible that VR could be used to elicit the knowledge and experiences of other groups who have difficulties making their voices heard in planning processes. Blackman et al. (2007), for example, have successfully used a VR-based method for evaluating outdoor environments with people with dementia. Another group that might benefit from the VR technology, for example by learning social skills, is people with autism spectrum disorders (e.g. Mitchell, Parsons, & Leonard, 2007).

The occupational therapists who would supervise the VR training and the planners who would utilise the VR methodology can also be considered as a sort of user group. It is important to consider these secondary users when designing the VR technology. For example, a VR training tool should have an intuitive user interface that allows an occupational therapist to easily follow the patient's progress, change the level of difficulty, switch between training tasks, etc. As technology develops it is likely to become easier to handle. For example, an immersive VR system, like the one used in Papers III and IV, can nowadays be driven by a single personal computer which greatly simplifies its handling. Another aspect is that the so-called Nintendo generation is currently entering working life. This generation has grown up with computer games that provide them with the prerequisites to handle VR technology.

5.3 Taking the users' point of view: attitudes and ethics

This thesis has demonstrated that VR technology has great potential as a tool for people with ABI, but how is it perceived by the end-users themselves? The attitude of the users when introducing technology in a new context is crucial. In general, the subjects with ABI in these studies had a positive attitude to the VR technology. Furthermore, an occupational therapist in the reference group made an interesting point regarding the subjects' attitude to the VR methodology (Papers III and IV): When the participants understand that somebody has gone to great efforts to learn about their everyday problems they are likely to feel involved and motivated. It is important, however, to remember that the individuals who were willing to participate in this research probably were more likely to have a positive attitude from the start. There is also a risk that the subjects might have felt flattered by the attention from the research group, thereby unwittingly trying to help the experimenter obtain good results. Despite this, I believe it is fair to say that the participants accepted the VR technology and had a rather positive attitude to it.

What ethical issues are raised when investigating VR technology as a tool for people with ABI? Approval for the two projects described in this thesis was obtained from Lund University's Ethics Committee, but this is no guarantee that subjects are not exposed to unpleasant experiences. Ethical issues must be considered in every moment of the research process since some people with ABI might be more susceptible to the negative effects of VR technology than able-bodied people. Behr, Nosper, Klimmt and Hartmann (2005) have identified four major potential risks that might expose the subject of a scientific study using VR technology to discomfort: (1) simulator sickness, (2) information overload, (3) intensification of experience and (4) re-entry into the real world. There is good reason to believe that simulator sickness (see chapter 2.3.6), presents the largest risks for discomfort in the subjects. In Papers I and II, desktop VR was used. Since this technology offers a low degree of immersion, the risk for simulator sickness is small (Nichols & Patel, 2002). Also, if the user feels overwhelmed by the experience it is enough to look away from the screen. Nevertheless, 10% of the subjects reported dizziness or nausea in the first study of Paper 1, possibly due to the varying frame rate that sometimes resulted in larger and less controlled movements. The immersive VR equipment used in Papers III and IV required precautionary measures since this VR technology brings about increased risk for simulator sickness. All subjects were screened for motion sickness susceptibility before participation and efforts were made to make sure that they had understood the experiment and the associated risks for simulator sickness. It was also carefully explained to them that they could stop the experiment at any time. After the experiment the subject was offered a cup of coffee in order to give him/her time to readapt to the real world before going home. Measures were also taken during the design of the virtual environment. For example, high rates of linear and rotational acceleration in the virtual environment were avoided. Despite these precautions nine subjects out of 15 reported dizziness, which is regarded as a symptom of simulator sickness (Kennedy et al., 1993). Finally, it all boils down to this question: Is the knowledge about how to improve public transport accessibility worth the risk for simulator sickness? I believe the answer is yes. The overall purpose of using VR technology in this thesis has been to improve the life situation of people with ABI. The subjects have not been used as a means to an end, and hence the potential risks for some discomfort in the subjects ought to be justifiable.

Another matter that can give raise to ethical concerns is how the VR technology is integrated in a brain injury rehabilitation process. VR can never substitute the professional knowledge and skill of an occupational therapist and should therefore be seen for what it is: a complement to conventional rehabilitation procedures. It is very important to be aware of the pros and cons of VR technology to avoid the temptation to cut down on personnel and funding by replacing conventional rehabilitation with VR-based rehabilitation procedures.

5.4 Methodological issues

The research on which this thesis is based has been carried out in the framework of two multi-disciplinary projects, and I believe this to be a strength with regards to quality. The research group of the VR training project (Papers I and II) had competency in brain injury rehabilitation, occupational therapy, neuropsychology, human computer interaction and VR. I strongly believe that it is necessary to have expertise in all these areas to develop VR applications that will work sufficiently well for people with ABI. A similar approach was used in the second project (Papers III and IV). Among the people involved in the project, there were experts in traffic planning, accessibility, occupational therapy, neuropsychology, human-computer interaction and VR.

Another strength of this thesis is that three different virtual environments have been evaluated with people with ABI. They portrayed three different scenarios: route finding in a hospital, a cash dispenser withdrawal, and a bus trip. They were built using different types of VR tools, which affected their appearance. For example, the first was built with a 3D game tool, whereas the other two were implemented with conventional VR tools. Furthermore, they were displayed with both non-immersive and immersive VR systems. They also had different types of user interfaces. The fact that all three virtual environments worked sufficiently well for the subjects with ABI gives further support to the statement that VR technology is a feasible tool for this population.

Case study methodology was the predominant research approach. As has already been mentioned in chapter three, I used this approach since it appeared to be the best methodology for the research objectives. Case study methodology is often criticised for being context-dependent, only useful for exploratory research, prone to researcher bias, impossible to generalise and difficult to summarise into theories. Flyvberg (2006) has responded to this criticism by drawing parallels to human learning: It is only because of experience with cases that a beginner can become an expert. Significant for all experts is context-dependent knowledge and experience from several thousand concrete cases in their areas of expertise. Flyvberg concludes that "a scientific discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars and a discipline without exemplars is an ineffective one". I have used exemplars extensively in my teaching and can therefore easily embrace this statement. Accordingly, it constitutes my main argument for using case study methodology.

Qualitative data collection techniques were used in the Papers II-IV studies to investigate how individuals with ABI can use the VR technology. This brings up questions about the quality of the research. For example, limited memory and communication abilities can negatively affect the credibility of interview responses, the richness of data and the researcher's interpretation (Lloyd, Gatherer, & Kalsy, 2006). To avoid these problems, great efforts were made to formulate the interview questions in a clear manner, not using technical terms or unnecessarily complicated vocabulary. Furthermore, I have striven to improve my interviewing skills by carefully observing how the occupational therapists engaged in the research interact with patients. A strategy that can be used to improve the quality of the researcher's interpretations is to understand his/her biases and perspectives (Peshkin, 1988). As a VR researcher, it has been important for me to avoid the risk of unwittingly neglecting data that speaks against the VR technology. Another strategy that was used to improve the quality of the research was to let a reference group give continuous input to the research process.

Looking back on my work, I realise that several things could have been done differently. First and foremost, I would have more systematically selected subjects in the Paper II study. A more purposeful sampling procedure could have been used to see how different types of cognitive limitations affect the usage of the VR training tool. However, the brain injury patients' limited capacity and energy and collision with rehabilitation procedures forced me to select participants on the basis of accessibility and available time. As for Papers III and IV, more focus should have been put on reliability. However, the highly exploratory nature of the research made it very difficult to categorise the observations in order to investigate the inter-observer reliability, i.e. the degree of agreement among observers that can be achieved with the VR methodology. Another thing that could have been done differently was the choice of input device in Paper II: A regular keyboard and two degrees of freedom was used, which proved a bit difficult for some of the participants to use. Why did I not use the *IntelliKeys* keyboard with its simplified interface, which was evaluated with good results in Paper I? The reason was one of operative system compatibility: The *IntelliKeys* keyboard only worked under *Windows 98* whereas the virtual environment worked best under *Windows 2000*. I probably could have solved this problem somehow, but once again time constraints threw a spanner into the works.

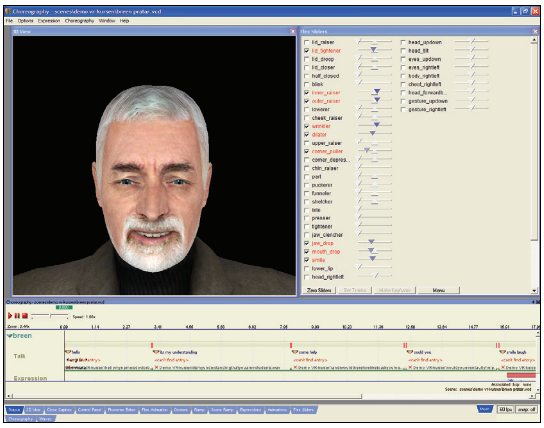
5.5 From research to product

The results of this thesis suggest that VR technology has great potential as a tool for people with ABI. However, its real impact outside the research community has been minimal so far, and will probably remain so unless commercial actors enter the scene. In the USA, the development and distribution of VR technology and services for rehabilitation and therapy is a slowly but steadily growing sector. For example, the *Virtual Reality Medical Centre* in San Diego offers treatment of anxiety disorders, such as fear of heights and social phobia, by exposing the client to a virtual environment in which he/she experiences various stimuli related to his/her phobia. *Virtually Better*, *Digital Mediaworks* and *Psychology Software Tools* are examples of American companies that design and distribute VR applications for rehabilitation and therapy. Interestingly, a non-commercial VR tool for therapy and research has just emerged: *NeuroVR* (Riva et al., 2007). It is based on open source software and equipped with an easy to use interface that allows a clinical professional to create or alter virtual environments to be used in therapy sessions. This demonstrates the significant potential of open source software in this area.

5.6 New technology, new possibilities

What other possibilities will computer technology offer in the future? Both hardware and software is improving at a fast pace. This development is mainly driven by the gaming industry, which currently has a higher turnover than the film industry. For example, there is a trend in the gaming community to use wide field of view systems, so-called surround gaming (Fig. 14a). As the demand for such computer systems increases, prices will fall making this type of equipment affordable for rehabilitation hospitals. The *Nintendo Wii* console offers a more intuitive way of playing games by letting the user control the game with his/her body movements (Fig. 1d). As this technology also becomes available for personal computers, new possibilities will open up for both cognitive and physical rehabilitation. On the software side, new opportunities appear as game studios make their software development kits (SDK) available, allowing gamers to create new games or to modify existing ones. An example is the *Source SDK* by *Valve Software*, which was used to create the popular game *Half-Life 2*. The *Source SDK* contains the *FacePoser* tool that can be used to equip 3D characters with speech, movements and behaviour (Fig. 14b). Such a tool could be used to create a virtual training coach with the purpose of making VR training more fun and efficient.

(a) VR training with a surround gaming computer



(b) FacePoser

Figure 14. Examples of game technology offering future possibilities

Today, more and more design and construction is done with 3D modelling tools such as *Pro/ENGINEER*, *ArchiCAD* and *AliasStudio*. The increased availability of 3D data will offer new opportunities to visualise artefacts and environments that only exist in the heads of the people designing them. Furthermore, projection technology is improving fast, resulting in cheaper and more compact VR systems able to project high quality images. Taken together, this technology development will provide means for urban planning and public transport authorities to evaluate public spaces early in the planning process by involving end-users and individuals with expert knowledge about the end-users.

The TV of the future will offer many possibilities currently only available with a computer. For example, Abdelmassih Waller, Jönsson and Östlund (2007) investigated the use of TV photo albums for older persons at a nursing home with good results.

New opportunities will open up for individuals who for some reason do not want to or cannot use a computer: With its familiar appearance and interface the TV can offer easily accessible services such as VR training or other types of telerehabilitation.

Also portable technology such as mobile phones and palmtop computers will give raise to interesting possibilities. New 3D graphics hardware, such as *Nvidia*'s *GoForce*® technology, will make it possible to run interactive 3D applications of high quality on handheld devices. Imagine, for example, a person with ABI who feels very insecure about using cash dispensers. Before making a money withdrawal he could practise this activity on his palmtop computer, to refresh his memory and to gain self-confidence.

Not only the computer technology but also people with ABI will be different in the future. With time, more and more individuals with brain injury will have experience of computer games and other 3D applications. It is likely that this population will perceive the VR technology as a natural part of their lives: a tool among others. On the other hand, they will probably have higher expectations for the technology, which might create problems. For example, a VR training tool with insufficient graphics might render their attitude negative no matter how well designed the tool is in other aspects.

6 FURTHER RESEARCH

VR technology is currently entering a mature phase, but a lot of research is still needed to investigate how it can be a useful tool for people with ABI. Regarding VR training, efforts should be made to investigate how much and in what way the training can be generalised to similar tasks. For example, consider a patient who has used VR training to practise a train ticket machine. Will this training also be of use when he/she is using other types of ticket machines? Brain injury patients can have difficulties generalising from conventional rehabilitation training to real world tasks (Manly, 2002) and further research should investigate if and how this phenomenon would be different for VR training. The long term effects of VR training are largely unexplored, particularly in people with ABI. Do the limited stimuli and restricted body movements of VR training produce qualitatively different training results compared to real world training? Another important issue is the actual integration of VR training in a brain injury rehabilitation process. What effects can be expected in a longer perspective? How should conventional and VR-based training be combined to optimise the outcomes of rehabilitation procedures? To the knowledge of our research group, no research has been carried out so far to investigate these issues.

The laboratory experiments of Papers III and IV produced many interesting results but were not part of a planning context. To fully understand the usefulness of the VR methodology it should be applied in a real planning situation. An interesting case study could be to let the transport system authorities of a Swedish town use the VR methodology when purchasing new buses. A virtual environment in which one can make a bus trip with the buses in question could be built using 3D construction data from the bus manufacturers. Among other things, such a case study could address the attitudes among public transport planners to the VR methodology. Their work is to satisfy different groups of stakeholders by finding a balance between various design parameters. Understanding how the VR methodology could fit in the overall planning process is crucial and should be investigated in further work in this area.

Another group whose knowledge might be interesting to elicit with the VR methodology are engineers with expert knowledge about information technology. By directly experiencing the problems that can occur for people with ABI and by elaborating on the suggested solutions from occupational therapists they could suggest concrete technical solutions. Since engineers are familiar with the possibilities of modern information technology, they may also be able to suggest innovative solutions for long-term improvements of the public transport system. Their suggested technical solutions could then be evaluated with the VR methodology to see how they work for the end-users and how they can be improved.

The VR methodology can, of course, also be used to address accessibility for people with ABI in the planning of other facilities such as hospitals, libraries, and supermarkets. Investigating the applicability of the VR methodology in these contexts could be a good way to learn more about it.

There is currently a large interest in telerehabilitation as a complement to conventional rehabilitation, also among people with ABI (Ricker et al., 2002). VR training could be one of several components in future telerehabilitation systems (Rizzo, Strickland, & Bouchard, 2004). The rehabilitation process could be supported by a therapist who communicates with the user through a web camera. Another possibility could be to facilitate independent training by equipping the VR training application with a help function. How this help function should be designed could be the subject for further research. One solution could be to create "virtual therapists" who aid and motivate the care recipient. For example, Bickmore, Caruso, Clough-Gorr, and Heeren (2007) showed that a computer-generated relational agent could motivate a group of elderly people to do physical exercises. Further research is needed to investigate how such agents should be designed for people with ABI in a brain injury rehabilitation context.

7 RELEVANCE TO SOCIETY

Virtual reality (VR) technology will become an increasingly important part of modern society. Traditionally, the two most important application areas for VR technology have been military and medical training simulators and entertainment. However, as 3D graphics hardware becomes less expensive and more compact, a broader spectrum of VR-based products and services will become available to the general public.

Two application areas of VR technology for people with acquired brain injury (ABI) have been investigated in the research presented in this thesis. Regarding VR as a training tool, a rehabilitation hospital could use the results as the basis for setting up VR-based rehabilitation procedures. Furthermore, the virtual cash dispenser, described in Paper II, can be used without charge by anyone who wishes to do so. The virtual public transport system used in the studies of Papers III and IV could also be slightly modified to allow bus training in a rehabilitation context. On a national level, it is possible that VR-based training can save money for rehabilitation facilities. It could constitute a cost-efficient complement to conventional rehabilitation techniques as the number of care recipients increases and health care budgets get tighter. Moreover, time and energy could be saved for patients with brain injuries by making VR-based telerehabilitation part of the rehabilitation.

The VR methodology described in Papers III and IV could be used by public transport authorities that wish to address accessibility for people with cognitive disabilities. A more accessible public transport system would allow more citizens to travel by bus and train, increasing their independence and quality of life. Fewer people using subsidised transportations services would also save a considerable amount of money for the state. Moreover, considerable costs could be cut by designing for accessibility from the start, not having to rebuild and adjust in the future.

VR technology is not only relevant for people with ABI. Another plausible user group is elderly people, a group with increasingly high demands on society with regard to independence and quality of life. VR as a tool for training and involvement in planning processes seems highly relevant for elderly people who wish to remain independent and mobile.

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Initial usability testing of navigation and interaction methods in virtual environments: developing usable interfaces for brain injury rehabilitation

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Initial Usability Testing of Navigation and Interaction Methods in Virtual Environments: Developing Usable Interfaces for Brain Injury Rehabilitation

Abstract

It is speculated that virtual environments (VE) might be used as a training tool in brain injury rehabilitation. The rehabilitation process often involves practicing so-called instrumental activities of daily living (IADL), such as shopping, cooking, and using a telephone. If a brain injury patient is to practice such activities in a VE, the patient must be able to navigate the viewpoint and interact with virtual objects in an understandable way. People with brain injury may be less tolerant to a poor interface and a VE might therefore become unusable due to, for example, an unsuitable input device. In this paper we present two studies aimed to do initial usability testing of VE interaction methods on people without experience of 3D computer graphics. In the first study four navigation input device configurations were compared: the IntelliKeys keyboard and the Microsoft Sidewinder joystick, both programmed with two and three degrees of freedom (DOF). The purpose of the second study was to evaluate a method for interaction with objects, and to find a sufficiently usable input device for this purpose. The keyboard was found to be more suitable for navigation tasks in which the user wants to give the viewpoint a more advantageous position and orientation for carrying out a specific task. No big differences could be found between two and three DOFs. The method for interaction with objects was found to work sufficiently well. No difference in performance could be found between mouse and touch screen, but some evidence was found that they affect the usability of the VE interface in different ways.

1 Introduction

1.1 Virtual Reality in Cognitive Rehabilitation

Although a relatively young area of research a number of research groups have managed to produce evidence that support the hypothesis that Virtual Reality (VR) can be a useful tool for people with cognitive disabilities. Several cognitive domains have been investigated. For example, the use of VR for assessment of attention processes in people with ADHD and unilateral visual neglect have been investigated by Rizzo et al. (2002) and Gupta, Knott and

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Kodgi (2000) respectively. Also, VR has proven to be a good medium for assessment of memory skills. Brooks et al. (2004) have shown that VR can be used to test stroke patients' prospective memory ability, that is, remembering to perform actions in the future. The use of VR for assessment of functional skills in people with traumatic brain injury (TBI) has been thoroughly investigated by Christiansen et al. (1998). The same group has also showed that the VR assessment method has high construct validity (Zhang et al., 2003). That VR can be used for skill learning in children and adults with learning disabilities has been shown by Brown, Neale, Cobb, and Reynolds (1999). Executive functioning (i.e., planning, sequencing, cognitive flexibility, etc.) is a very complex cognitive process, which makes rehabilitation and assessment with traditional methodologies questionable (Elkind, 1998). This problem has been addressed by Pugnetti et al. (1998), who have developed a VR system specifically designed for executive functioning in people with TBI, multiple sclerosis (MS), and stroke, based on the Wisconsin Card Sorting Test (WCST).

1.2 Brain Injury and Brain Injury Rehabilitation

Brain injury can be caused by external violence to the head in, for example, traffic accidents, falls, and sports activities. Other causes to brain injury may be stroke, tumors, brain tissue inflammation, or anoxia (Kolb & Whishaw, 1996). The incidence in Sweden (nine million inhabitants) of severe or moderate TBI has been estimated at 40 per 100,000 inhabitants (Hårdemark & Persson, 2000) and of stroke at 235 per 100,000 (Johansson, Norrving, & Lindgren, 2000). The nature of acquired brain injury (ABI) is a range of complex physical, cognitive, behavioral, and emotional problems. The extent of these problems varies for each individual (Finlayson & Garner, 1994). Memory problems are among the most commonly reported deficits after brain injury (McKinlay & Watkiss, 1999). These include difficulty in learning new information as well as retaining and later retrieving it. Another problem after brain injury is slowness in information processing. This may lead to reduced capacity to sustain attention when learning new tasks but also difficulties in keeping the mind on more than one task at a time. Executive problems are also common after brain injury and difficulties may arise with planning, initiation, and also problem solving. Occupational therapy is focused on engaging people in meaningful and purposeful doing and enhancing their ability to perform the daily tasks they need and want to perform (Fisher, 1998). One important part in the rehabilitation is to assess a patient's ability to perform, safely and effectively, daily living tasks to be able to plan and evaluate different actions. There are several methods for functional assessment, for example questionnaires, checklists, and rating scales. However, the most important method is observation (Giles, 1994).

1.3 Project Description

The Division of Ergonomics at the Department of Design Sciences, Lund University in Sweden and the Department of Rehabilitation, Lund University Hospital are currently collaborating in a long-term project. The overall goal of the project is to investigate if VR can have a role in brain injury rehabilitation as a complement to conventional rehabilitation techniques. More specifically the project aims to:

- find a usable interface between a VE and the user, with emphasis on navigation of the viewpoint and interaction with objects;
- investigate transfer of training from a VE to the real world; and
- develop at least three practical applications of VE for rehabilitation

The Division of Ergonomics is performing research on the interplay between man and technology and has expertise in human computer interaction and development of VEs for various applications. The Department of Rehabilitation is specialized in the practical and theoretical aspects of rehabilitation of people with acquired brain injury. The rehabilitation team consists of several professions that work in an interdisciplinary manner. Participating in this project were two occupational therapists, a neuropsychologist, and a computer engineer, with many years experience of how technology can be used in rehabilitation.

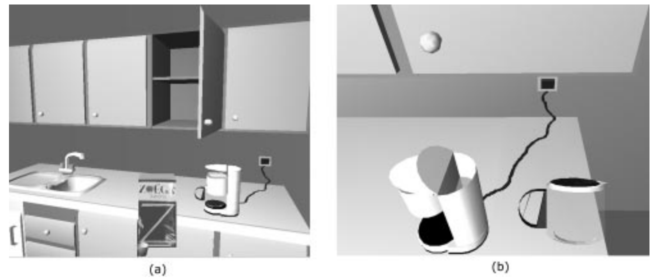

Figure 1. *The coffee brewing VE: a) Overview; and b) The viewpoint is close to the kitchen counter.*

1.4 Interaction with VEs

A number of guidelines regarding interaction with VEs have been published. The problem with most of these guidelines is that they are either too general or based on experience and intuition, and not from empirical results (Bowman, Johnson, & Hodges, 2001). Also, guidelines for VE design may not be suitable for all types of user groups (Neale, Cobb, & Wilson, 2000). Regarding people with cognitive disabilities the interaction factors require extra focus. Even if a user with cognitive problems is able to interact with a VE at a basic level, the extra cognitive load might remove some of the user's attention from the task that is to be performed in the VE. Rizzo, Buckwalter, and van der Zaag (2002) suggest that increased generalization of learning to the real world might be expected if the VE interaction more closely resembles the way interaction is done in the real environment. Further, Rizzo et al. (2002) point to the fact that an unnatural or awkward VE interface might reduce the motivation of first time users, since they might feel that it's "more work than it is worth."

1.4.1 Navigation. Navigation in a VE can have two meanings; a motor aspect called *travel* and a cognitive aspect called *wayfinding* (Bowman, Kruijff, LaViola, & Poupyrev, 2001). Travel is the movement of the viewpoint from one location to another, whereas wayfinding can be described as the cognitive process of determining a path through the environment to the desired destination. This paper is only concerned with the travel aspect of navigation. Bowman, Kruijff, et al. (2001) have also defined three categories of navigation tasks. In an *exploration task* the user is investigating the surroundings with no special target in mind. In a *search task* the user is moving to reach a special target location. Finally, a *maneuvering task* is performed when the user wants to give the viewpoint a more advantageous position and orientation for carrying out a specific task. Most IADL tasks take place in spatially limited environments, for example, a kitchen, a laundry room, or a supermarket. Therefore, we have only considered the maneuvering and search task in this study. There are basically three methods for moving the viewpoint: automatic, half-automatic, and self-controlled navigation. With automatic navigation the VE application uses the input of the user to calculate a suitable position and orientation for the viewpoint. We investigated this navigation method in a pilot study in which two brain injury patients and four able-bodied subjects performed the task of brewing coffee in a virtual kitchen environment (Lindén et al., 2000; see Figure 1). The navigation appeared to provide no difficulties for the subjects except when the viewpoint was close to the kitchen bench and the subject wanted to move backwards in order to take a whole view again (Figure 1b). The coffee brewing VE is small enough to be viewed on one screen, but some IADL tasks, for example shopping and preparing a meal, are performed in larger environments. A VE like this requires some sort of self-controlled navigation since the user might want to perform an action in a part of the VE that is not visible in the view. In between automatic and self-controlled navigation there is what may be dubbed half-automatic navigation. With this method the user controls the movements of the viewpoint but the computer is allowed to aid in an intelligent way. There are basically two types of self-controlled navigation; fly-through and walk-through. In the former case the user can move freely in 3D space and may also tilt and pan the viewpoint. This type of self-controlled navigation might be too complicated for people with cognitive disabilities to handle since it requires the user to control at least four degrees of freedom (DOFs). Walk-through navigation is a simplification of real world navigation since it is not possible to raise or lower the viewpoint. However, the navigation of the viewpoint is just a means for practicing tasks in the VE and therefore walk-through navigation is probably more suitable in this context.

1.4.2 Interaction with Objects. According to Bowman, Kruijff, et al. (2001) interaction techniques for manipulation of objects should support at least one of three basic tasks: object selection, object positioning, and object rotation. In the pilot study described above (Lindén et al., 2000) our research group defined the following three tasks which we found to be more applicable for our application area:

- activate objects such as opening a door, turning on a switch or turning on or off a tap;
- move objects from one place to another and rotate if appropriate; and
- use one object with another (object–object interplay), for example, using a coffee scoop to take coffee from a package to put into a filter.

We did not consider the object rotation task since we believed allowing manipulation of both position and rotation of objects would make the interaction too hard to handle for some people with cognitive disabilities. In general, there seems to be a lack of studies investigating object interaction in VEs for people with cognitive disabilities. Nevertheless, Neale et al. (2000) have made the following recommendations regarding interaction with objects in VEs for people with learning disabilities:

- Task design should be realistic, equally as complex as in the real world, and flexible (allowing users to carry out sub-tasks in any order).
- Metaphors used to interact with objects should reflect real world behavior.
- Representations of objects in the VE must be obvious.
- Use set viewpoints to focus attention on objects.
- Highlight objects to indicate interactivity.

In our pilot study we investigated the three ways of interacting with objects described above (Lindén et al., 2000). In an experiment two people with brain injury and four able-bodied people solved the task of preparing coffee in a coffee brewing VE. In this VE a virtual object could be moved by clicking on it, which placed it in the foreground as though carried by an invisible hand (Figure 1). The object could then be placed by clicking on the location. To activate an object, for example turning on the coffee machine, the user simply clicked on it. This interaction method, which we refer to as point-and-click, was also used in a cash dispenser VE (Wallergård et al., 2001), which is one of the applications that has been developed in this project. The coffee brewing study revealed the following problems regarding interaction with objects:

- The area around the object that is sensitive to clicking (the active area) was often missed.
- Some subjects had problems understanding that the object was being held.
- Object-object interplay sometimes caused problems when a click could be interpreted in more than one way.

These results indicated that there was a need for more work on interaction with VEs for people with brain injury. A more natural interaction technique that avoids abstractions seemed to be desirable for this population. An example of such a natural interaction technique is the tangible interface developed for stroke patients developed by Hilton, Cobb, Pridmore, and Gladstone (2002). The tangible interface was developed for a coffee brewing activity and allows the user to interact with the objects in the VE through real world objects such as an electric kettle, a jar of coffee, and so on. Another observation made in the study by Lindén et al. (2000) was that the subjects initially tended to try to drag and drop the objects, which inspired us to investigate if drag-and-drop is a more natural interaction technique.

The coffee brewing environment is a fairly small VE and therefore automatic navigation of the viewpoint worked well for this application. However, in a VE that is too large to be viewed in one screen some form of self-controlled navigation must be used. This poses a problem when the user wants to move an object to a location outside the view, since he then has to carry the object and navigate the viewpoint at the same time. This led to the idea of investigating if the concept of carrying the object in a virtual hand could make these object movements easier. The reason for choosing a virtual hand was to resemble reality; a strategy that agrees with the second recommendation by Neele et al. (2000), namely, that metaphors used to interact with objects should reflect real world behavior. A similar concept was used in the Supermarket VE developed by Brown et al. (1999). During the payment procedure the user can put coins and bills in a representation of the user's hand and then pay when the hand holds a sufficient amount of money.

1.4.3 Input Devices. The usability of a VE is also governed by the input device that is used. We believe that the most important thing to consider, when designing a VE interface for people with cognitive disabilities, is to use separate input devices for navigation and interaction with objects. This hypothesis is based on our research group's experience of people with brain injury; memory problems and insufficient divided attention might make it very hard for a person with cognitive disabilities to understand a dual purpose input device with different modes. Research on suitable input devices for people with learning disabilities has produced results that support this hypothesis (Lannen, 2002; Standen, Brown, Anderton, & Battersby, 2004).

Overall, there is limited empirical research on the usability of input devices for desktop VEs. Nevertheless, there is research on input devices for regular 2D computer applications that might be of relevance for the choice of input device for interaction with objects. For example, Karat, McDonald, and Anderson (1986) have compared touch screen, mouse, and keyboard. The authors found that the touch screen was easier to use but that it generated more errors and fatigue. Pretor-Pinney and Rengger (1990) describe an experiment in which the performance of 38 novice and 20 expert users using touch screen and mouse was compared for three selection tasks and one manipulation task. The novices performed faster with the touch screen than with the mouse in all tasks except a small target selection task. Both the novices and the experts had more errors with the touch screen for the object manipulation task. Mack and Montaniz (1991) have produced results that are contradictory to the studies described above. They compared the performance of 10 participants using mouse, stylus, and touch screen. They results suggest that the mouse is faster and products less errors compared to the touch screen. However, the subjects' task was more advanced than in the studies described above; they had to use standard office applications like a calendar and a spreadsheet. Similarly, Martin and Allan (1991) found that the touch screen had no advantage in comparison to the mouse in an experiment in which 26 students performed a digit input task. Recently, input devices for palm computers have received some attention. Chamberlain and Kawalsky (2004) compared the performance of 20 subjects using a touch screen stylus and an off-table mouse. The touch screen stylus was faster and also had lower cognitive workload compared to the mouse, but was also found to have a significantly higher error rate.

To this date, there are no empirical results on input device issues for people with cognitive disabilities due to brain injury. There are examples of studies in which populations with cognitive difficulties have managed to interact with virtual objects using a desktop mouse (e.g., Brooks et al., 2004; Cromby, Standen, Newman, & Tasker, 1996; Lindén et al., 2000). However, input device factors were not the primary research target of these studies. Nevertheless, there are studies on input devices for populations with special demands that might be relevant. For example, Robertson and Hix (1994) compared the performance of 12 people with moderate developmental disability using mouse, touch screen, and trackball. The touch screen was found to be the fastest of the three input devices, but the subjects appreciated the mouse the most. The trackball proved difficult for the subjects to use. The needs of novice older users with regards to input devices for Internet use have been addressed by Rau and Hsu (2005). In a series of experiments they compared the performance of 24 novice older users with three input device combinations: 1) touch screen and handwriting recognition, 2) mouse and keyboard, and 3) voice control and voice input. The participants performed worse with mouse and keyboard in terms of task completion time compared with the other two combinations. Pak, McLaughlin, Lin, Rogers, and Fisk (2002) compared touch screen with a rotary encoder in an experiment with 40 young adults and 40 middle-age to older adults. Overall, participants performed tasks more quickly using the touch screen. However, the rotary encoder outperformed the touch screen when participants were required to manipulate sliders precisely on the screen. The authors concluded that touch screen is the preferable device for pointing tasks. There are also some studies that have targeted young children's performance with various input devices. Lu and Frye (1992) compared touch screen and mouse for three selection tasks and a move task in an experiment with 12 preschoolers. The touch screen was significantly faster for all four tasks. Scaife and Bond (1991) investigated the performance of children in a tracking task using touch screen, mouse, and joystick. The authors concluded from one of their experiments that the touch screen was by far the easiest input device to use followed by the mouse and then the joystick. In a study by Battenberg and Merbler (1989), 40 developmentally delayed and 40 non-delayed kindergarten children completed an alphabet matching task and a spelling task using a touch screen and a keyboard. Through measurements of task completion time and error rate the authors found that the touch screen generally improved the performance of both groups. Cress and French (1994) performed an experiment in which touch screen, mouse, keyboard, trackball, and locking trackball were compared. Nineteen computer-experienced adults, 39 normally developing children, and 15 children with mental retardation participated, performing a series of object movement tasks with each of the five input devices. Among other things, the authors found that for each of the groups except children with mental retardation the touch screen was the fastest input device followed by mouse, trackball, locking track ball, and keyboard. Also, both trackball devices were significantly more likely to be failed by the children with mental retardation than by the normally developing children.

Very little research has been done also on input devices for navigation in desktop VEs. Several studies have reported that neurological patient populations have managed to navigate in VEs using a joystick (e.g., Brooks et al., 2004; Flynn et al., 2003; Mendozzi et al., 2000), but input device factors were not their primary research target. Regarding VRML browsers, the mouse has become the de facto standard input device for navigation of the viewpoint. Usually the two DOF mouse cursor movements are mapped onto various translation and rotation degrees of freedom by using two different modes: walk mode and pan mode. According to Zhai, Kandogan, Smith, and Selker (1999) this technique has many disadvantages where the following are the most noticeable:

- The result of the mouse movement depends on the current mode.
- Usually the cursor motions are mapped to movement speed, that is, the farther the mouse is moved from the initial click position the faster the movement is. Experiments have shown that input devices such as the mouse that lack a self-centering mechanism are poor in rate control tasks (Zhai et al., 1999).

From an experiment in which six students with severe learning difficulties participated, Brown, Kerr, and Crosier (1997) concluded that a joystick is a better input device for VE navigation than keyboard and mouse. Similar results are reported by Standen, Brown, Anderton, and Battersby (2004). They compared the performance of 40 people with severe intellectual disabilities using joystick and keyboard for a series of navigation tasks. The results suggested that the joystick is a better input device for this purpose. Very little empirical work has been done on what role DOF mapping has on the usability of navigation interfaces for desktop VEs. Nevertheless, Lapointe and Vinson (2002) compared 16 subjects' performance using joystick with two and three DOFs and found no difference in task completion time between the two joystick versions. The authors suggest that the third DOF does not hamper performance, while allowing more complex movements.

Even though good research, the studies described above tend to focus on 2D tasks and able-bodied populations. A VE is fundamentally different from a 2D application and the needs of people with brain injury put unique demands on the usability of VE input devices. Hence, there is a need for more knowledge on how the choice of input devices for navigation and interaction with objects affects the usability of a desktop VE that is to be used by people with brain injury.

2 The Two Studies

We present two studies that were performed to gain knowledge regarding interaction with VEs for people with no 3D computer graphics experience. This population was chosen since we wanted to first identify *fundamental* usability issues. We are currently investigating how the results from the two studies apply for people with brain injury, and this will therefore not be discussed in this paper.

2.1 Study One: Navigation of the Viewpoint

2.1.1 Aim. The aim of the first study was to find a usable input device and configuration of DOFs for navigation in VEs for people with no 3D computer graphics experience.

2.1.2 Method. The study was performed in two steps:

1. The research group started the study with a discussion on what properties an input device should have to be usable for navigation in VEs by people with brain injury. This discussion resulted in a list of desirable qualities that were used to select four input device configurations.
2. The four input device configurations were then tested on people with no 3D computer graphics experience.

In step 1 the research group used its experience of brain injury rehabilitation and human computer interaction to produce the following list of desirable properties for a navigation input device:

- The most obvious property is that it should be an input device primarily designed for navigation and not for interaction with objects.
- Memory problems are among the most commonly reported deficits after brain injury, and therefore the input device should not have different modes of operation.
- For the same reason the input device should have a limited number of DOFs, but still many enough to allow convenient navigation.
- A brain injury also often results in decreased motor performance. Therefore the input device should be one that can be operated by people with fine-motor difficulties.
- It is essential that the input device gives necessary feedback to make the user understand that an action has been registered.
- The mapping of the input device should be as natural as possible.
- The input device should have good affordance, that is, it should provide the user with clues about its functionality.
- A more practical, but not less important, detail is that the input device should be easily found in retail trade and should not be too expensive.

Various multi-DOF input devices were discussed, including the SpaceMouse and the SpaceBall. There are several reasons why these input devices are not suitable for this particular application:

- According to Zhai et al. (1999) six DOF hand controllers such as the SpaceBall "are designed primarily as 'manipulation,' not as 'navigation' devices."
- Our research group's experience of people with brain injury indicated that these input devices are not robust enough for this population.
- These input devices are quite expensive. Cost and availability are factors that must be considered when introducing VR technology to the hospital environment.

Based on the list above and earlier work on navigation input devices for desktop VEs (Brown et al., 1997;

(a) (b) (c)

Figure 2. *The IntelliKeys keyboard with a) Two DOFs and b) Three DOFs respectively and c) The Microsoft Sidewinder joystick.*

Zhai et al., 1999; Standen et al., 2004) we decided to make a comparison between joystick and keyboard.

The IntelliKeys keyboard is a programmable keyboard whose look and functionality can be changed by sliding in different overlays. In this way any type of button based interface can be created. For this study two overlays were created; one for a two DOF version of the input device (Figure 2a) and one for a three DOF version (Figure 2b). The overlays contained arrows and text that described the function of the arrows (forward, turn left, etc.). The IntelliKeys keyboard has been used at the Department of Rehabilitation to simplify computer interaction for brain-injured people, and the research group assumed it to be a candidate for the experiment for the following reasons:

- It is based on the principle of "knowledge in the world" (Norman, 1988), that is, the knowledge of how it is used is visible to the user.
- It does not require a high degree of fine-motor ability since it can be operated with simple press movements.
- It is easy to create a clear interface for it that only contains the necessary information.

The Microsoft Sidewinder is a joystick that can be set to control up to three DOFs (Figure 2c). Its stick can be moved forward, backward, and sideways and it can also be rotated. We considered it to be a candidate for the experiment for the following reasons:

- It does not require fine-motor capabilities since it can be operated with a palm grip.
- It is an input device that most people recognize and in some cases probably also have experience of.
- It can be used both as a two and three DOF input device since its stick can be rotated.

Nevertheless, the Sidewinder joystick has a property that might be a drawback for this user group: it allows activation of several DOFs at the same time. The user can for example make a forward movement and rotate at the same time. This might disturb the users' mental model of how the joystick works since it is also possible to control it by activating only one DOF at a time.

We also discussed how many DOFs the input device should have. We wanted as few DOFs as possible in order to minimize the users' cognitive load, but enough to enable convenient navigation. Two DOFs is the minimum number for walk-through navigation in a VE. This allows the user to move the viewpoint backwards and forwards and to rotate it to the left and to the right. By adding a third DOF it would be possible for the user to also move sideways, which might lead to more convenient navigation. The user could for example use the third DOF for moving sideways along a kitchen bench. Results by Lapointe and Vinson (2002) indicate that a third DOF in a joystick does not hamper performance, while allowing more complex movements.

Finally, we decided to evaluate the following four input device variations: IntelliKeys keyboard with two and three DOFs, and Microsoft Sidewinder joystick with two and three DOFs.

In step 2 an experiment was conducted, which aimed to compare the four input device variations above. Sixty

Table 1. *Demographic Data N = 60*

Group	Input device	Subjects	Age (median)	Age (range)	Computer use hr/week (median)
1	Keyboard 2 DOFs	9 female 6 males	31	23–58	4
2	Keyboard 3 DOFs	9 females 6 males	33	22–56	4
3	Joystick 2 DOFs	10 females 5 males	37	21–58	3.5
4	Joystick 3 DOFs	9 females 6 males	38	21–52	4

hospital personnel and students at the Department of Rehabilitation participated. The subjects were informed about the project and were asked to fill in a questionnaire concerning their computer experience. People who had experience with 3D computer graphics, such as 3D computer games and CAD applications, were excluded. Then four groups, one for each input device variation, were formed. Each group consisted of 15 subjects and was assembled so that the subject variables age, gender, and computer experience were as similar as possible for all four groups (Table 1).

Desktop VR was used in this study mainly because of the cost and availability of such computer equipment in the hospital environment. Also, Brown et al. (1999) have shown that people with learning disabilities can learn well using desktop VR. The VE was developed using World Up, an object-oriented VR developer's kit in which virtual environments and objects with complex behaviors can be created. The main reason for choosing this VR software was that it works on ordinary personal computers, such as those normally found in a rehabilitation hospital. Another advantage is that the World Up player needed to run the VE application comes for free. The VE consisted of a U-shaped corridor and a kitchen, and it contained 11 targets (Figure 3a,b). The purpose of the corridor was to study how the subjects solved a search task, that is how they transported the viewpoint from one location to another when collecting targets. The purpose of the kitchen was to study the subjects when solving a series of maneuvering tasks, in which they had to give the viewpoint the correct position and orientation to be able to collect the targets. The kitchen was designed to look like the real training kitchen at the hospital and contained various kitchen fittings such as a stove, dishwasher, refrigerator, and kitchen furniture. The corridor contained no objects except the targets.

The subjects' task was to collect targets in the VE by walking into them at a right angle. The 11 targets were placed along a path starting in the corridor, leading into the kitchen and then back to the end of the corridor again (Figure 3c). When one target had been collected the next one appeared, which meant that the subject could only see one target at the time. A plan drawing illustrating the placement of the targets in the VE was placed next to the computer to prevent the subject from getting lost. Each subject was asked to complete the navigation task five times in a row and then to fill in a questionnaire containing five questions. The questionnaire aimed at establishing the subjects' experiences of the navigation in the corridor and the kitchen, degree of control of the movements, orientation in the VE, and the input device. The subjects graded their experience of these issues on a five point Likert scale reaching from "very easy" to "very hard." The subject also had to comment each of the answers. A World Up script was used to log data on the navigation of the subjects in the VE. The script logged time, position, and orientation of the viewpoint, and the input device operations made by the user.

Three video cameras were used to capture facial expressions, body language, and hand movements of the subject when performing the navigation task in the VE. The monitor signal was converted into an analog video signal and mixed with the three video camera signals using a video quad mixer (Figure 3d). In this way all four signals could be recorded on the same videotape to

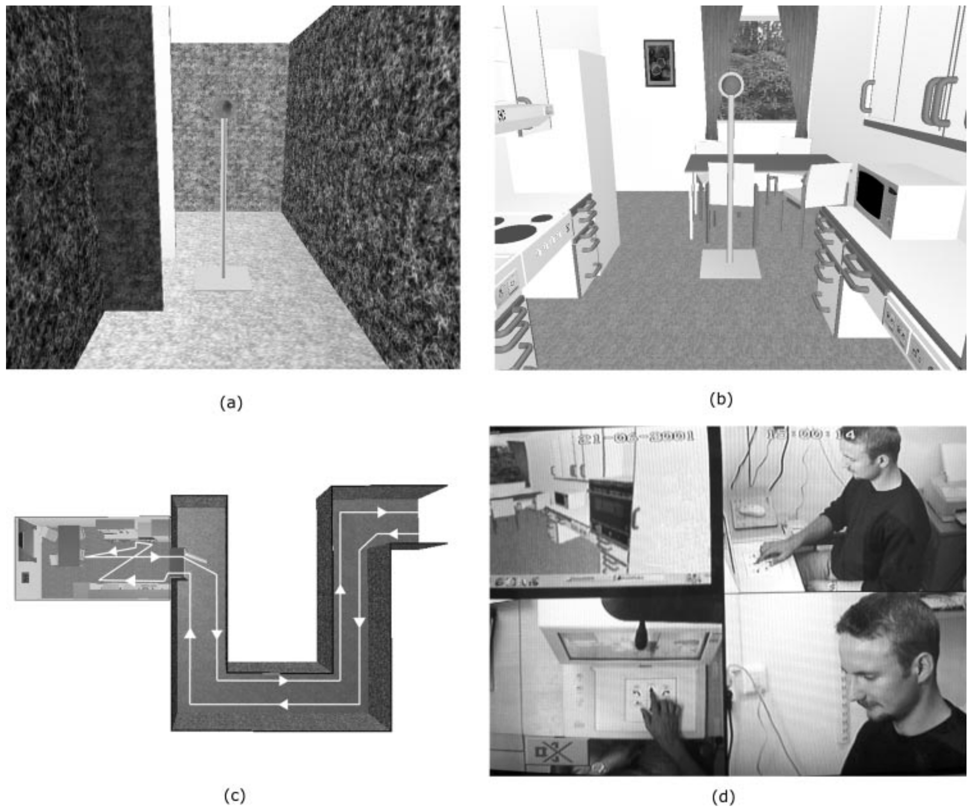

Figure 3. *a) The virtual corridor, b) The virtual kitchen, c) The path of the navigation task, and d) The video signal from the quad mixer.*

facilitate the analysis. A microphone was used to record the subjects' comments.

The analysis of the quantitative data was performed in three steps. In the first step a program analyzed each of the five trial files and generated a single file for each of the 60 subjects, and then summarized the data for each subject group. In the second step, Excel spreadsheets containing tables and diagrams were made. Finally, the statistics package SPSS was used to perform a series of between subjects two-way ANOVAs. The independent variables were type of input device (keyboard, joystick) and number of DOFs (two, three). The six dependent variables were distance, time, and number of direction changes for the kitchen and corridor (Table 2). Distance and number of direction changes (Figure 4) were used as measures for the subject's control over the input device, whereas time was used as a complementary mea-

Table 2. *The Dependent Variables*

Variable	Description
Distance	Distance covered when collecting the targets in the kitchen and in the corridor
Time	Time to collect the targets in the kitchen and in the corridor
Number of direction changes	Number of times the subject changes direction when collecting the targets in the kitchen and in the corridor

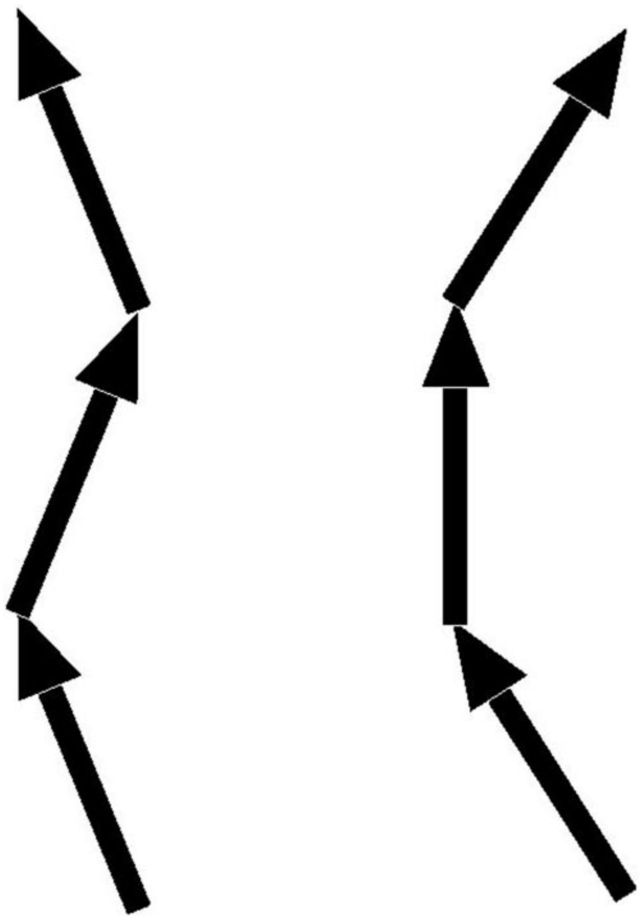

Figure 4. *a) The movement changes from clockwise rotation to counterclockwise rotation and is therefore registered as a direction change. b) The movement has only clockwise rotation and hence is not registered as a direction change.*

sure. We considered time to be a less vital factor for this particular application since the important thing is that the user is able to perform the activities in an easy and intuitive way. Our hypothesis was that the lower the values on the dependent variables, the better the subject's control over the input device. The total score, that is, the sum of each subject's performance over the five trials, was used for the dependent variables in the statistical analysis. The significance value of alpha = 0.05 was chosen for the statistical tests.

A qualitative analysis of the subjects' performance was performed from the video material. Two members of the research group analyzed the video material independently of each other and thereafter discussed their respective findings. When a difference of opinion arose, the video sequence of interest was analyzed once again. The following three items were used as a basis for the observations:

- How is the subject navigating the VE?
- How is the subject handling the input device?
- In what way is the subject using his or her hands?

2.1.3 Quantitative Results. *2.1.3.1 The Corridor.* Table 3 shows mean and standard deviation for the dependent variables in the corridor. Univariate ANOVA results showed significant main effects for input device ($F(1, 56) = 6.501, p < .05$) and number of DOFs ($F(1, 56) = 13.53, p < .05$) on distance in the corridor. For the time in the corridor, a significant main effect was found for input device ($F(1, 56) = 52.337, p < .05$). No significant main effect for input device was found regarding number of direction changes ($F(1, 56) = 0.949, p < .05$). The effect of number of DOFs on direction changes was not regarded. This would be a biased comparison since the three DOFs subjects had the possibility to correct their course not only by rotating the viewpoint but also by moving it sideways. A significant interaction between the two independent variables was found for distance ($F(1, 56) = 5.302, p < .05$).

As can be seen in Figure 5a the trend for distance was relatively flat for keyboard. The distance for joystick was twice the distance for keyboard in the first trial but sank quickly in the subsequent trials. The trend for two DOFs was rather flat whereas the distance for three DOFs was twice as long as the one of two DOFs in the first trial and then leveled out at two-thirds of the initial value. The time for keyboard was twice the one of joystick in the first trial and then slowly sank (Figure 5b). The time for joystick plateaued in the fourth trial. The time trends for two and three DOFs respectively were very similar and plateaued in the fourth trial. Figure 6 shows the trend regarding median number of direction changes for keyboard and joystick respectively. The

Table 3. *Mean and Standard Deviation for the Dependent Variables in the Corridor*

Independent variable	Case	Distance	Time	Number of direction changes
Input device	Keyboard	179.34 (12.98)	307.09 (81.40)	29.87 (11.25)
	Joystick	193.78 (32.75)	170.12 (63.58)	32.40 (10.38)
Number of DOFs	2 DOFs	176.14 (9.68)	226.97 (91.51)	35.40 (10.06)
	3 DOFs	196.97 (32.11)	250.23 (108.25)	26.87 (9.93)

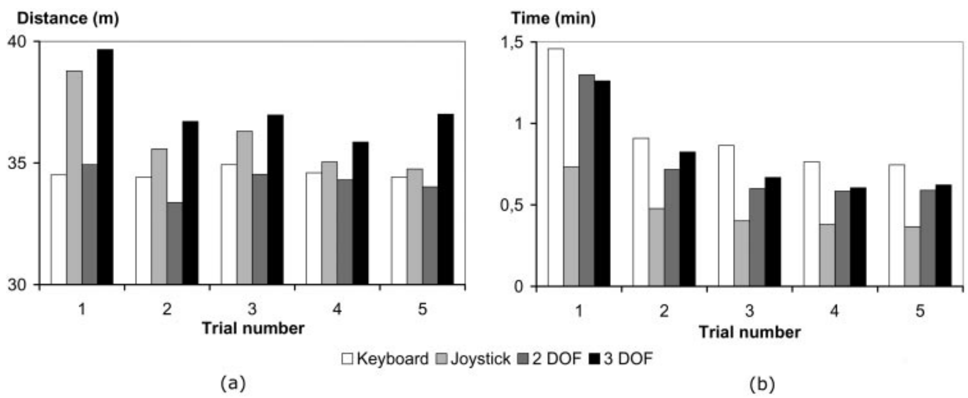

Figure 5. *a) Median distance and b) Median time in the corridor, trial 1–5.*

trend was decreasing for both input devices but the decrease was slightly more apparent for keyboard.

2.1.3.2 The Kitchen. The mean and standard deviation for the dependent variables in the kitchen can be seen in Table 4. A significant main effect for input device was found for the variable distance ($F(1, 56) = 7.327, p < .05$). For the variable time no significant main effects were found neither for input device ($F(1, 56) = 2.822, p < .05$) nor for number of DOFs ($F(1, 56) = 0.134, p < .05$). The input device was found to have a significant main effect on the dependent variable number of direction changes ($F(1, 56) = 7.479, p < .05$). The distance for keyboard was exhibiting a decreasing trend in the first three trials and then plateaued (Figure 7a). The distance for joystick was almost twice the distance for keyboard in the first trial but then sank quickly until it plateaued in the fourth trial. The dis-

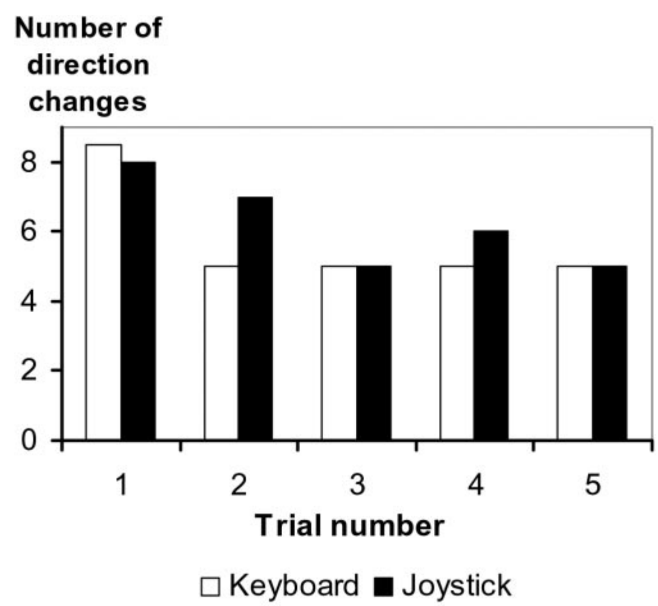

Figure 6. *The median number of direction changes in the corridor for keyboard and joystick, trial 1–5.*

Table 4. *Mean and Standard Deviation for the Dependent Variables in the Kitchen*

Independent variable	Case	Distance	Time	Number of direction changes
Input device	Keyboard	94.23 (41.30)	11.12 (4.38)	58.43 (32.44)
	Joystick	132.23 (64.39)	8.80 (9.71)	86.37 (53.33)
Number of DOFs	2 DOFs	105.14 (50.46)	10.22 (6.60)	91.33 (50.30)
	3 DOFs	121.33 (62.60)	9.71 (3.82)	53.47 (32.07)

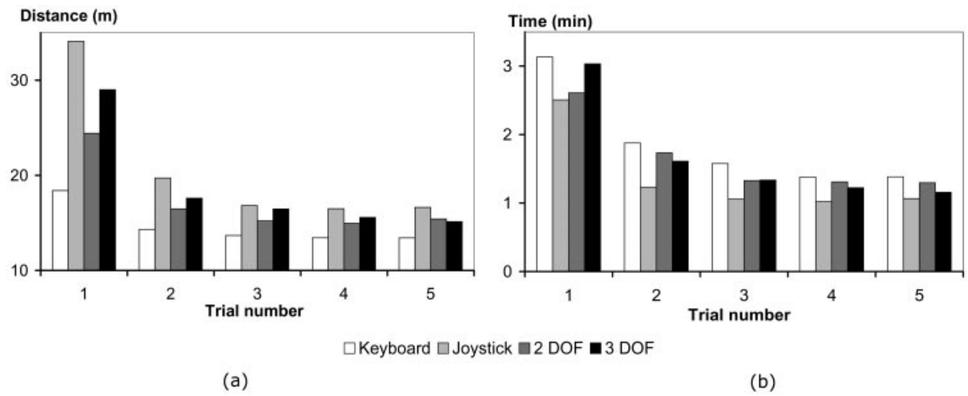

Figure 7. *a) Median distance and b) Median time in the kitchen, trial 1–5.*

tance trends for two and three DOFs respectively were quite similar except in the first trial. Both sank quickly after the first trial and then plateaued in the third trial. The time trend for keyboard decreased quickly after the first trial and then plateaued in the fourth trial (Figure 7b). Time for joystick was exhibiting a similar trend but plateaued in the third trial. The time trends for two and three DOFs were quite similar except in the first trial. Both sank quickly after the first trial and then plateaued in the third trial.

The median number of direction changes was evidently lower for keyboard compared to joystick, especially in trial number five (Figure 8). Both input devices exhibited a decreasing trend and plateaued in the third trial.

2.1.3.3 The Questionnaire. A multivariate ANOVA was performed on the questionnaire. No significant main effect of input device or number of DOFs was found for any of the five questions.

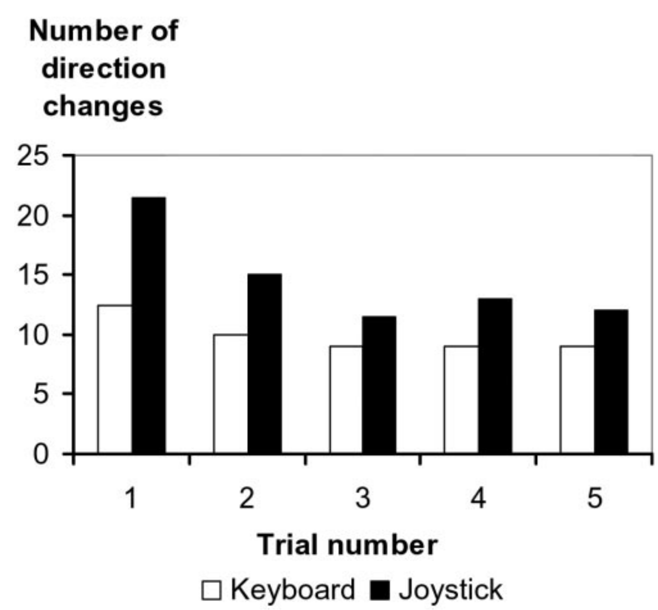

Figure 8. *The median number of direction changes in the kitchen for keyboard and joystick, trial 1–5.*

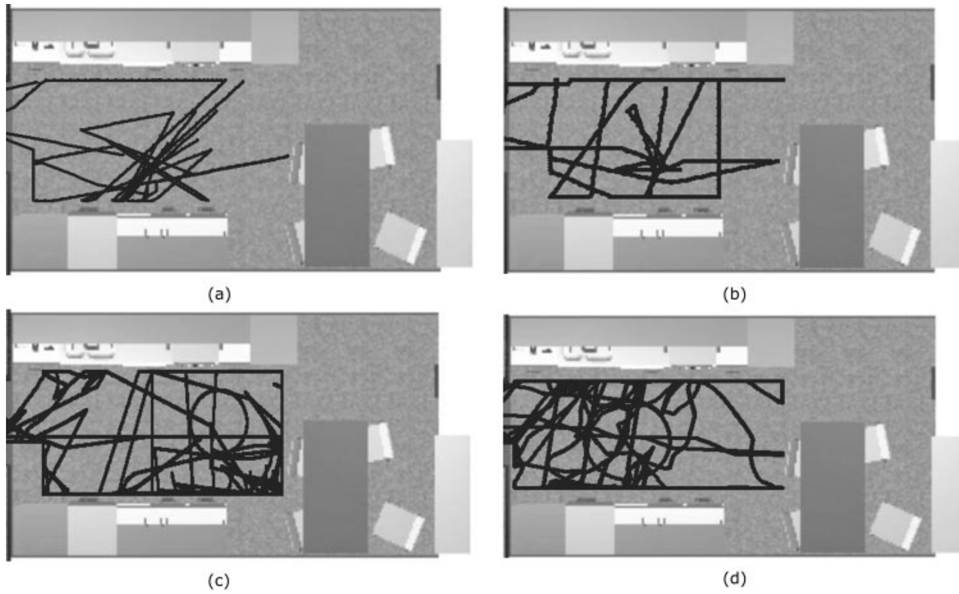

Figure 9. *The first trial's navigation path in the kitchen for the subjects who were judged to have the worst performance in each group: a) Keyboard two DOFs; b) Keyboard three DOFs; c) Joystick two DOFs; and d) Joystick three DOFs.*

2.1.4 Qualitative Results. *2.1.4.1 How the Subjects Navigated the Viewpoint.* The general impression from the video analysis was that there were differences in how the keyboard and joystick groups navigated the viewpoint. The joystick subjects tended to navigate in a wobbly manner and sometimes overshot the targets by, for example, walking past them. The keyboard subjects navigated the viewpoint in a more controlled way. The navigation for the subjects that were judged to have the worst performance in each group is described. Also, the kitchen navigation path for each of these four subjects is shown in Figure 9.

- The keyboard two DOFs subject had problems in placing and orienting the viewpoint effectively on some occasions in all five trials.
- Also the keyboard three DOFs subject had problems in placing and orienting the viewpoint effectively on some occasions, but the problems gradually disappeared over the five trials.
- The joystick two DOFs subject controlled the joystick with rather jerky movements and sometimes moved or rotated in the wrong direction. The subject had vast problems in placing and orienting the viewpoint effectively, especially in the kitchen, and only improved her performance slightly over the five trials.
- The joystick three DOFs subject also controlled the joystick with jerky movements and had some problems in placing and orienting the viewpoint effectively. The subject improved his performance over the five trials but also had some problems in trial number five.

2.1.4.2 How the Subjects Used the DOFs. Three out of 15 subjects in the keyboard three DOFs group used all three DOFs in their navigation. Three subjects gradually went from only using two DOFs to also using the third DOF, and had incorporated it completely in their navigation from the fourth trial. Three subjects used the third DOF occasionally and one of them commented that two DOFs were enough. Six subjects only used two of the three DOFs. In the joystick three DOFs group the third DOF was used by five out of 15 subjects. Seven subjects used it occasionally, and the remaining three subjects did not use the third DOF at all. With the joystick it was possible to activate more than one DOF at the same time. Five out of 15 subjects in the joystick two DOFs group used this possibility whereas five subjects chose to use one DOF at a time. The remaining five subjects occasionally used the two DOFs simultaneously but never learned to do this in an efficient way. In the joystick three DOFs group six subjects used one DOF at a time, whereas nine subjects used more than one DOF simultaneously.

2.1.4.3 Physical Aspects on How the Subjects Used the Input Devices. Two different methods of using the hands were observed among the keyboard subjects. Eight out of 15 subjects in the keyboard two DOFs group operated the keyboard with both hands, whereas the remaining seven subjects only used their dominant hand. In the keyboard three DOFs group eight subjects used both their hands and seven chose to operate the keyboard with one hand. Five keyboard subjects reported that the keyboard buttons were hard to press. One of the subjects spontaneously commented that further use of the keyboard would have caused pain in her arm. None of the joystick subjects reported anything similar. One of the subjects in the joystick two DOFs group thought that it would have been more natural to rotate the stick of the joystick in order to rotate the viewpoint instead of moving it sideways.

2.1.4.4 The Subjects' Orientation in the VE. Three subjects using the joystick with three DOFs had problems with their orientation in the VE, and one of them needed information from the test leader at one occasion to be able to find the way.

2.1.4.5 Subjects that Became Stuck. One subject from each group except the keyboard with two DOFs group had problems getting out of the kitchen two times during the experiment. They got stuck with the virtual shoulder in the doorframe and did not seem to understand what was hindering them.

2.1.4.6 Nausea. Two subjects in the joystick with two DOFs group and three in the joystick with three DOFs group spontaneously reported that they became nauseated during the test. One of the latter subjects also complained about dizziness. Also, one subject using the keyboard with two DOFs reported nausea during the first trial but made no comment about it when filling in the questionnaire.

2.2 Study Two: Interaction with Objects

2.2.1 Aim. The second study aimed to evaluate a method of interacting with objects in VEs on people with no 3D computer graphics experience, and to find a sufficiently usable input device for this purpose.

2.2.2 Method. The study was performed in three steps:

1. The research group started the study by discussing different methods for interaction with objects. This discussion resulted in a proposed method for interaction with objects.
2. The next phase concerned what properties an input device should have to be usable for people with brain injury, for the purpose of interaction with objects in a VE. Aspects of occupational therapy, human–computer interaction, and VR were considered in the discussion, which resulted in a list of desirable qualities. This list was then used to select two input devices: mouse and touch screen.
3. Our proposed method for interaction with objects was then tested with mouse and touch screen on able-bodied people with no experience of 3D computer graphics.

In step 1 the research group discussed different methods for interaction with objects. As described in the introduction, interacting with objects in a VE can be performed in at least three ways: activate objects, move objects, and use one object with another (object–object interplay). We chose to limit this study to the former two; object–object interplay will hence be investigated later in the project. Activating objects with a click posed no problems for the brain injury patients in our pilot study (Lindén et al., 2000). However, two ideas concerning moving objects evolved during the pilot study: the use of drag-and-drop for moving objects within the view, and a virtual hand for carrying objects in order to facilitate object movements out of the view. Finally, our proposed method for interaction with objects consisted of the following four parts:

- Drag-and-drop for moving the object within the view. Example: the user moves a package of macaroni from a cupboard to the kitchen counter.
- A virtual hand for carrying the object when moving it to a location outside the view. Example: the user moves a carton of milk from the refrigerator to the kitchen table that is outside the present view.
- A single click for activating the object. Example: the user turns a tap or opens a cupboard door.
- Automatic rotation of the object. Example: the fork is automatically given a proper orientation when the user places it on the table next to a plate.

In step 2 we used our experience from the pilot study and knowledge of brain injury rehabilitation and human computer interaction to produce the following list of desirable input device properties:

- Memory problems are among the most commonly reported deficits after brain injury, and therefore the input device should not have different modes of operation.
- It is essential that the input device give necessary feedback to users to make them understand that an action has been registered.
- A brain injury may also result in decreased motor performance. Therefore the input device should be one that can be operated by people with fine-motor difficulties.
- A more practical, but not less important, detail is that the input device should be easily found in the retail trade and should not be too expensive.

Two of the most common six DOFs input devices are the Spaceball and the Spacemouse. The problem with these input devices is that they are designed for multi-DOF interaction and therefore might be hard to use for people with limited motor and cognitive abilities. The fact that they are relatively expensive (approximately $500) is another drawback since cost and availability are important factors to consider when introducing VR technology in a hospital or home environment. For these reasons they were not considered candidates for the experiment. Another six DOFs input device which is commonly used in immersive VEs is the dataglove. There are several reasons why we did not consider the dataglove to be a candidate for the experiment:

- A dataglove with a tracking system is very expensive (approximately $20,000).
- Interference with the user's navigation in the VE might appear when the user interacts with the navigation input device.
- Ergonomic reasons: a dataglove might not fit for very small and very large hands.

The trackball has proven hard to use for people with cognitive difficulties (Robertson & Hix, 1994; Cress & French, 1994) and was hence judged to be unsuitable for people with brain injury.

A number of studies have suggested that the touch screen is faster and easier to use than other input devices (Karat et al., 1986; Pretor-Pinney & Rengger, 1990; Chamberlain & Kawalsky, 2004; Robertson & Hix, 1994; Rau & Hsu, 2005; Pak et al., 2002; Lu & Frye, 1992; Battenberg & Merbler, 1989). This seems to hold true for normal populations as well as for people with special demands. According to Shneiderman (1991) the touch screen has an unrivaled immediacy, a rewarding sense of control and the engaging experience of direct manipulation. However, touch screens also have some disadvantages (Shneiderman, 1991):

- The hand of the user may obscure the screen.
- In order to reduce arm fatigue the touch screen needs to be tilted and placed at a lower position.
- Some reduction in image brightness may occur.

Another flaw of the touch screen is the lack of proprioceptive feedback (Bender, 1999). For example, selecting an object on the screen does not give the same feedback as pressing down the button of a mouse. Also, some studies have shown that the touch screen pro-

Table 5. *Demographic Data and Input Devices N = 20*

Group	Input device	Subjects		Age (median)	Computer use hrs/ week (median)
1	Touch screen	6 females	4 males	36	6.8
2	Mouse	6 females	4 males	31.5	6

duces more errors than other input devices (Karat et al., 1986; Pretor-Pinney & Rengger, 1990; Mack & Montaniz, 1991; Chamberlain & Kawalsky, 2004). There are basically three types of touch screen technologies: capacitive, resistive, and surface wave technology. The basic difference between them is the way in which they register the touch of the user. Unlike capacitive touch screens, resistive and surface wave touch screens don't require electrical contact between the user and the screen and can therefore be controlled with an object (for example a pencil) as well as a finger. Traditionally, touch screens have been quite expensive but are now becoming more affordable. For example, a 19 inch CRT touch screen based on surface wave technology costs around $500. It has been reported that a touch screen might be unsuitable for people with learning disabilities due to technical flaws (Brown et al., 1997). These technical problems have decreased as touch screen technology has become more sophisticated.

The most obvious advantage of the mouse is the fact that it is the de facto standard input device for personal computers, together with the keyboard. There is also evidence that the mouse is better than the touch screen for tasks that demand precision (Mack & Montaniz, 1991). The mouse is an indirect-control input device, and hence it requires more cognitive processing and hand-eye coordination (Shneiderman, 1998).

Based on the discussion above we finally decided to evaluate our interaction method with touch screen and mouse respectively.

In step 3 an experiment that aimed to evaluate our interaction method with touch screen and mouse was conducted. Twenty hospital staff with minor experience of 3D computer graphics participated in the experiment. They were selected from the navigation study described above in such a way that subjects with extreme scores (best and worst) were excluded. The subjects were then divided into two groups. The first group used a regular desktop mouse for interaction and the second group used a 19 inch capacitive touch screen (Table 5). Both groups used the IntelliKeys keyboard with three DOF for navigation of the viewpoint.

The kitchen VE from the navigation study was used also for this experiment (Figure 10a). Some parts of the kitchen fittings in the VE were programmed with one or both of two properties; "possible to activate with a click" and "possible to place objects on/in." The size of the area around an object sensitive to input device events, hereby referred to as the active area, was determined during the implementation of the VE. The doors of the cupboards could be opened and closed with a click. A virtual hand was placed in the lower right corner of the screen (Figure 10b). An object placed in the virtual hand remained there until moved. Included in the VE were also three food packages that had the property "possible to move with drag-and-drop" (Figure 10c). The size of the packages differed depending on if they were being moved, or if they were placed in the virtual hand or on a kitchen surface. When a package was being moved its size was approximately ten percent of the screen height and did not change (Figure 10d). When placed in the virtual hand the package had a predefined size in scale with the virtual hand, and when placed on a kitchen surface the size of the package varied with the distance from the viewpoint. These variations in size were due to the way in which the VE was programmed. Implementing the possibility to move objects in a VE with drag-and-drop in a realistic way is not an easy task and we chose this implementation due to time constraints. When the cursor arrow was located

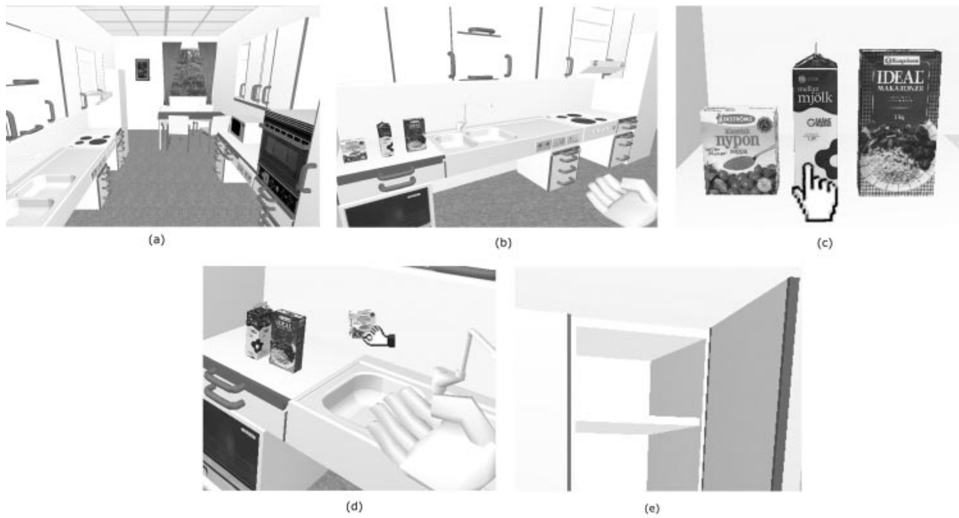

Figure 10. *The kitchen VE: a) Overview of the VE; b) The virtual hand; c) The three packages soup (soppa), milk (mjölk), and macaroni (makaroner); d) Dragging an object (the soup); and e) The top shelf of the cupboard, the destination for the soup.*

over an object that was possible to interact with, it changed to a pointing hand (Figure 10c). When the user moved or activated an object the cursor was transformed into a holding hand to give feedback to the user that the object was manipulated (Figure 10d). The method for interaction with objects was exactly the same for mouse and touch screen.

Walk-through navigation was used and an IntelliKeys keyboard with three DOFs was used as navigation input device (Figure 2b). Ten of the 20 subjects had already used the IntelliKeys keyboard in the navigation study. To eliminate the differences between the subjects preknowledge of the keyboard as much as possible, each subject started the test session by using the keyboard in a navigation task that lasted for approximately three minutes. The observation equipment from the navigation study was used to record the subject's behavior during the trial.

The subjects were to perform four different interaction tasks (Table 6) a total of five times. The subject was told to use the mouse/touch screen for interaction with objects and the IntelliKeys keyboard for navigation but received no other information about the functionality of the kitchen VE. The reason for this was that we wanted to study the subjects' spontaneous, uninstructed behavior when interacting with the objects in the VE, especially the virtual hand. If the subjects did not use the virtual hand in the first trial they received information on how to use it from the test leader, before the second trial.

At the end of the session, an interview consisting of six categories of questions was conducted and video recorded. The questions concerned moving objects within and out of view, the virtual hand, placing an object on the top shelf, opening and closing cupboard doors, the input device and also miscellaneous issues.

Two members of the research group were responsible for the analysis of the experimental data. They analyzed each subject's trial independently and thereafter discussed their observations. When a difference of opinion arose the video sequence of interest was analyzed once again. The following seven points were used as a basis for the observations:

- Is the subject spontaneously using drag-and-drop in the first trial?
- Is the subject using the virtual hand for carrying objects *before* receiving information about it?

Table 6. *Description and Purpose of the Interaction Tasks*

Task	Description	Purpose
1	Move a package of soup from the counter to the sink.	To study the procedure of moving an object within the view.
2	Move a carton of milk from the counter to the table.	To study the procedure of moving an object to a location that is outside the view.
3	Move a package of macaroni to the opposite side of the kitchen, open the cupboard door, place the package on the shelf and close the door.	To study the procedure of moving an object to a location that is outside the view and opening and closing a cupboard door.
4	Move the package of soup to the opposite side of the kitchen, open the cupboard door, place the package on the top shelf (Figure 10e) and close the door.	As above and additionally placing the object on a high location that might be out of view.

- Is the subject using the virtual hand for carrying objects *after* receiving information about it?
- How does the subject proceed to open and close the cupboard doors?
- How does the subject proceed to place an object on the high shelf?
- Is the subject having any problems with the input device?
- In what way is the subject using his or her hands?

The main concepts of each subject's interview were also discussed and written down.

2.2.3 Results. Nineteen subjects out of 20 managed to solve the four interaction tasks without help in all five trials. The 20th subject had to be given instructions on how to open the cupboard doors on one occasion.

2.2.3.1 Moving Objects within the View (Task 1). All mouse subjects used drag-and-drop spontaneously in trial one, while four out of ten touch screen subjects tried point-and-click, that is they tried to move the object by first clicking on the object and then on the destination. Nine subjects used the virtual hand spontaneously when moving objects within the view in the first trial. In total, the virtual hand was used 37 times for the touch screen and 12 times for the mouse during task 1 (Table 7). Two touch screen subjects and three mouse subjects used another strategy. They held the object by holding down the mouse button, moved the viewpoint (even if it was not necessary) and then dropped the object at the destination. The remaining subjects dragged the object directly to the destination.

2.2.3.2 Moving Objects out of the View (Tasks 2–4). Two strategies for moving objects out of the view were observed. The first strategy, hereby referred to as the hand strategy, was to put the object in the virtual hand, then navigate the viewpoint and finally put down the object at the destination. The subjects that used the second strategy, hereby referred to as the hold strategy, kept the object in drag mode by holding down the mouse button while navigating the viewpoint and then placed the object. All touch screen subjects used the hand strategy after having received information from the test leader (Table 7). Five mouse subjects applied the hold strategy and only used the virtual hand occasionally. On two occasions one person was observed to hold the object over the virtual hand without using it. One of the subjects using the hold strategy used the virtual hand twice to place objects when opening or closing cupboard doors.

2.2.3.3 Placing Objects on the Top Shelf (Task 4). Occasionally, the subjects had to move backwards to be able to see the top shelf when standing in front of a cupboard. This did not cause any problems for the majority of the subjects; only one mouse subject had some problems placing the viewpoint in an appropriate way. However, when the subjects were to put the object on the top shelf a problem arose. The nature of the problem was that the subjects put the object on the edge of the top

Table 7. *Number of Subjects Who Used the Virtual Hand in Each Trial (N = 20; Ten Touch Screen Subjects and Ten Mouse Subjects)*

	Task 1		Task 2		Task 3		Task 4	
Trial	Touch screen	Mouse	Touch screen	Mouse	Touch screen	Mouse	Touch screen	Mouse
1	5	4	4	4	4	4	4	4
2	10	2	10	6	10	6	10	7
3	8	2	10	7	10	6	10	6
4	8	2	10	5	10	6	10	6
5	6	2	10	6	10	6	10	6
Sum	*37/50*	*12/50*	*44/50*	*28/50*	*44/50*	*28/50*	*44/50*	*29/50*

Table 8. *Number of Times the Touch Screen Subjects (T_{1-10}) Failed to Place Objects on the Top Shelf in Trial 1–5, N = 10*

Subject	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	Total
Trial											
1	1	0	3	0	2	5	1	0	0	0	12
2	4	0	1	0	0	0	0	0	2	1	8
3	0	0	0	0	0	0	0	0	1	0	1
4	1	2	1	4	0	6	0	0	1	0	15
5	0	0	0	3	1	0	0	0	0	0	4
Total	*6/20*	*2/20*	*5/20*	*7/20*	*3/20*	*11/20*	*1/20*	*0/20*	*4/20*	*1/20*	*40/200*

shelf. The edge did not have the property "possible to place objects on," and the object therefore returned to its previous location. Each time that the subject failed to place the object on the top shelf was counted (Table 8 and 9). Subjects M_2, M_3, M_4, and T_6 stood for the majority of the problems in placing objects on the top shelf. Subject M_2 failed to place the object 15 times in the second trial. He had problems finding a suitable position for the viewpoint when placing the object and therefore accidentally placed it on a lower shelf.

2.2.3.4 Open and Close Cupboard Doors (Tasks 3–4). One touch screen subject and two mouse subjects opened and closed the cupboard doors without any problems during the five trials. The remaining subjects had problems in opening and/or closing the cupboard doors in one or several trials. As can be seen in Table 10, four touch screen subjects, T_1, T_3, T_4, and T_6, had problems in all five trials, whereas none of the mouse subjects had problems after trial 3 (Table 11). The nature of the problem was that the subjects tried to open and/or close the cupboard doors with drag-and-drop instead of clicking. The problem was registered in the following manner; if the subject had problems opening as well as closing the cupboard door in task 3 this was counted as "two." If the subject only had problems opening or closing the cupboard door this was counted as "one." Task 4 was registered in the same way. This means that the maximum score for problems to open and close the cupboard doors was "four."

Table 9. *Number of Times the Mouse Subjects (M_{1-10}) Failed to Place Objects on the Top Shelf in Trial 1–5, N = 10*

Subject	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}	Total
Trial											
1	2	1	3	1	0	1	2	3	0	5	18
2	0	15	4	3	1	0	0	0	0	1	24
3	2	1	3	2	0	0	0	1	0	0	9
4	0	1	0	3	0	1	0	3	0	0	8
5	3	1	3	4	2	1	0	0	1	0	15
Total	*7/20*	*19/20*	*13/20*	*13/20*	*3/20*	*3/20*	*2/20*	*7/20*	*1/20*	*6/20*	*74/200*

Table 10. *Registration of Problems to Open and Close Cupboard Doors for Touch Screen Subjects (T_{1-10}), Trial 1–5 N = 10*

Subject	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	Total
Trial											
1	3	2	2	3	0	3	2	3	1	3	
2	2	3	2	2	0	4	1	0	0	3	
3	2	0	2	2	0	2	0	2	1	3	
4	3	1	2	2	0	3	0	1	0	0	
5	2	1	1	1	0	4	0	2	0	2	
Total	*12*	*7*	*9*	*10*	*0*	*16*	*3*	*8*	*2*	*11*	*78*

Table 11. *Registration of Problems to Open and Close Cupboard Doors for Mouse Subjects (M_{1-10}), Trial 1–5 N = 10*

Subject	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}	Total
Trial											
1	0	3	3	2	2	1	1	0	3	2	
2	0	2	0	1	0	0	0	0	0	0	
3	0	0	0	1	0	0	0	0	1	0	
4	0	0	0	0	0	0	0	0	0	0	
5	0	0	0	0	0	0	0	0	0	0	
Total	*0*	*5*	*3*	*4*	*2*	*1*	*1*	*0*	*4*	*2*	*22*

2.2.3.5 Dropping and Failing to Get Hold of Objects (Tasks 1–4). In general, all subjects managed to drag-and-drop objects. However, two problems were noted: either the subject had difficulties getting hold of the object or dropped the object before it was placed. Tables 12 and 13 describe how many times the subjects dropped or failed to get hold of objects for touch screen and mouse, respectively. As can be seen in Table 12, two touch screen subjects had problems in all five trials. For the mouse subjects the problems appeared mainly in

Table 12. *Number of Times the Touch Screen Subjects (T_{1-10}) Dropped or Failed to Get Hold of an Object in Trial 1–5 N = 10*

Subject Trial	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	Total
1	0	0	2	0	2	0	3	1	0	0	8
2	0	3	10	0	1	0	1	0	0	1	16
3	0	1	2	0	1	0	1	0	0	0	5
4	0	0	4	0	1	2	1	0	0	5	13
5	0	0	8	0	1	2	0	0	0	2	13
Total	*0*	*4*	*26*	*0*	*6*	*4*	*6*	*1*	*0*	*8*	*55*

Table 13. *Number of Times the Mouse Subjects (M_{1-10}) Dropped or Failed to Get Hold of an Object in Trial 1–5 N = 10*

Subject Trial	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}	Total
1	0	0	0	0	1	0	1	3	1	1	7
2	0	0	0	0	0	2	0	0	0	0	2
3	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	0	0	0	0	0	0	0	1
5	1	0	0	0	0	0	0	0	0	0	1
Total	*1*	*0*	*1*	*0*	*1*	*2*	*1*	*3*	*1*	*1*	*11*

the first trial and none of them had problems in more than one trial.

2.2.3.6 How the Subjects Used their Hands (Tasks 1–4). Six touch screen subjects used their dominant hand for both navigation and interaction with objects and did not use their non-dominant hand at all. The remaining four subjects used both their hands when navigating and their dominant hand when interacting with objects. Six mouse subjects navigated with their non-dominant hand and interacted with their dominant hand. They only let go of the mouse in one or two occasions in the beginning of the trial. One mouse subject used the dominant hand for both navigation and interaction and did not use the non-dominant hand at all. The remaining three subjects used their dominant hand for both navigation and interaction and sometimes used both hands for navigation. Three mouse subjects navigated the viewpoint and interacted with objects simultaneously at one or several occasions. For example, they dragged an object over the screen while navigating.

3 Discussion

In the navigation study most subjects managed to solve the navigation task and improved their performance over the five trials. The distance covered in the kitchen part of the VE was significantly shorter for the keyboard compared with the joystick. This, in combination with the fact that the number of direction changes was significantly smaller for the keyboard, indicates that the keyboard is easier to control than the joystick for a maneuvering task. The observations from the video analysis support this. The joystick subjects tended to navigate in a wobbly manner compared to the keyboard subjects. Also, some of the joystick subjects never fully learned how to control the joystick effectively. The distance covered in the corridor part of the VE was significantly shorter for the keyboard compared with the joystick, whereas no significant difference regarding number of direction changes could be found between the two input devices. These results suggest that the keyboard might be slightly easier to control than the joystick for a search task. However, the keyboard was found to be approximately 80% slower than the joystick. This might be due to the fact that the keyboard is controlled with discrete input events whereas the joystick is a continuous input device. Even if we consider time to be a less important factor than distance and number of direction changes, this might make the keyboard an inconvenient input device for VE applications that only involve search navigation tasks. The findings described above contradict results by Brown et al. (1997) and Standen et al. (2004). In these two studies a joystick was found to be a better navigation input device than a keyboard for people with intellectual disabilities. However, the tasks performed were more search tasks than maneuvering tasks (for example slalom skiing) and the compared input devices had two DOFs. Interestingly, in this study there was no significant difference (except in time) between keyboard and joystick in the case of two DOFs for the search task. The pattern that appears when comparing this result with the findings of Brown et al. (1997) and Standen et al. (2004) is that the keyboard is more suitable for maneuvering tasks whereas the joystick with two DOFs might be the preferable input device for search tasks. However, an important difference between our study and the studies of Brown et al. (1997) and Standen et al. (2004) is the type of keyboard that was used. We were using an IntelliKeys keyboard tailor-made for the purpose of navigation, whereas Brown et al. (1997) and Standen et al. (2004) used a regular desktop keyboard. It is possible that the relatively more complex appearance of the desktop keyboard makes it harder to use.

Broadly, the performance of all four subject groups improved over the five trials. In trial one, the joystick subjects' median distance in the corridor was around 50% larger than the keyboard subjects'. However, it decreased over the five trials and was almost at a level with the keyboard groups' median distance in trial five. A similar pattern could be seen for the distance in the kitchen. This indicates that the joystick is harder to use in the beginning but gradually becomes as easy to use as the keyboard. However, when the number of direction changes for the kitchen part of the VE is considered a different pattern appears. The joystick subjects' median number of direction changes plateaued at a value approximately 40% larger than the keyboard subjects'. This indicates that for maneuvering tasks the joystick is harder to use than the keyboard also when considering learning effects. For people with cognitive disabilities due to brain injury it might not be enough that the navigation input device is learnable in the sense that it is possible to learn how to use it; it must also be easy to use without a lot of training. Users with memory problems, for example, might forget how the input device works between, and maybe even within, training sessions. Our results suggest that the keyboard might fulfill both of these two demands better than the joystick in the case of maneuvering tasks. However, brain injury patients in lower ages might have extensive experience of joysticks from playing computer games, and it is therefore possible that the joystick is a sufficiently usable input device for this sub-population to also cover maneuvering tasks.

Approximately half of the joystick subjects activated several DOFs simultaneously by, for example, rotating and moving forward at the same time. Zhai et al. (1999) point out that when people are manipulating objects in real life the DOFs tend to be integrated, whereas they seldom use all the DOFs simultaneously when moving. They mainly stay on a 2D surface, move in a given direction, turn around or move up and down when for example climbing the stairs. This speaks in favor for the keyboard since one of our main assumptions is that the VE interface should resemble reality. Also, controlling several DOFs at the same time might induce higher cognitive load in people with brain injury who have problems with divided attention.

A significantly longer distance in the corridor part of the VE was found for three DOFs. This suggests that two DOFs are better for VE applications that only involve search navigation. However, the interaction between the two independent variables was found to be significant which implies that this only holds true for the joystick. No significant differences could be found between two and three DOFs for the kitchen part of the VR. Nevertheless, the third DOF (sideways movement) seemed to facilitate the subjects' navigation in the kitchen when, for example, they were moving along the kitchen sink or when they became stuck with their virtual shoulder when passing through the doorway. This implies that three DOFs are preferable for VEs that involve maneuvering tasks. This conclusion is in accordance with findings of Lapointe and Vison (2002) which suggests that a third DOF does not hamper performance, while allowing more complex movements. Nevertheless, it is important to remember that the third DOF might mean increased cognitive load for some people with brain injury since it makes the keyboard more visually cluttered and the mapping of the joystick more complex.

Sixteen out of 30 keyboard subjects operated the keyboard with both hands. The possibility to operate the keyboard with both hands might be an advantage due to a more natural mapping. If users want to turn or move to the *left* they use their *left* hand and if they want to turn or move to the *right* they use their *right* hand.

Surprisingly enough, several joystick subjects spontaneously reported nausea or dizziness, without being asked about it. This might indicate that the subjects experienced cybersickness, a phenomenon usually associated with immersive VR (Cobb, Nichols, Ramsey, & Wilson, 1999). The cybersickness experienced by the joystick subjects might be connected to the fact that the frame rate was approximately 30% higher in the corridor than in the kitchen due to less objects to be rendered. The joystick was therefore more sensitive in the corridor, resulting in larger and less controlled movements of the viewpoint. The effects of cybersickness, for example nausea and vomiting, might be augmented and unpredictable in people with brain injury. Therefore, if a joystick is used as navigation input device its sensitivity should be chosen with great care.

Some subjects experienced discomfort when pressing the keyboard, which may be a result of its inelastic surface. This problem might be even larger for long-term use and we therefore suggest that the buttons of the keyboard be covered with some sort of elastic material. Another disadvantage of the keyboard's inelastic surface is that the user does not receive proprioceptive feedback. It does, however, give auditive feedback through a beep, which might compensate for this flaw, at least to some extent.

In the study regarding interaction with objects, all the subjects carried out all four interaction tasks without major difficulties. The majority of them used drag-and-drop spontaneously when moving an object within the view in the first trial. However, some touch screen subjects tried to move objects with point-and-click. Two of these subjects participated in a previous study in which point-and-click was used (Lindén et al., 2000) and might have been influenced by this interaction technique. The fact that all mouse subjects used drag-and-drop spontaneously could be due to previous experience of Windows applications in which mouse and drag-and-drop are used.

Approximately half of the subjects used the virtual hand without information in the first trial. However, five subjects pointed out that it was not obvious how to use the virtual hand and that they would not have understood its meaning without information. This might be explained by the concepts of visibility and affordance discussed by Norman (1988). It is possible that some of the subjects simply did not notice the hand due to bad visibility. The fact that some subjects interpreted the virtual hand as an inviting instead of a carrying hand indicates that it sends the wrong signals to the user and thereby has flawed affordance. Its size, shape, and color should be changed to make it more conspicuous and appear more like a hand to carry things. For an able-bodied person, information about the virtual hand might be enough to understand how to use it. However, it is important to consider the fact that memory problems are among the most commonly reported deficits after brain injury (McKinlay & Watkiss, 1999). These problems include difficulty in learning new information as well as retaining and later retrieving it. Therefore, for brain injury patients with these problems it might not be enough that it is possible to learn how to use the virtual hand. The virtual hand should be as self-explanatory as possible since it is possible that the patient might forget how to use it between, and maybe also within, training sessions. Helping the patient understand how the virtual hand works by giving it good visibility and affordance is probably the key to achieving this. Another reason why some subjects did not understand the purpose of the virtual hand could be that they suddenly had *two* right hands; the real one and the virtual one. A solution could be to simply move the virtual hand to the left side of the screen.

The usage of the virtual hand after information differed between the two subject groups. The touch screen subjects, in contrast to the mouse subjects, used the virtual hand every time when moving objects out of view and for the most part also within the view. Approximately half of the mouse subjects preferred the hold strategy, that is, they kept the object in drag mode by holding down the mouse button, and many of them did not release their hold of the mouse during the trials. This is probably connected to the mouse subjects' experience of using a mouse, but it nevertheless indicates that it was more natural for the touch screen subjects to use the virtual hand.

More than half the subjects had problems placing an object on the top shelf due to difficulties in dropping it within the active area in the space above the shelf. This also emerged during the interview; ten subjects said that they had difficulties doing this. They seemed to prefer to drop the object on the edge or on the under side of the top shelf. A possible explanation might be that these areas have the same color as the inside of the cupboard and therefore can be perceived as being the shelf surface. If the object was not dropped within the active area it returned to the place from where it was picked up. If the subject had moved the object with the hold strategy, it returned to its place of origin and possibly disappeared from view. This might pose a problem for a person with memory problems who could have forgotten where the object cause from. One way to reduce the problem could be to include the edge of the shelf in the active area. Interestingly, the phenomenon was seen almost twice as often in the mouse subjects. A possible explanation to this might be that the mouse cursor was a stronger point of reference for the mouse subjects than was the fingertip for the touch screen subjects. Following this theory the mouse subjects would drop the object when the cursor was over the visible part of the shelf (which was not an active area) whereas the touch screen subjects would use the object itself as reference and hence drop it in the space above the shelf (which was an active area).

The most obvious interaction problem, especially for the touch screen subjects, was opening and closing the cupboard doors with a click. This partially contradicts one of the conclusions from our pilot study (Lindén et al., 2000), that people seem to have an inherent understanding of "click-to-activate." The mouse subjects learned faster how to open the cupboard doors, none of them failed after the third trial, whereas most of the touch screen subjects had problems in four out of five trials. This indicates that activating an object with a click is more natural with the mouse than with the touch screen. This may be due to the subjects' previous experience of clicking with the mouse when working with Windows applications. In contrast, the touch screen subjects tended to imitate the way things are done in real life, that is, they tried to open and close the cupboard doors with drag-and-drop. The reason for this might be that the touch screen is a more transparent input device than the mouse, a point that has also been made by Scaife and Bond (1991). This tendency came to light also in the interviews. Several touch screen subjects said that they did not find a good strategy for opening and closing the cupboard doors and also commented that cupboard doors are not opened with a click in real life. It is important that the way in which activities are performed in a VE resemble the way they are done in reality. This seems to be extra important if a touch screen is used as input device for interaction with objects, which leads us to believe that VEs for brain injury rehabilitation should be programmed to allow several interaction styles. It should, for example, be possible to open or close a cupboard door both with a single click and with drag-and-drop.

Interestingly, some subjects spontaneously commented on the possibility of placing objects far away. It seemed as if several subjects experienced this as being a bit unreal but also effective since they quickly adopted this way of transporting objects. If realism of movement is a requirement, "magic" techniques not based on a natural movement metaphor should be avoided (Bowman, Johnson, et al., 2001). Also, Neale et al. (2000) suggest that "metaphors used to interact with objects should reflect real world behavior" in VEs for people with learning disabilities. Applied on the kitchen VE this would mean that the user would have to approach the kitchen counter to be able to place an object on it. However, we are not only striving to simplify the interaction with objects but also to make it sufficiently effective. Once again, the best solution is probably to allow more than one interaction style; it should be possible to place the object both when being next to and far from the location.

Adequate feedback is of utmost importance in computer applications. Every action should result in some kind of response from the system (Shneiderman, 1998). The fact that the object did not change size until the cursor was outside the object means that the user did not get instant feedback that the object followed, which was pointed out by one of the subjects during the interview. The best way to solve this problem is probably to make the object change size immediately when the user is clicking on it.

Opinions regarding the variations in object size emerged during the interviews. These variations might be confusing for a person with cognitive disabilities since they do not reflect real world behavior. However, the variations in size are due to the way in which the object interaction is programmed. One must also consider what is possible to implement in a reasonable time when discussing VE usability. Nevertheless, the objects should be smaller when placed in the hand. Then the difference in size would be smaller and it would also block the view less.

Part of the purpose of the second study was to find a sufficiently usable input device for the evaluated interaction method. The opinions of the subjects regarding the two input devices were mainly positive. However, some problems came to light during the analysis. An interaction problem that was particularly obvious for the touch screen subjects was that they dropped or failed to get hold of the object. Several touch screen subjects had constant problems whereas the mouse subjects only had occasional problems. A higher error rate for touch screen compared with mouse has been observed in several studies (Chamberlain & Kawalsky, 2004; Karat et al., 1986; Mack & Montaniz, 1991; Pretor-Pinney & Rengger, 1990). In this study, the higher error rate for touch screen might be partially explained by the fact that the touch response varies due to the user's body size, finger dryness, or whether they are electrically grounded, and some people may therefore have problems getting sufficient contact with the touch screen surface (Elo TouchSystems, 2002). This could be avoided by using a touch screen built either with resistive or surface-wave technology since these types of touch screens do not require electrical contact between the screen surface and the user. Another flaw of the touch screen that has been reported is fatigue (Pretor-Pinney & Rengger, 1990). However, in this study none of the touch screen subjects spontaneously complained about fatigue, even though the touch screen was neither tilted nor lowered. Nevertheless, the test sessions were relatively short (approximately 15 minutes), and it is possible that long-term use might lead to fatigue in the arms.

All touch screen subjects used one input device at a time, whereas several mouse subjects used their non-dominant hand for controlling the keyboard and their dominant hand for operating the mouse. This indicates that it is more natural to remove the hand from the touch screen when the interaction is finished compared to the mouse. Clearly separating navigation and interaction in the interface might facilitate use for those with limited divided attention, and therefore the touch screen might be a better interaction input device than the mouse for this population.

Overall, we saw no large difference in performance between the mouse group and the touch screen group. It is nevertheless important to remember that the mouse subjects had previous mouse experience, whereas the subjects in the other group had little or no experience of the touch screen. The mouse might be a sufficiently usable input device for people with brain injury who are experienced users. The fact that it is the de facto standard input device for personal computers, together with the keyboard, is another advantage of the mouse. Some studies have found that the mouse is an input device with greater precision than the touch screen (Mack & Montaniz, 1991; Pretor-Pinney & Rengger; 1990), but no proof for this distinction was found in this study. However, the screen objects in these two studies were small, which was not the case in the kitchen VE.

In summary, the results from the first study indicated that the keyboard was easier to use than the joystick for people with no experience of 3D computer graphics when performing a maneuvering task. No significant difference could be found between two and three DOFs, but the third DOF seemed to simplify navigation in some situations. In the second study, the method for interaction with objects was found to work relatively well. However, the results showed that there are details that need to be improved. For example, it seems important to allow more than one way of interacting with objects, especially if a touch screen is used. No big difference in performance between the mouse and touch screen subjects was found, but the two input devices seem to affect the usability of a VE in two different ways. A tendency that it was more natural for the touch screen subjects to use the virtual hand was observed. Many more occasions of subjects dropping or failing to get hold of objects were noted for the touch screen, which might have been a consequence of the touch screen technology chosen for this study.

The two studies described in this paper used people with no experience of 3D computer graphics as subjects, since we wanted to first identify *fundamental* usability issues before involving people with cognitive disabilities due to brain injury. How much of the knowledge from these two studies that can be generalized to this population still remains to be seen. We are currently setting up an experiment that aims to investigate how well our results apply to people with brain injury. A group of subjects will perform an IADL task in the kitchen VE using the keyboard with three DOFs for navigation and the touch screen for interaction with objects.

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II

Investigating virtual reality training for brain injury rehabilitation

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Abstract

This paper presents two studies addressing virtual reality (VR) training for people with acquired brain injury (ABI). The first study investigated the transfer of route knowledge from a virtual to a real environment in people with ABI. Five participants practised a route in a virtual environment (VE) using a laptop computer and then walked the same route in the real environment. All five subjects managed to transfer some route knowledge from the VE to the real environment. Interestingly, they managed well to walk the route back to the starting point even though they had not practised this in the VE. The aim of the second study was to develop and evaluate a virtual cash dispenser that can be used as a training tool in brain injury rehabilitation. An iterative design process was applied in three stages. Seven people with ABI practised withdrawing money using the virtual cash dispenser on a desktop computer. In general, all subjects managed to learn how to use the virtual cash dispenser. However, some usability problems, mainly related to moving and rotating virtual objects were noted. On the whole, the subjects of the two studies had a positive attitude to the VR training.

1. Introduction

There is an increasing amount of evidence that virtual reality (VR) technology can be a feasible tool for training. Regarding vocational training, VR training has been studied for a wide spectrum of occupations including medical doctors [19], surgeons [46], soldiers [16], machine operators [10] and astronauts [41]. As VR equipment has became more inexpensive and easier to use, VR has become recognized as a useful training tool for brain injury rehabilitation as well. In a recent review paper, Rose, Brooks and Rizzo [42] conclude that "the use of VR in brain damage rehabilitation is expanding dramatically and will become an integral part of cognitive assessment and rehabilitation in the future." The authors also point out that much of the research performed in this area has been concerned with assessment of cognitive abilities, but that there is a new trend towards more focus on rehabilitation training strategies. Above all, great potential has been found in VR training for people with memory impairment [3, 6, 35]. The feasibility of VR training for people with unilateral spatial neglect has also been investigated with promising results [21, 50].

A basic distinction can be made between immersive and non-immersive VR systems. With the former, the user is partially or completely surrounded by the virtual environment (VE). In a CAVE™ system, for example, the VE is projected on three screens and the floor, thus almost completely encompassing the user. Non-immersive VR systems use simpler technology, for example a desktop computer that displays the VE on a standard monitor and uses standard input devices such as a mouse or a touch screen.

Since 1996, the Department of Design Sciences at Lund University in Sweden has collaborated with the Department of Rehabilitation at Lund University Hospital. The Department of Rehabilitation is CARF accredited and offers medical rehabilitation for people with disabilities due to injuries and diseases of the brain, spinal cord, peripheral nervous system or musculoskeletal system and chronic pain. In a recently completed co-operative project, the use of VR as a training tool in brain injury rehabilitation was targeted. More specifically, the project aimed at:

- finding a usable interface between the VR technology and the user, with emphasis on navigation of the viewpoint and interaction with objects in the VE [26, 49]
- investigating transfer of training by people with acquired brain injury (ABI) from a VE to the real world; and
- developing and evaluating practical VR applications for rehabilitation [11, 48].

We have also had a general interest in if and how VR training can be integrated into the brain injury rehabilitation process, even if this has not been an explicit research goal in the project. Standard desktop computer equipment was used in the project. Non-immersive VR in the form of a standard desktop computer and standard input devices was used in the project because it is:

- more inexpensive and easier to handle which is advantageous in a hospital environment
- less likely to induce so-called simulator sickness in the user, compared to VR systems using head-mounted display technology [33].

In this paper we present results from two studies targeting VR training for people with ABI:

1. Transfer of route training from a VE to the real world
2. Development and evaluation of a practical VR application: the virtual cash dispenser

Selecting participants with brain injury in a rehabilitation context is a complex procedure, which makes it hard to gather large populations or purposefully selected subjects for case studies. The brain injury patients who participated in the two studies of the present paper were positive towards participating, had the capacity and energy to participate in a meaningful way and were judged to not get disturbed in their rehabilitation process by participating. Approval for the project was obtained from Lund University's Ethics Committee.

2. Study 1: Transfer of route training from a VE to the real world

How much knowledge can able-bodied people transfer from training in a VE to the corresponding real task? In their pioneering work, Kozak, Hancock, Arthur and Chrysler [23] found no transfer of training from a motor-perceptual task trained in a VE to the corresponding real world task. The authors concluded that what the subjects learnt in the VE was specific for a VE context, and suggested that a task "which emphasizes cognitive skills, such as memory, may benefit more from virtual training than the presently described experiment." Way-finding is such a task involving cognitive skills such as memory and attention. Waller, Hunt and Knapp [47] and Witmer, Bailey, Knerr and Parsons [51] have demonstrated that people can learn routes in a VE and then apply this knowledge in the corresponding real environment. But to what extent can people with impaired cognitive abilities transfer knowledge from a virtual to a real environment? Some exploratory studies have produced positive results. For example, Mendozzi et al. [32] found that people with learning disabilities can learn functional tasks such as grocery shopping through VR training. In a similar study Brooks, Rose, Attree and Elliot-Square [5] got positive results for a food preparation task. In a single-case study by Brooks et al. [3], a woman with amnesia practised route finding in a hospital environment using VR training and successfully performed the routes in the real environment afterwards.

The aim of Study 1 was to investigate the transfer of route knowledge from a virtual to a real environment in people with cognitive impairments due to ABI. This task was chosen since impaired way-finding ability is rather common in this population [1], and since way-finding skills are crucial for independent living.

2.1 Method

2.1.1 Participants

Five people with ABI participated (Table 1). They were all patients at the Department of Rehabilitation who had the will and opportunity to participate. The only inclusion criterion was that they had never visited the part of the Department of Rehabilitation included in the way-finding task.

Table 1. Participants, Study 1

Subject	Sex	Age	Description
1	M	58	Impaired memory and slight initiation deficit.
2	M	53	Impaired memory and executive function.
3	F	64	Impaired memory, learning and planning. Experiences slowness in thought and action.
4	M	47	Impaired memory and planning. Slight attention deficit.
5	M	28	Impaired memory and concentration. Difficulties to orientate in new environments.

2.1.2 Materials

A route in the Department of Rehabilitation was chosen for practical reasons, but also since this building is known to be hard to navigate. It consists of two connected buildings that have different ground levels due to the surrounding topography (Fig. 1). The route started outside the occupational therapists' office on the ground floor (Fig. 2a) and led up to the first floor via stairs (Fig. 2b). It continued on the first floor along a long corridor and passed an elevator (Fig. 2d) before it reached a second elevator near the end of the corridor (Fig. 2e). After a trip in this elevator to the fifth floor, the route reached the goal which was the reception of the patient hotel. It took approximately three minutes to traverse this route at normal walking speed (elevator trip included).

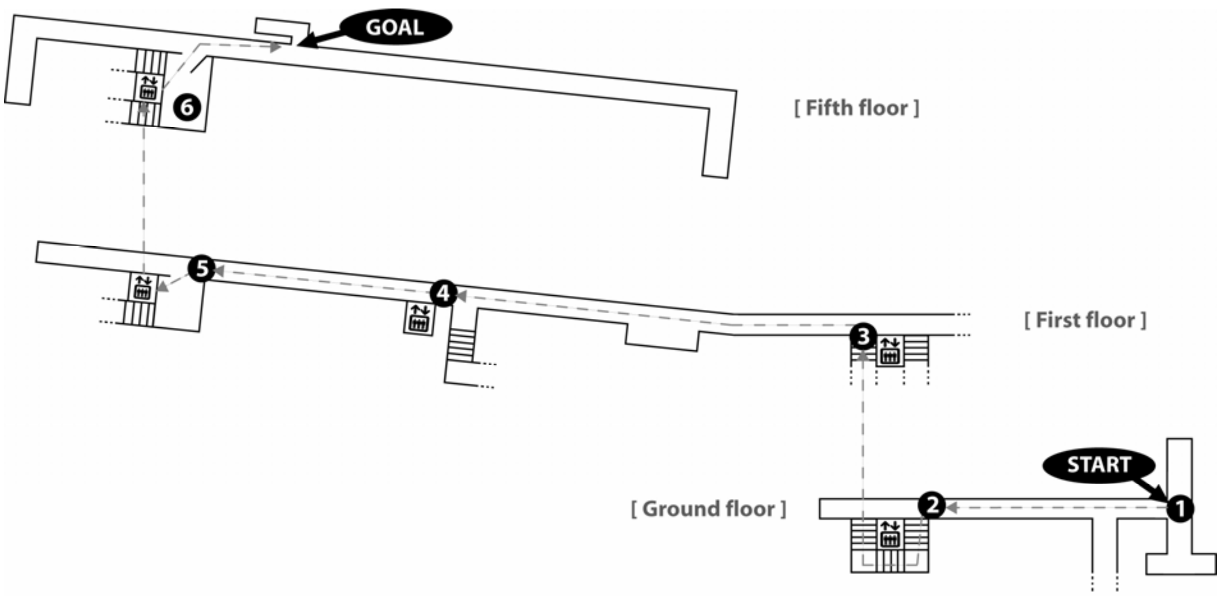

Figure 1. Floor plan drawing of the route in the Department of Rehabilitation

(a) ❶ The starting point

(b) ❷ The stairs

(c) ❸ The entrance to the first floor corridor

(d) ❹ The wrong elevator

(e) ❺ The entrance to the elevator

(f) ❻ Outside the hotel door

Figure 2. Screenshots along the route in the VE from the points marked in Fig.1

The VE ran on a laptop computer with a 15 inch monitor. The VE was developed with the *Valve Hammer Editor* software, which is a world creation program for the popular computer game *Half-Life*. The VE was designed to resemble the Department of Rehabilitation as closely as possible and contained all distinguishing landmarks such as pieces of furniture, paintings and signs that could be found in the real environment. However, the VE still appeared different since it lacked many of the objects that could be found in the real environment. For example, the real environment contained many temporary objects such as carts and wheelchairs that did not exist in the VE. Moreover, the VE gave a brighter and more colourful impression than the real environment. Sounds from doors, elevators and the user's footsteps were included to add realism. The subjects navigated the view in the VE with the cursor keys of the laptop computer's keyboard. The view could be moved forwards and backwards and rotated to the left and right. Furthermore, the subject could push elevator buttons and open doors by placing himself/herself in front of the button/door and pressing the E button on the keyboard.

2.1.3 Procedure

Two researchers, an occupational therapist (Researcher A) and a computer engineer (Researcher B), conducted the experiment. First, the experiment was described to the subject, and then his/her informed consent was obtained. The experiment began with a structured interview targeting the subject's experience of computers, interactive 3D computer graphics and his/her sense of direction. Before the VR training started, the subject was shown how to move from the starting point to the hotel reception in the VE. The subject then practised this route three times. If the subject went the wrong way, the test leader waited. If the subject did not realize his/her mistake the test leader revealed that it was the wrong way. If the subject still did not manage after this information, he/she received a verbal clue from the test leader. After the training, another structured interview was conducted. The questions targeted the subject's subjective experience of the VR training.

Thereafter the subject was brought to the starting point of the route in the real environment, marked as "Start" in Fig. 1. The subject was asked to try to find the reception of the patient hotel, marked as "Goal" in Fig. 1. Researcher A handled the communication with the subject and Researcher B documented the events with a video camera. Both researchers walked behind the subject in order to avoid aiding him/her by mistake. If the subject took the wrong way, Researcher A waited to see if the subject would correct his/her mistake. If not, the subject was told that it was the wrong way. If the subject could not find the way after this information, he/she received a verbal clue from Researcher A. When the subject had reached the hotel reception, he/she was asked to try to find the way back to the starting point, since we were interested in how the subjects would be able to traverse a route that they had not practised.

Afterwards, a retrospective think-aloud protocol [14] was used to elicit the subjects' thoughts during the real world way-finding task. RTA is commonly used in, for example, usability testing [17]. The subject was asked to think aloud about how he/she was thinking during the way-finding task while watching the video material. Finally, a third, structured interview was conducted. The questions concerned the subject's subjective experience of solving the way-finding task in the real environment. The behaviour and comments of the subject during the VR training, the retrospective think-aloud session and the interviews were recorded using three video cameras and a microphone (Fig. 3).

The interviews, training and real world way-finding tasks were all conducted in one session with the subject, which lasted approximately one hour.

Before the real trials with the ABI subjects were conducted, the whole experiment was performed with seven able-bodied people (2 males, 5 females). The purpose was to give the researchers practice in the realization of the experiment and to gain an understanding of the complexity of the way-finding task.

(a) (b)

Figure 3. The experimental set-up: a) the VR training, b) the retrospective think-aloud session

2.1.4 Analysis

The video material was analysed using an observation schedule which broke down the subject's way-finding in the virtual and real world into three parts to facilitate the analysis. Each part corresponded to one of the floors along the route. Observations of how the subject went about finding his/her way were written down. The observations included the subject's behaviour (e.g. gaze direction and signs of hesitation) and comments (e.g. exclamations). The analysis of the VR training sessions included the subject's interaction with the VE. The data from the retrospective think-aloud session and the interviews were transcribed using reformulation and concentration and grouped with the real world observations in the observation schedule. In this way, the recordings from the observations and the think-aloud session could be easily analysed in parallel.

2.2 Results

Subjects 1, 4 and 5 seemed relatively relaxed during the whole experiment, whereas Subjects 2 and 3 appeared to be tired. Subject 2 tired so easily that the researchers decided to skip the interviews and go directly to the VR training and way-finding tasks. Furthermore, Subject 3 seemed stressed and nervous and revealed during the interview that she felt very unsure due to her disorder. This is illustrated by the following excerpt from the think-aloud session:

R: What were you thinking here (at the starting point)?
S3: Well… you know… then it became chaos. I was thinking 'Oh my god, so much to think about!'

Table 2 quantitatively presents the number of times the subjects showed signs of hesitation or asked the researchers for confirmation (noted as "Hesitation" in Table 2) and the number of mistakes they made, both during the VR training and in the real world. During the VR training, all subjects improved their way-finding performance but only Subject 5 was completely flawless in the last trial. Subjects 1 and 2 improved their performance during the training only marginally. Overall, the subjects managed to perform the way-finding task in the real world well.

Table 2. The way-finding performance of the subjects (from the starting point to the goal)

Trial / Subject	**Training 1**		**Training 2**		**Training 3**		**Real world**	
	Hesitation	Mistake	Hesitation	Mistake	Hesitation	Mistake	Hesitation	Mistake
1	4	1	3	2	2	2	0	1
2	1	4	3	6	0	3	3	1
3	3	3	3	3	3	0	2	0
4	1	1	0	1	0	1	1	1
5	0	2	0	0	0	0	0	0

The seven able-bodied subjects in the pilot trials all made occasional mistakes during the VR training but had no problems at all in the real environment. They did, however, perceive differences between the virtual and the real environment. One subject commented that many details were missing in the VE and another subject felt that the stairs to the first floor felt much bigger in the VE.

2.2.1 The ground floor

For the most part, none of the subjects with ABI had any major problems finding the stairs leading to the first floor (Fig. 2b) during the VR training. Subject 3 was a bit unsure if she should take the stairs or not and needed confirmation from the researcher in all three training sessions. In the real environment, she found the stairs but asked the researcher if they were the same stairs as in the VE. When asked during the think-aloud session if she recognized them, she confirmed but did not seem completely convinced. Subject 2 commented during the think-aloud session that he was unsure if it was the correct stairs since they "felt much smaller and narrower than in the computer." The remaining three subjects had no problems finding and taking the stairs, either in the virtual or in the real environment.

2.2.2 The first floor

Subjects 1, 2, 3 and 5 showed signs of hesitation when reaching the first floor during the VR training (Fig. 2c). For example, Subjects 1 and 5 went to the right instead of left in the corridor in one training session each, while Subject 2 did so in all three sessions. Subject 3, instead, took the correct way in all training sessions but needed confirmation from the researcher in two of them. In the real environment, all subjects took the correct way. However, Subjects 2 and 3 showed signs of hesitation. Subject 2, for example, stopped at the top of the stairs, looked left, right and left again and then walked to the left. The researcher brought this up during the retrospective think-aloud session:

R: And what were you thinking here?
S2: Here I was totally blocked. I didn't recognize the surroundings at all.

R: But you did go left anyway?
S2: Mm… was that correct?

This indicates that he did not know where to go, but for some reason decided to go left anyway. Also Subject 5 revealed during the interview that he was not exactly sure if he should go left or right even though he chose the correct way: “I was looking for… I wasn’t completely sure to be honest. I was just walking.” Subject 4 took the correct way in all VR training sessions and also in the real environment.

All subjects except Subject 5 had difficulties finding the elevator (Fig. 2e) during the VR training and also in the real environment. Subject 1 mistook the wrong elevator for the right one in the third training session. He also had problems finding the elevator in the real environment: he started to go up the stairs to the left of the wrong elevator (Fig. 2d). After intervention by the researcher he found the elevator, however. The problem of Subject 2 was that he passed the entrance to the elevator in all VR training sessions. This behaviour was then repeated in the real environment; he looked at the entrance to the elevator when passing it, but continued down the corridor anyway:

R: Were you a bit lost here or..?
S2: Yes, I didn’t recognize the environment at all.
R: Did you know approximately what you were searching for?
S2: Yes, approximately. I walked too far also in the computer.

During the retrospective think-aloud session, Subject 2 commented that he remembered that the elevator was placed directly in the corridor in the VE, which probably made it harder for him to find it in the real environment. Subject 3 stopped by the wrong elevator (Fig. 2d) in two training sessions and asked the test leader if it was the right one. She repeated this behaviour in the real environment, but then found the elevator without further problems. Subject 4 stopped briefly by the wrong elevator in all three training sessions. When he reached the wrong elevator in the real environment he halted saying: “This is certainly an elevator.” Then he continued to walk down the corridor. Approximately five meters before the entrance to the elevator he turned around and went back. After having been informed by the researcher, Subject 4 then found the elevator without problems.

2.2.3 The fifth floor

The subjects had no problems finding the hotel door during the VR training, except Subject 3 who tried to take the stairs situated to the left of the elevator (Fig. 2f) in two training sessions. In the real environment all subjects managed to find the hotel door. However, Subject 2 showed signs of hesitation when he approached the hotel door in the real environment. Subjects 1 and 5 went left instead of right in the hotel corridor in one training session, Subjects 4 in two sessions and Subject 2 in all three sessions. Subject 3 did not know where to go in two of the training sessions and needed help from the researcher. Despite these problems, all subjects found the hotel reception in the real environment without any problems.

2.2.4 Back to the starting point (in the real environment)

Subjects 1 and 5 found their way back to the starting point without any need of help. However, Subject 1 showed small signs of hesitation on three occasions. For example, by the entrance to the stairs next to the wrong elevator (Fig. 2d) he stopped briefly and looked at it. The other subjects found their way until they came to the stairs leading down to the ground floor (Fig. 2c). Subject 2 stopped by the stairs and looked around while stroking his chin in a thoughtful manner. The researcher tried to give him clues since he did not seem to know where he was heading. After a short conversation the researcher accidentally said: “We are going down to the computer training room.” Subject 2 answered “Down?” and then started to walk down the stairs. During the retrospective think-aloud session he explained: “When I started to walk, I knew where I was heading.” He then went all the way to the starting point without problems. Subject 3 also stopped by the stairs and asked the researcher where to go. The researcher answered that she should go back to the starting point, whereupon Subject 3 pointed at the stairs and walked down to the ground floor. She then found the starting point without any problems. Subject 4 passed the stairs going down and instead started to take the stairs going up, whereupon the researcher intervened. During the retrospective think-aloud session Subject 4 noted that: “I had forgotten that I should go to the right.” Nevertheless, he eventually decided to take the stairs down to the ground floor. When asked if there was something he recognized that made him take the stairs, he answered: “I had forgotten where I should go, and simply had to try and see what would happen.” He then found the starting point without problems.

2.3 Discussion

All five subjects managed to transfer some route knowledge from the VE to the real environment. Nevertheless, the data revealed that they all experienced problems in the real environment. Furthermore, Subjects 1, 2 and 4 made mistakes that demanded intervention from the researcher on one occasion each. Interestingly, the help was needed in a part of the route that they also had problems with during the VR training. For example, Subject 2 passed the entrance to the elevator (Fig. 2e) in all three training sessions and did so as well in the real environment. The reason for this could be the way-finding task itself; the subjects needed help at difficult parts of the route. Another explanation could be that trial-and-error learning did not work well for the subjects. Lloyd, Powell, Smith and Persaud [27] compared errorless versus errorful route learning in people with ABI in a virtual town. They found errorless learning to be more effective than traditional trial-and-error for route learning tasks. Similarly, Brooks et al. [3] successfully trained an amnesia patient in route finding with a desktop VR system using errorless training as far as possible. The patient managed to learn four routes in a hospital environment by practising in the virtual version of the hospital. Accordingly, it is possible that errorless learning is the preferred method for people with ABI when it comes to route learning in VEs. However, Evans et al. [15] found that trial-and-error learning led to greater learning than errorless learning in people with memory impairment due to ABI. The reason for these contradictory results might be that route learning in an interactive 3D environment is fundamentally different from the paper based route learning used by Evans et al. [15]. In any case, more research is needed in this area.

There is another possible explanation as to why the subjects needed help during the real world way-finding task. Subjects 1, 3 and 4 confused the wrong elevator (Fig. 2d) with the right one. The reason for this could be that the navigation speed in the VE was higher than the subjects’ walking speed in the real environment. It is therefore possible that they believed they had reached the right elevator since they had been walking approximately the same amount of time as in the VE. As a matter of fact, three of the able bodied subjects from the pilot tests commented that the long corridor on the first floor felt longer in the real environment. The fact that there were differences in appearance between the virtual and the real environment might also have contributed to the mistakes and hesitations of the subjects in the real environment. On two occasions, Subject 2 pointed out that he did not recognize the real environment at all. Three of the able-bodied subjects made similar comments.

None of the subjects had problems finding the hotel reception when entering the hotel corridor even if they all had problems doing so during the VR training. Why did these problems not transfer to the real environment as did the subjects’ problems in finding the right elevator? The reason might be differences in how the virtual and real environments were perceived. In the real world the subjects saw the hotel reception immediately when entering the hotel corridor. In the VE they did not, due to the computer monitor’s restricted field of view (approximately 60 degrees).

Interestingly, all five subjects managed quite well to find their way back to the starting point even if they had not practised this route. Subjects 1 and 5 had no problems at all while Subjects 2, 3 and 4 needed help from the test leader by the stairs leading down to the ground floor (Fig. 2c). The subjects were, of course, helped by the fact that they had already traversed the route in one direction. Their performance is still interesting, though, especially since it has been suggested that the learning outcomes of VE route training is specific for the practised route. Clawson, Miller and Sebrechts [8] found that participants hesitated more when walking a route in a direction opposite to that of VR training, compared to map training and real world training.

The performance of the subjects in the real environment becomes particularly interesting when considering that they did not practice until their performance was flawless. They practiced the route no more than three times each and still were able to transfer a great deal of route knowledge. However, to consider the VR training efficient, it should have some long-term effect. This was beyond the scopes of the present study, but results by Brooks et al. [3] suggest that the route knowledge from VR training can be lasting. A woman with dementia who practised route finding in a virtual hospital environment successfully performed the routes in the real environment afterwards. She also retained the route knowledge for the rest of the study, despite not receiving any further training on these routes.

Just like Brooks et al. [3] the present study suggests that relatively simple VR equipment can be used for spatial skills training by people with ABI. This is supported by two studies that have shown that training with non-immersive VR can be as effective as immersive VR training for transfer of spatial knowledge [22, 47]. On the other hand, there is some evidence that a small field of view is likely to render the user's spatial orientation and navigation worse [38, 43]. The fact that all the subjects had problems finding the hotel reception in the VE but not in the real environment supports this assumption. It is possible that a compromise between non-immersive and immersive VR is desirable in a rehabilitation context. As a matter of fact, the rapid development in the computer game industry has produced computer systems that can display a VE with wide field of view using just one computer and three standard monitors, called surround gaming (Fig. 4). As such equipment becomes more popular and hence less expensive it may be an affordable alternative for rehabilitation hospitals as well as for independent training in the patients' own homes.

Figure 4. Route training in a city environment using surround gaming technology

Also problems interacting with the VE were observed. All five subjects collided with the walls and objects and also had problems assuming a proper position when clicking the elevator button or opening the hotel door since the VE demanded the user to place the view right in front of the button or door to be able to manipulate it. The user could move forwards and backwards and could also rotate to the left and right. The possibility to move sideways can allow for more complex movements and hence facilitate a user's movements in a VE [24, 49]. The results clearly showed the necessity of offering the user the ability to move sideways to make the navigation as easy as possible. However, this would increase the number of buttons, eventually making the VR tool's interface more complex.

3. Study 2: Development and evaluation of the virtual cash dispenser

Before introducing a VR training tool in a brain injury rehabilitation context, one must carefully consider how the intended users will be able to use it. Even if patients are capable of interacting with a VR training tool at a basic level, the extra nonautomatic cognitive effort may restrain the rehabilitation process [39]. Edmans et al. [12] investigated the validity of VR training for stroke rehabilitation in a study in which fifty stroke patients prepared a hot drink in a real environment and in a VE. Doing so was found to be more difficult in the VE and the authors suggested that "interface and technical problems contributed to the difference between real and virtual performance." Interface issues seem to play a crucial role for the feasibility of VR training in brain injury rehabilitation and have been described by Rizzo and Kim [40] as “an area that needs the most attention in the current state of affairs for VR rehabilitation.”

The purpose of this study was to develop and evaluate a virtual cash dispenser that can be used as a training tool in brain injury rehabilitation. Special emphasis was put on interface issues. The virtual cash dispenser was developed in an iterative design process in which all members of the research group contributed with their specific competence. The design process involved three stages:

I. Development and evaluation of a paper prototype
II. Development and evaluation of a computer prototype
III. Evaluation of the virtual cash dispenser as a rehabilitation tool

The cash dispenser of the Swedish bank *Sparbanken Finn* was chosen as the model. A withdrawal from this cash dispenser involves six steps:

1. Insert the card in the card reader
2. Type in the code
3. Choose the amount of money
4. Choose if you want a receipt
5. Take the card
6. Take the money (and the receipt)

3.1 Stage I: Development and evaluation of a paper prototype

Stage I was initiated with a discussion of what features the virtual cash dispenser should have. Several design ideas was implemented in a paper prototype (Fig. 5), which was tested on six able-bodied people with little or moderate computer experience and no experience of interactive 3D graphics. The prototype was also reviewed by three occupational therapists with long experience of brain injury rehabilitation and a human-computer interaction expert. This research is described in Wallergård et al. [48].

Figure 5. The paper prototype

3.2 Stage II: Development and evaluation of a computer prototype

In stage II, the results from the evaluation of the paper prototype were used to develop a first computer version of the virtual cash dispenser. It had all the components and functionality of a real cash dispenser (Fig. 6a-b).

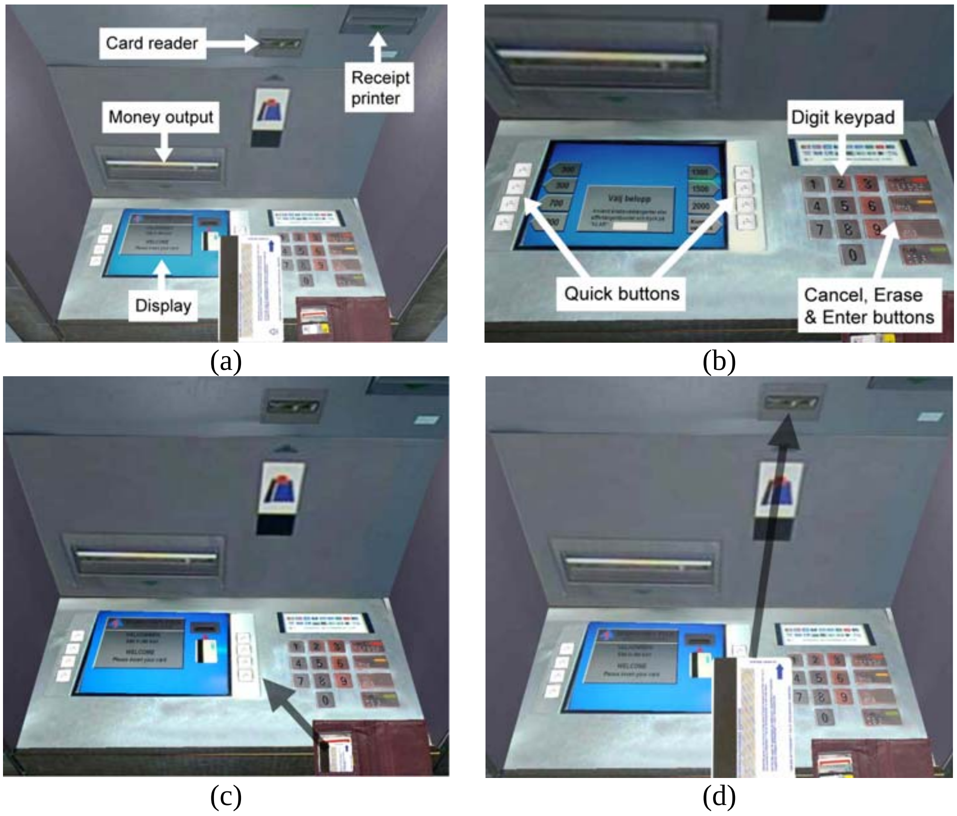

Figure 6. The computer prototype of the virtual cash dispenser

When the virtual cash dispenser program started, a wallet appeared in the lower right corner of the screen. The user could move the virtual objects (the card, the money and the receipt) in the following way:

1. First the user clicks on the object to be moved, which makes it move into the foreground as if held by an invisible hand (Fig. 6c).
2. Then the user clicks on the destination, which makes the object move there (Fig. 6d).

This way of moving objects is referred to as point-and-click. An alternative would have been to use drag-and-drop, allowing the user to simply drag the object over the screen to move it. In a pilot study we noticed that some subjects tended to spontaneously use drag-and-drop [26], which indicates that this is an intuitive way to move virtual objects. Nonetheless, we discarded drag-and-drop since it would not have been possible to turn the card with this interaction method as it cannot discriminate "click for dragging" from "click for turning". Turning the card in the right direction is difficult for many people with ABI and we hence believed this feature to be important. With point-and-click the card can be turned by simply clicking on it. Each time the user clicked on the card, it alternately rotated 180 degrees around its horizontal or vertical axis. The navigation of the view was handled by the VR application itself. For example, when the user had inserted the card, the VR application zoomed in to a more convenient view, as is illustrated in Fig. 6b. The software used to develop the computer prototype was the VR developer's kit *World Up*.

The purpose of the evaluation of the virtual cash dispenser prototype was to investigate:

- the usability of its interface
- what attitude the users had towards it

3.2.1 Method

3.2.1.1 Participants

Five people with ABI participated (Table 3). They were all patients at the Department of Rehabilitation who had the will and opportunity to participate.

Table 3. Participants, Stage II, Study 2

Subject	Sex	Age	Description	Cash dispenser usage	Withdrawals
6	F	51	Impaired memory and executive function.	Frequent	3
7	M	58	Impaired executive function.	Approximately six times per month.	5
8	F	52	Impaired reading and executive function. Difficulties to calculate time.	None	9
9	M	28	Impaired memory, recognition and orientation.	Approximately once per week.	4
10	F	29	Impaired memory, learning, and concentration. Limited stamina.	Very seldom after her injury.	5

3.2.1.2 Materials and procedure

A 15 inch capacitive touch screen was used to visualize and control the virtual cash dispenser (Fig. 7a). The same recording equipment as in Study 1 was used to document the experiment (Fig. 7b). A researcher who was an occupational therapist conducted the experiment. The subject was informed about the experiment and then his/her informed consent was obtained. The task of the subject was to withdraw 500 Swedish Crowns and a receipt. The number of money withdrawals of each subject was a bit different depending on his/her available time and energy. The subject was informed that the virtual cash dispenser worked exactly like a real cash dispenser and that the bank card code was 1-2-3-4. The subject was also shown how to use the touch screen. Except for this, the subject received no information about the virtual cash dispenser's functionality, since we were interested in his/her uninformed performance. The occupational therapist intervened if the subject had problems or became passive. After the VR training a structured interview with the subject was conducted with the purpose of learning about his/her experience of using the virtual cash dispenser.

(a) (b)

Figure 7. The experimental set-up

3.2.1.3 Analysis

An observation schedule was used to analyse the video material. It broke down the money withdrawal into three parts to facilitate the analysis. Observations of the subject's actions, behaviour, comments as well as the interventions made by the occupational therapist were noted. There was also a place to jot down reflections on the observations. The interview was transcribed using reformulation and concentration. Themes within and between the subjects were established using colour coding.

3.2.2 Results

Overall, the five subjects managed to learn how to use the virtual cash dispenser and improved their performance during the training. Subjects 6, 9 and 10 quickly understood how it worked and had only minor problems. Subject 7 had greater difficulties but gradually improved his performance. Subject 8 had difficulties understanding the functionality of the virtual cash dispenser but nevertheless improved over the nine withdrawals. During her first four withdrawals the occupational therapist had to intervene no less than fifteen times, but just twice during the remaining five withdrawals. The observations made during the analysis were divided into the five following themes:

3.2.2.1 Understanding how to interact with virtual objects

The most evident problem was the difficulty in interacting with the virtual objects of the virtual cash dispenser, i.e. moving and rotating them. Subjects 7 and 8 had rather extensive problems, whereas Subjects 9 and 10 only had occasional problems. Subject 6 tried to grab the objects instead of clicking on them in the first withdrawal. Otherwise she had no problems at all interacting with the virtual objects.

On one or several occasions, all subjects except Subject 6 tried to drag the virtual objects, which did not work since the virtual cash dispenser did not support this function.

Subjects 7 and 8 had problems understanding how to move the virtual objects. When Subject 7 was to insert the card for the first withdrawal he clicked on the card reader (Fig. 8a), but the card did not move since it was not turned correctly. He therefore tried to drag the card to the card reader. Once again nothing happened, which seemed to confuse him. Subject 8 had considerable problems inserting the bank card for the first two withdrawals. When she was to insert the card after having turned it correctly, she clicked on it and then immediately on the card reader. This made the card turn to the wrong side, and hence nothing happened when she clicked on the card reader. On several occasions, she clicked on the money or the receipt before clicking on the wallet even if it was enough to just click on the wallet since the virtual object was held by the invisible hand. Subjects 7 and 9 also did this on a couple of occasions.

Another problem of Subject 8 appeared when she clicked on the wallet while the money or the receipt was still on its way to the invisible hand in the foreground. The virtual cash dispenser was programmed in such a way that this was not possible. This flaw seemed to make it even more difficult for Subject 8 to build up an understanding of how to move objects. Her difficulties in moving objects culminated in withdrawal number seven. After an intervention from the occupational therapist she said, “I understand absolutely nothing!” During the interview, she commented that moving the objects felt a bit unreal.

Subjects 7 and 8 had initial problems understanding how to rotate the card. On a couple of occasions, Subject 8 clicked on different positions along the edges of the card when trying to turn it. Subject 7 also did this on one occasion.

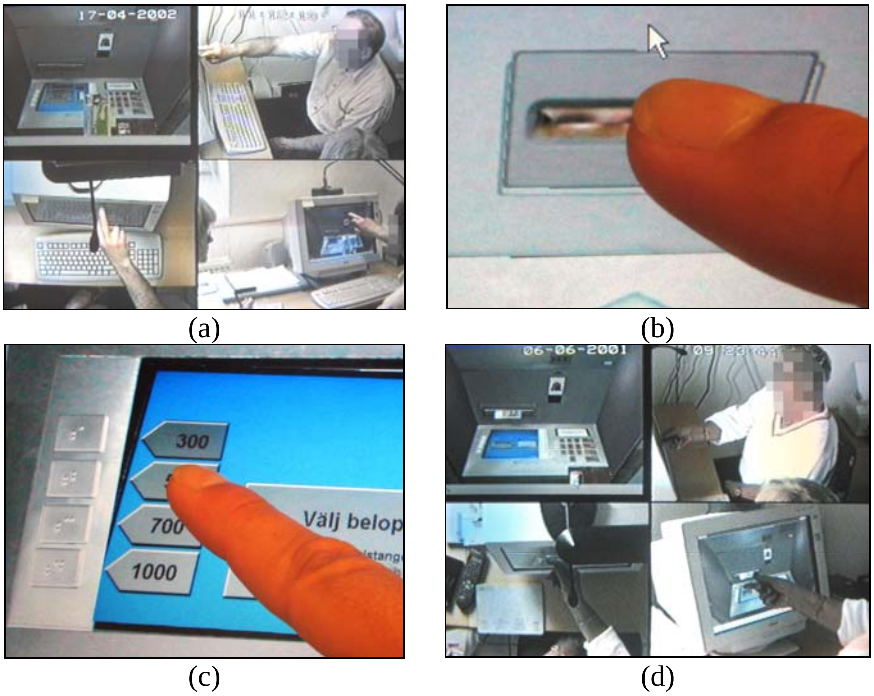

Figure 8. a) Subject 7 trying to insert the bank card. b) The calibration problem. c) Clicking on the arrow instead of the button. d) Subject 6 trying to grab the money.

3.2.2.2 Using the touch screen

All five subjects experienced problems with the touch screen. The main problem was insufficient calibration, which made the cursor appear approximately one centimetre above the point of contact (Fig. 8b). Another problem experienced by Subject 10 on three occasions was that her finger was not registered by the touch screen.

3.2.2.3 Perceiving the virtual cash dispenser

Subjects 6 and 7 pointed out several times during the interview that some parts of the virtual cash dispenser were visually unclear. Subject 7 emphasized this several times during the interview: “It has to be clearer. I mean, look at the buttons… You can tell that it’s not done professionally. […] Make it clearer and it will work well!” The unclearness was due to insufficient resolution and contrast in the digital photographs used to build the computer prototype.

On four occasions Subject 8 clicked on the image of the bank card on the cash dispenser display and it seemed she thought she actually was clicking on the card. Similarly, Subject 7 clicked on the image of the bank card under the card reader on one occasion. Subject 6 commented during the interview that the information on the cash dispenser display should have been bigger. Similarly, Subject 8 commented that she had problems reading the text in the cash dispenser display.

All subjects except Subject 10 clicked on the arrow pointing at the button instead of the button itself on one or several occasions (Fig. 8c).

Subjects 6, 7 and 8 tried to grab the bank card or the money with their hand (Fig. 8d). This phenomenon was especially apparent in Subject 6 who did this on four occasions.

3.2.2.4 Attitude to the virtual cash dispenser

All five subjects were positive about the virtual cash dispenser. Subject 6 spontaneously commented: “Gosh, I have never experienced anything like this!” Subject 7 said: “How clever! Damn good thing you have invented!” Before the VR training, Subject 8 was not sure if she wanted to participate, and seemed a bit nervous and insecure during the first three withdrawals. However, she gradually relaxed and after the sixth withdrawal she revealed a positive attitude:

R: This time you did well!
S8: It was actually really fun!
R: Were you worried before the training started?
S8: Before I came here I was thinking, 'Will I make a fool of myself now again?'

3.2.2.5 Miscellaneous

At the end of one of his withdrawals, Subject 7 asked the occupational therapist how to remove the wallet. The wallet remained in the lower right corner of the screen and it is possible that Subject 7 felt that the withdrawal was not finished until he had taken it.

The evaluation of stage II showed that the subjects seemed to be able to use the virtual cash dispenser, but also demonstrated that the computer prototype needed to be improved. First, its visual appearance was made clearer. Second, its interaction model was improved. It was not possible to click on a destination while an object was moving to the invisible hand, which seemed to confuse Subject 8. The virtual cash dispenser was hence re-programmed to allow this. Moreover, sounds were added to enhance realism. A click sound was added to the buttons, and money and receipt output sounds were recorded from a real cash dispenser and added to the application.

3.3 Stage III: Evaluation of the of the virtual cash dispenser as a rehabilitation tool

The purpose of stage III was to investigate how the virtual cash dispenser would work in a real rehabilitation situation.

3.3.1 Method

3.3.1.1 Participants

Three people with ABI participated (Table 4). They were all patients at the Department of Rehabilitation who had the will and opportunity to participate. Subject 10 from stage II participated once again.

Table 4. Participants, Stage III, Study 2

Subject	Sex	Age	Description	Cash dispenser usage	Withdrawals 1st	Withdrawals 2nd
10	F	29	Impaired memory, learning, and concentration. Limited stamina.	Very seldom after her injury.	7	6 (1 week after)
11	M	40	Memory impairment, learning and orientation.	Never by himself after his injury.	7	6 (1 week after)
12	F	35	Impaired memory and reading.	Regularly	6	3 (2 weeks after)

3.3.1.2 Material and procedure

The same computer and recording equipment as in stage II was used. The subject was informed about the experiment and then his/her informed consent was obtained. All three subjects participated on two training occasions (Table 3) with one or two weeks in between. The number of withdrawals depended on the available time in the subjects' rehabilitation schedule. Just as in stage II the subject's task was to withdraw 500 Swedish Crowns and a receipt. The subject was informed that the virtual cash dispenser worked like a real *Sparbanken Finn* cash dispenser and was also shown how to use the touch screen. The subject used his/her real bank card code, which he/she entered in a dialogue box that appeared when the virtual cash dispenser was started. The subject was informed that the virtual cash dispenser would not save the code and that only people involved in the project would have access to the video material. The occupational therapist who conducted stage II supervised the training. She used the same rehabilitation strategies she would have used in any other rehabilitation situation.

3.3.1.3 Analysis

As in stage II, the video material was analysed using an observation schedule in which the withdrawal was broken down into three steps. The following three points were used as a basis for the observations:

- How does the subject manage the activity of withdrawing money?
- How does the subject handle the interface of the virtual cash dispenser?
- What attitude does the subject have to the VR training?

Two researchers, one occupational therapist and one computer engineer, analysed the video material together. When a difference of opinion arose the video sequence of interest was analysed once again.

3.3.2 Results

3.3.2.1 Subject 10

Since Subject 10 participated also in stage II, she had no problems handling the interface of the virtual cash dispenser on the two training occasions. The occupational therapist did not have to intervene at all. However, Subject 10 often failed to click objects or buttons due to the still insufficient calibration of the touch screen. On a couple of occasions she also failed to get electrical contact with the touch screen, whereupon nothing happened when she clicked. This did not seem to disturb her, however, and she appeared to accept that several clicks sometimes were necessary. No difference in performance between the two training occasions was observed, which indicates that she had no problems remembering how the interface of the virtual cash dispenser worked between the two occasions. Likewise, she had no problems at all with the activity of withdrawing money on any of the two training occasions.

Subject 10 had a clearly positive attitude towards training with the virtual cash dispenser during both training occasions. During the second training occasion, she exclaimed twice: “Why, this is going excellently!”

3.3.2.2 Subject 11

Overall, Subject 11 had no problems understanding the interface of the virtual cash dispenser. However, he failed on several occasions to click objects or buttons due to the still insufficient calibration of the touch screen, but not as often as Subject 10. He also needed help to insert the bank card for the first withdrawal of the second training session since he had forgotten how to do so.

He had difficulties performing the withdrawals but improved during the training. His largest problem was remembering the code. On the first training occasion he only managed in one of the seven withdrawals whereas in the second he managed in three out of six. The occupational therapist used an errorless learning approach and stopped him immediately when he entered the wrong number and told him to consult his palm computer in which he had put his code. Subject 11 also had difficulties inserting the card correctly, four times during the first training occasion and once during the second. He explained to the occupational therapist that the card is inserted differently in his bank’s cash dispenser. Five times during the first training occasion Subject 11 stopped as if he did not know how to proceed. The occupational therapist then reminded him or asked him a question to help him get back on track.

Subject 11 displayed a rather neutral attitude towards training with the virtual cash dispenser.

3.3.2.3 Subject 12

Subject 12 quickly understood how the interface of the virtual cash dispenser worked and had no problems controlling it. However, she often failed to click objects or buttons due to the above mentioned calibration problem. Her performance on the activity of withdrawing money in the VE improved with time. However, four times during the first training occasion she had problems turning the card correctly. On three of these occasions, she solved the problem by herself. On the remaining occasion the occupational therapist had to intervene by asking her questions, thereby leading her to turn the card right.

On one occasion, Subject 12 tried to grab the money with her hand as it came out of the cash dispenser: "I thought it was real…" she commented, giggling.

Subject 12 displayed a rather positive attitude towards training with the virtual cash dispenser. When asked by the occupational therapist if she felt comfortable with the training she confirmed this. She also added that she usually has to repeat the code silently to herself when waiting in the queue of a real cash dispenser. Her point seemed to be that the virtual cash dispenser enables training under secure conditions.

3.3.3 Discussion

Overall, all seven subjects improved their performance on the activity of withdrawing money with the virtual cash dispenser and also became better at handling its interface. Nevertheless, difficulties were noted, especially for Subject 8. The problems were due to details that might be easy for able-bodied people to overcome, but difficult for a person with impaired cognitive ability. The largest problem of the subjects was understanding how to interact with the virtual objects. Four of the subjects tried to drag them, which suggests that this is a more intuitive way to move virtual objects. Nevertheless, it seemed our proposed point-and-click method was learnable, even if not perfectly intuitive. This is supported by the performance of the three subjects in stage III: they seemed to remember sufficiently well how to use it between the two training occasions. Furthermore, using point-and-click is supported by results from Pridmore, Hilton, Eastgate and Cobb [37]. In an experiment in which nine patients with stroke participated they compared two interaction techniques for touch screen: drag-and-drop and a variant of point-and-click. Not only did the subjects have less difficulties with point-and-click but also preferred it to drag-and-drop.

Many of the subjects' problems seemed to be due to unclear feedback from the VR interface. Relevant feedback is regarded as fundamental in the human-computer interaction literature [34, 45]. According to Norman [34], each action should result in an immediate and obvious effect, which was not always the case with the virtual cash dispenser. For example, nothing happened when the subjects tried to insert the card incorrectly. Subject 7 seemed to be especially confused by this. A better solution would be to let the card move to the card reader and then back, to let the user know he/she had made a mistake. Another feedback related problem was that the user could not initiate a new object movement if the object was already moving. This seemed to make it very hard for Subject 8 to build a sound mental model of the interaction method. The problem was remedied in the improved version of the virtual cash dispenser and the problem did not appear in stage III.

Feedback is clearly important, but what if an errorless learning approach is used (i.e. errors are avoided or minimized)? In this case it might be better not to show the patient the consequences of the faulty action. One alternative could be to make it possible to run the virtual cash dispenser in various modes that provide different amounts of feedback. For example, in the errorless learning mode it would only be possible to perform correct actions. This would allow for more tailor made training for patients with different cognitive impairments.

Subjects 7, 8 and 9 seemed to believe that an object was moved by first clicking on it and then on the location, even when the virtual object was placed in the invisible hand. This did not present any problems when the money or the receipt had to be put in the wallet. It did, however, create problems for Subject 8 when she tried to insert the bank card, since clicking on the card before the card reader made the card turn around. The root of the problem might be that the concept of the indivisible hand holding the virtual objects is unclear. One way to make it easier to for the user would be to include a virtual hand in the simulation that holds the virtual objects.

Subjects 7 and 8 clicked at different positions on the card, apparently believing that they could control the direction of the rotation in this way. This actually seems to be a much more intuitive way of rotating the card. For example, a click on the left part of the card would make it rotate to the left, as illustrated in Fig. 9. Norman [34] refers to this as natural mapping and suggests that it is an effective way to reduce the need for information in the user's memory.

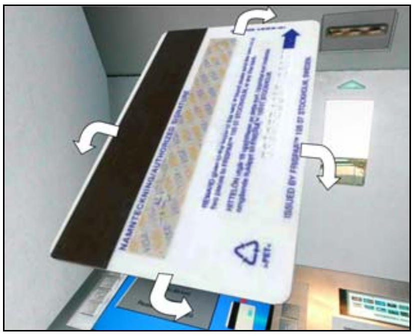

Figure 9. A more intuitive way to rotate the bank card

On a couple of occasions, Subjects 7 and 8 clicked on the 2D images of the bank card instead of the card itself. This might have been due to difficulties in discriminating 2D and 3D representations of objects from each other in a VE. This could be remedied with a stereoscopic display that provides more realistic depth perception [18]. The disadvantage of such a display is that it makes the VR equipment more expensive and more difficult to handle. Furthermore, the user needs to wear special glasses, which might be perceived as uncomfortable by some individuals. Nevertheless, the problem was not very frequent and did not seem to confuse the subjects to any larger extent.

Interestingly, what seemed to be a usability problem of the interface of the real *Sparbanken Finn* cash dispenser was observed. Six of the seven subjects clicked on the arrows on the display instead of the physical buttons (Fig. 8c). The reason for this could be that the arrows look like buttons usually do in *MS Windows* software. It is plausible, however, that this phenomenon also was partially due to the VR technology: a display is probably not perceived in the same way in a VE as in the real world. This highlights a possible disadvantage of VR training: it might sometimes be difficult to tell if a user's problems are due to the activity being trained or the VR technology.

Subjects 6, 7 and 8 tried to physically grab the virtual objects on a couple of occasions. This is very interesting since it suggests that they performed the activity approximately like they would have performed it in reality. There is good reason to believe that the touch screen was the reason for this. This is supported by results from a former study in which we compared mouse and touch screen in a kitchen VE [49]. We saw that the touch screen subjects tended to imitate the way things are done in real life. This supports using a touch screen for VR training in brain injury rehabilitation since the virtual activity resembles the real world activity.

Using a touch screen may have some disadvantages, however. For example, several studies have shown that the touch screen is more error-prone than other input devices [7, 30, 20, 36]. In the present study, the touch screen also caused many of the subjects' mistakes. However, the majority of the mistakes were due to the non-optimal calibration of the touch screen, a problem that would normally not appear with a carefully calibrated screen. Occasionally it also happened that the touch screen did not respond to the users' input. A touch screen built on capacitive technology was used and this technology requires the user to have sufficient electrical contact with the touch screen's surface. The response of a capacitive touch screen may vary due to the user's body size, ground path, or finger dryness and some people may therefore have problems giving input to the touch screen [13]. We have observed this problem in another study [49] and believe that the best way to avoid it is to use a touch screen built either with resistive or surface-wave technology since these types of touch screens do not require electrical contact between the screen surface and the user. Despite these disadvantages we believe the touch screen to be the preferred input device for applications like the virtual cash dispenser. Several studies have found the touch screen to be easier or faster to use than other input devices, despite the sometimes higher error rate [2, 9, 28, 44, 20].

The virtual cash dispenser can still be improved in several ways. For example, other types of sounds could be added to create a more realistic overall experience or to make the withdrawal activity more stressful. Examples include traffic sounds and sounds of people waiting in a queue. Subject 7 wondered how he could put away his wallet when the withdrawal was concluded. To give the user a feeling of closure, the wallet should automatically move off the screen. Another suggestion that came up in stage II was the possibility of throwing away the receipt. Furthermore, it should be easier to see exactly how much money comes out of the virtual cash dispenser. Currently this is difficult since the notes come out in a pile.

The virtual cash dispenser was developed using an iterative user-centred design approach. Our research group's competence in brain injury rehabilitation, occupational therapy, neuropsychology, VR, and human-computer interaction was used in the design process to make the virtual cash dispenser as usable as possible for the target group. We believe this to be the most suitable method for developing VEs for brain injury rehabilitation. In their comprehensive analysis of the VR rehabilitation field Rizzo and Kim [40] support this statement: "Applications need to be developed with strong multidisciplinary collaboration and with continuous user-centred input/evaluation methods." Seemingly very small usability problems can make a VE very difficult to use for a person with brain injury. Knowledge about cognitive impairments and guidelines from VR and HCI research are simply not enough to address usability problems like these. In order for VR training to be truly useful in brain injury rehabilitation, usability problems like these must be remedied. An iterative, user-centred design process, in which several professions collaborate, is probably the best way to do this.

4. Conclusions

Two studies addressing VR as a training tool for people with ABI were performed. Overall, the twelve subjects of the two studies managed to perform well in the two VEs despite their cognitive impairments. Study 1 provided further proof for the hypothesis that VR technology can provide a means for route learning in people with ABI. Transfer of training was not the objective of Study 2, but anecdotal evidence suggests that a transfer effect is also possible with the virtual cash dispenser. An occupational therapist observed Subject 10 as she made a withdrawal from a real cash dispenser before and after the VR training. Before training, Subject 10 had problems remembering her code. After training she performed a real withdrawal without any difficulties. Of course, this observation should be taken with a grain of salt as there are several other possible sources for her improvement.

Study 2 described the development and evaluation of a virtual cash dispenser to be used as a training tool in brain injury rehabilitation with special emphasis on interface issues. In general, the subjects managed to learn how to operate the virtual cash dispenser but the results also showed the need for improvements. Seemingly small usability problems in the interface of the VR tool could create big difficulties for the subjects. Due to time constraints, some suggested improvements from stage II were not implemented, for example the more intuitive way of rotating the card and the possibility of moving objects to the wrong place (e.g. the card to the money output slot). They will be implemented, however, in a new version of the virtual cash dispenser that is currently being developed with a more advanced VR developer's kit called *EON Studio*. This version will be used in a coming project called *E-learning for all*, which aims at developing Internet based VEs in which various everyday activities can be practised. The primary target groups are people with cognitive impairments, elderly people, people with dementia and other individuals who wishes to improve their performance on these activities to be able to lead a more independent life.

Subject 11 had substantial problems remembering his bank card code and used a palm computer to look it up if he was unsure. This illustrates how VR training could be combined with other rehabilitation strategies such as behavioural compensation strategies. In front of a real cash dispenser it would have been very difficult for Subject 11 to keep track of the cash dispenser, his wallet, his card and the palm computer at the same time. In line with this, Brooks and Rose [4] point out that "future research should be directed towards using a combination of VR-based memory training and behavioural compensation techniques." Another rehabilitation technology that can be combined with VR training is video feedback, which has shown great potential in the rehabilitation of patients with left visuo-spatial neglect [29]. In Study 2 the occupational therapist let Subjects 10, 11 and 12 watch the video material from the VR training afterwards. In this way they could see how they performed the withdrawals, what mistakes they made and could also review strategies that they had been taught by the occupational therapist during the VR training. As for route training, Brooks et al. [3] tried a backwards training method, which involved the subject walking backwards from the target location for a short distance and then walking forward to the target location again. The distance was gradually increased until it included the whole route. The subject carried out route training in this way both in a real environment and in a VE. The authors found the VE to be more suitable for the backwards training method since walking backwards in the real environment presented a potential danger to the subject, due to such things as other patients driving electric wheelchairs.

One of the most apparent advantages of VR training is the possibility to perform many training sessions in a relatively short time. Brooks et al. [3] found that a patient with amnesia benefited more from virtual route training than real world route training. The authors suggested the reason might be that the VE enabled a route to be performed many times without distractions. In Study 1 of the present paper, it took about 3.5 minutes on average for the patients to traverse the route in the VE and approximately 4.5 minutes in the real environment. A withdrawal with the virtual cash dispenser took approximately 1.5 minutes on average. Transport logistics, queues and unexpected events can make training with a real cash dispenser a rather time consuming activity. This suggests that VR training might provide a time efficient complement to conventional rehabilitation techniques. However, excluding the chaos and inconveniences of the real world also is a disadvantage. At the end of the day, the activity is to be performed in the real world and the patient needs to learn to adapt his/her behaviour to the ever changing demands of the surroundings. With current VR technology it is not possible to make exact simulations of the real world with all its complexity and randomness. It is possible that VR training is most suitable for the initial phases of rehabilitation when real world training might be too difficult and stressful for the patient. Strategies for combining VR training and real training in an optimal way should be the subject of future research.

Also from a technology point of view, the future for VR training in brain injury rehabilitation looks bright. For example, building VEs for outdoor route training has traditionally been a time-consuming task but the current trend towards building 3D cities will greatly simplify this. Today several companies such as *CyberCity AG* and *GeoSim Systems* offer highly detailed 3D city models. The prices and availability of such 3D cities will improve as the technology and methods for manufacturing them become more advanced. Furthermore, due to the popularity of 3D computer games more and more patients will have experience of 3D computer applications. For coming generations of patients with ABI, VR training will probably not be regarded with anxiety or suspicion, but rather as a natural part of the rehabilitation process.

In general, the subjects of the two studies demonstrated a positive attitude towards the VR training. They were engaged and seemed to enjoy it. There is good reason to believe that the patient's motivation is an important determinant of rehabilitation outcome [31]. Anecdotal evidence from one of the occupational therapists in the rehabilitation team of Subject 5 (28 years) revealed that Subject 5 had a rather negative attitude to the rehabilitation. However, the occupational therapist reported that he seemed more motivated after having participated in Study 1. One way to interpret this is that the VR training made the whole rehabilitation process seem more fun and exiting to him. The gaming factors of VR training is likely to have a positive effect on patients' motivation, a point which has been made by several other authors [4, 25, 40].

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A suggested virtual reality methodology allowing people with cognitive disabilities to communicate their knowledge and experiences of public transport systems

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III

A suggested virtual reality methodology allowing people with cognitive disabilities to communicate their knowledge and experiences of public transport systems

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Abstract. This paper presents a suggested methodology based on virtual reality (VR) technology that enables people with cognitive disabilities to communicate their knowledge and experiences of public transport systems. The users interacted with the VR system by verbally describing their actions to the person controlling the VR system and/or pointing with a laser pointer while seated in front of three screens on which the virtual environment (VE) was projected. A surround sound system was used to add realism. The users were video filmed as they took a virtual bus trip and were then asked to think aloud about their experience while watching the video material. The VR methodology was evaluated on seven people with stroke. Overall, the results suggested that the VR methodology is feasible for people with cognitive disabilities. Despite some initial difficulties, the subjects managed to communicate their intentions, some by combining verbalisations and pointing with the laser pointer in a very efficient manner. They were engaged in the virtual bus trip and made comments on the experience, including comments on emotional aspects. Interestingly, the subjects' verbal descriptions of what they wanted to do revealed in parts aspects of how they reasoned when taking the bus trip.

Keywords: virtual reality, cognitive disabilities, design, planning, public transport

1. Introduction

The political vision regarding the Swedish public transport system is that it should be accessible for all citizens by 2010, regardless of their physical and cognitive abilities. So far, most research on public transport accessibility has focused on people with physical disabilities e.g. [23]. The needs, possibilities and difficulties of people with cognitive disabilities have been given little attention in research. Achieving an accessible public transport system for this heterogeneous population is a complex task. The complete travel chain, defined as the events that occur while moving oneself from one location to another, must be considered [22]. All the links in the chain have to be accessible if the public transport system is to be considered accessible as a whole.

There are few examples of design guidelines on how to increase the accessibility of public transportation for people with cognitive disabilities. The problem with the few existing design guidelines, e.g. [50], is that they are unable to foresee all the difficulties that a person with cognitive limitations might encounter when using such a complex and dynamic system. There is clearly a need for other design methodologies. The philosophy of user-centred design advocates that the knowledge and experience of the user are crucial to achieve usability and accessibility [37]. However, it might be hard for users to give input to a design process due to difficulties they have in verbalising their knowledge and experiences, or due to the complexity of the design tools (plan drawings, CAD software, etc.). These difficulties obviously become magnified for users with cognitive disabilities. A desirable methodology would be to let the user experience the environment that is to be designed by directly interacting with it. But how can a person interact with an environment that only exists in the heads of the people planning it? The ideal situation would be to build the environment and carry out naturalistic observations of people with cognitive disabilities interacting with it, but this could be unreasonably expensive. What other alternatives are there? Let us paint a scenario:

> *John is 45 years old and lives in Lund, Sweden. He is a representative for* BrainPower, *a stakeholder organisation for people with cognitive disabilities. He has been invited to the transport system authorities of Lund municipality to discuss the latest proposal for new bus stops. Right now he is in the visualisation room with Lars and Katarina who are coordinating the project. The central part of Lund can be seen on three big screens around them. "Oh, now I see it. Let's go there!" John points at a bus stop at a corner of the main square. Lars moves the group over the square by pulling a joystick. John scans the bus stop but does not find what he is searching for. "Hmm… I'm not sure this is the right one. Which bus line is it? Can I go to the other side of the bus stop? Ah, number five. Now I see it!"*
>
> *Forty-five minutes later the meeting in the visualisation room is over. John has completed a bus trip in the virtual environment. Katarina has been taking notes that will be summarised in a document that will be discussed at the next meeting of the transport system authorities.*

Fig. 1. A virtual environment visualised with virtual reality technology

A methodology based on virtual reality (VR) technology allows John to experience a public transport system that does not yet exist in the physical world (Fig. 1). This enables him to communicate his knowledge and experiences through two communication channels:

1. His actions and behaviour while performing the task in the virtual environment (VE).
2. His verbal communication about his experience in the VE.

There is reason to believe that the first communication channel is the most valuable for people with cognitive disabilities, especially those with communicative dysfunctions such as expressive aphasia. Nevertheless, an individual's verbal communication about his experience in a VE may also be a feasible communication channel for some people with cognitive disabilities.

The present study is part of a larger research programme called "Accessibility in Public Transport for People with Cognitive Impairments – Survey, Methodological Development and Innovative IT Solutions". The programme is a collaboration between three departments at Lund University: Technology and Society, Health Sciences and Design Sciences. In the research programme, people with stroke have been chosen as the study population since 1) it is a big and growing group in Sweden, and 2) Riks-Stroke, the National Stroke Register, provides statistics on all stroke victims in Sweden [42].

1.1 Virtual reality

VR technology makes it possible to navigate and interact with three-dimensional, computer-generated environments. A 3D computer game is a good example of VR technology that uses modern computer graphics to create artificial environments of moving images and sounds that the players can interact with. There are several different types of VR technology and a basic distinction can be made between *immersive* and *non-immersive* VR systems. With an immersive VR system the user is partially or completely surrounded by the VE and perceives it approximately on a one to one scale. In a CAVE™ system the VE is projected on three screens and the floor, thus completely encompassing the user. The VE is usually projected in stereo which means that the user can perceive the VE with stereoscopic vision by wearing a special pair of glasses. Non-immersive VR systems use simpler technology. *Desktop VR*, for example, uses a standard desk-top computer that displays the VE on a standard monitor.

1.2 Virtual reality as a tool in design and planning

VR has shown potential in several different domains as a tool for involving users in a design process. The use of VR for participatory design of work environments has been investigated by several groups [2, 10, 55]. VR has also proven to be a useful tool for adaptation of workplaces and homes for people with physical disabilities [13]. Based on case studies of people with physical disabilities and occupational therapists, it was found that the VR tool could improve their understanding and encourage active participation. It has also been suggested that a 3D tool could enhance the involvement of the public in urban planning compared to traditional urban planning tools [1, 6].

We believe VR technology is a feasible tool for allowing people with cognitive disabilities to communicate their knowledge and experiences since it:

- makes it possible to simulate environments that do not yet exist or are difficult to access
- constitutes an arena for *doing, reflection* and *discussion*
- implements alternative design solutions in a relatively quick and inexpensive way
- makes it possible to experience an environment despite motor disabilities

Very few studies have been carried out in this area. Nevertheless, a group at Teeside University in UK is currently studying the use of VR to allow people with dementia to test outdoor environment designs. In a feasibility study the group examined fundamental issues such as user input, simulation fidelity and overall system usability [15]. The group has also presented preliminary results from an experiment in which 38 people with symptoms of mild to moderate dementia participated [52]. The subjects were rated as they performed walks in a virtual version of Middlesbrough town centre, visualized with an immersive VR system. The VE was then redesigned on the basis of the collected data before being tested again with subjects with dementia. Their performance improved, and the authors concluded that the VR-based method can be useful in the evaluation of outdoor environments and for identifying improvements for people with dementia.

In the *Virtual Bus Stop Project*, an immersive VR system was used as testing ground for design solutions in public transportation to it them more accessible, especially for people with cognitive disabilities [7]. The idea is that the users can reposition elements in a VE to their liking. The different design solutions can be saved and reloaded for further changes or discussion. The project group has not yet produced any empirical data from testing the method on people with cognitive disabilities.

The purpose of the present study was to explore the feasibility of a methodology based on VR technology that allows people with cognitive disabilities to communicate their knowledge and experiences regarding the public transport system.

2. Methods

The study was performed in two steps:

1. A discussion regarding different aspects of the VR methodology resulting in design considerations that served as a platform for step two.
2. A prototype for the VR methodology was evaluated in an experiment.

A reference group was involved in both steps. Its purpose was to provide input to the research process in the form of feedback and ideas. The group consisted of six people chosen for their competence in occupational therapy, cognitive disabilities, accessibility, architecture and public transport planning. Approval for the study was obtained from Lund University's Ethics Committee.

2.1 Introductory discussion of the features of the VR methodology

The discussion addressed features that were deemed crucial for a working VR methodology but also features thought to be desirable but not necessary. The research group, the reference group and other members from the larger research programme participated in the introductory discussion. A literature survey was also performed to gain better understanding of aspects of the discussed features.

2.1.1 Interaction with the VE

Interaction with a VE can be divided in two subtasks: navigation of the viewpoint and interaction with virtual objects. No matter how well designed, these two subtasks will inevitably increase the cognitive load on the user [3]. For people with cognitive disabilities this extraneous cognitive load might decrease their ability to concentrate on the task at hand. Several factors can negatively affect the interaction with the VE:

- Two input modes are needed: one for navigation of the viewpoint and one for interaction with objects. Some people might have problems separating the two.
- The interaction may be too abstract for some people. For example, some may find performing actions in a 3D environment with a 2D input device to be complicated.
- It might be hard to control an input device that requires fine-motor coordination. For example, a joystick might be hard to control for a person with motor limitations in his upper extremities.

We considered it of utmost importance that the user be able to perform actions in the VE as easily as possible. If the interaction was too complex it would be hard to tell if a problem was one of accessibility to the portrayed environment (e.g. problems locating the right bus stop) or if it was related to the VR interface itself (e.g. problems navigating the viewpoint). This would be a serious threat to the validity of a methodology based on VR technology. Furthermore, in an actual planning situation it would not be realistic to let the participant first practice VE interaction since this would be too time consuming. We thus decided that all interaction with the VE would be handled by another person. We came up with an interaction method that allows the user to interact with the VE by:

- verbally communicating his intentions to the person controlling the VR system and/or
- showing his intentions by pointing at the projector screens with a laser pointer

The use of an immersive VR system is another way to make it easier for the user to move around in the VE. Such a system offers a large field of view, which decreases the users' need to move since more of the VE is shown. In contrast, with a desktop VR system the user might have to rotate the viewpoint of the VR simulation to be able to see an object next to him.

2.1.2 Engagement, presence and immersion

There is good reason to believe that if a person feels engaged in a task to be performed in a VE, he/she will better be able to communicate his/her knowledge and experience. Likewise, it makes sense to assume that the level of engagement depends on the extent to which the person feels present in the VE. This is referred to as presence, defined as the subjective experience of being in the environment depicted by the VE [56]. If the user perceives the VE as very unrealistic or uninteresting then it would probably be harder for him/her to engage in the task. The ideal situation would be if the user performed and behaved as if in a real environment, but this cannot be achieved with current VR technology. Presence in turn, has been shown to depend on the level of immersion, which has been defined as "the extent to which the computer display is capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality" [47]. It has been shown that VR systems with large field of view provide a higher degree of presence [28, 46]. Hence, we decided that a large field of view system would be most suitable. Another way to increase the presence of the user is to display the VE in stereo [18]. However, we judged this to be unsuitable for the VR methodology since the effect of a stereoscopic display might be unpredictable in people with impaired visual perception. Spatialised sound has been shown to lead to higher presence than no sound or nonspatialised sound conditions [18]. Therefore, we decided that the VE should contain 3D sound that surrounded the user.

2.1.3 Risks for discomfort

Several side effects of VR use have been discussed in the literature, e.g. [32]. The one which we judged most likely to cause problems is simulator sickness, also referred to as cybersickness. It has been extensively discussed and is believed to be the result of conflicting input to the visual and vestibular senses [39]. Simulator sickness can induce a number of symptoms that are divided into three symptom groups: nausea, disorientation and oculomotor [24]. There are at least two reasons why the VR system needs to minimise the risk of evoking simulator sickness in the users:

- The effects of simulator sickness might be unpredictable in people with cognitive impairments due to stroke. It would be unethical to expose them to a system with a high probability of inducing simulator sickness.
- A person suffering from simulator sickness is likely to perform poorly and would not be able to optimally communicate his/her knowledge and experience.

Even though VR has been used for training and assessment of people with cognitive disabilities there is very little knowledge about simulator sickness in this population. Pugnetti et al. [38] found that patients with mild to moderate neurological impairments were not at an increased risk of side effects. However, the subjects were recruited from those with stable neurological conditions (e.g. no vestibular or severe cognitive disorders). Similar results were found in a study in which patients with Alzheimer's disease and stroke were exposed to a car simulator [43]. The neurologically impaired group did not differ from the able-bodied control group regarding sickness symptoms nor were they more likely to cancel the experiment.

Several studies have found a connection between field of view and simulator sickness, which speaks in favour of a low field of view system [11, 28, 46]. However, we considered the advantages (higher presence and easier interaction) to outweigh the risk for simulator sickness.

It has been found that when VE users have control of their movements, the severity of sickness symptoms are lower than when they have no control [33, 49]. On the other hand, for some novice users, this self-controlled navigation can lead to jerky and uncontrolled movements which could trigger simulator sickness. Once again, we considered the advantages of letting another person handle the VE interaction for the user (easier VE interaction) to outweigh the increased risk for simulator sickness.

Another factor that may increase the risk for simulator sickness is the use of a stereo display [12], which is why we decided not to use one. The presence of rotational movements in a VE has also been found to lead to significantly higher rates of simulator sickness [29]. Therefore, we decided to allow only yaw rotation of the viewpoint, i.e. it was only possible to rotate to the left and right. The position of the user can also affect the risk for simulator sickness: sitting appears to be better [26, 40], which is why we decided that the user should sit on a chair during the interaction with the VE.

2.2 The experiment

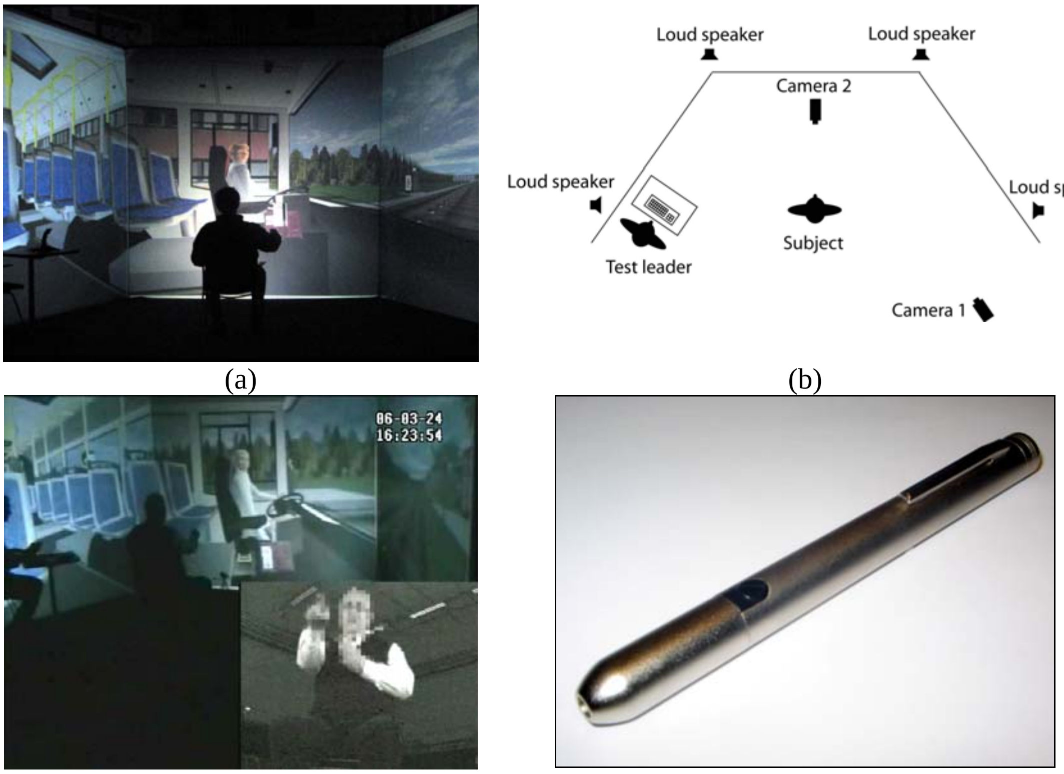
The introductory discussion resulted in five research questions that were to be addressed in an exploratory experiment:

1. How does the user understand and perceive the VE?
2. How does the communication work between the user and the person controlling the interaction with the VE?
3. What risks for user discomfort does the VR methodology present?
4. What is the user's subjective experience of the VR methodology?
5. How does the user reflect upon what he/she experienced in the VE?

Questions 1 to 3 deal with aspects in the VR methodology that are judged to be *crucial* to achieving a working VR methodology, while questions 4 and 5 address aspects that are *desirable* but *not necessary*.

2.2.1 Material

The VR hardware chosen was a back-projection system consisting of three *Barco* CRT projectors (800 ANSI Lumens) and three projector screens, each 3 x 3 metres (Fig. 2a-b). The resolution of the projected image was 800 x 800 pixels. The system was capable of covering approximately 180° of the user's horizontal field of view. Two video cameras were used to capture the actions of the subjects when performing the task in the VE. Camera 1 recorded an overview of the VR system from behind, and was placed in such a way that the subject did not cover the middle screen where most of the events took place. Camera 2 recorded a close-up of the subject (Fig. 2b). The two camera signals were mixed using a video quad mixer (Fig. 2c). Wearable microphones were used to record the comments of the subject and the test leader.



(a) (b) (c) (d)

Fig. 2. The VR system, mixed camera signals and laser pointer

The scenario of the VE had to meet the following requirements:

- Offer the subject a task to solve that generated interaction between the subject and the VE. The task complexity had to be carefully chosen so as not to be too easy or too hard.
- Offer occasions for both navigation of the viewpoint and interaction with objects

After discussing and rejecting various scenarios, it was decided that a bus trip would be built, a sufficiently complex task that involves both navigation (e.g. transporting oneself to the bus stop) and interaction with objects (e.g. pushing the stop button of the bus). The following scenario was chosen:

> *The subject wants to take the bus from his flat to a café. To do this he/she has to take bus number 11 to the city centre and transfer to bus number 1. The subject has a virtual wallet containing a bus card.*

The VE was made up by a small city centre with a square (Stortorget) and two small residential areas (Smedby and Norrliden). Bus lines 11 and 1 went in a loop and made four and five stops respectively (Fig. 3). Both bus lines had two end stations as indicated in Fig. 3. All bus stops were equipped with a bus sign and a timetable, and two of them had shelters (Fig. 4a and 4b). There were also bus stops for two bus lines that were not operating. The purpose was to create more visual clutter in the VE. The two buses were modelled after the city buses of Lund (Fig. 4c). They were equipped with a card reader, a ticket machine (Fig. 4d), a number of stop buttons and a display showing the name of the next bus stop (Fig. 4e), which was also read out loud by a pre-programmed female voice. The 3D bus driver was static but turned his head towards the doors when they opened (Fig. 4d). He carried out basic communication using expressions such as *Hello*, *Yes*, *No*, *Ok*, *Please put your bus card in the card reader* and *Please turn the card around*. The test leader controlled the bus driver's communication. When the user went onboard the bus, a wallet with a bus card appeared in front of the card reader (Fig. 4d). Each bus had a couple of passengers represented by static 3D models (Fig. 4e). Part of the scenario was that a passenger sometimes pushed the stop button, whereupon the bus stopped and the doors opened. The VE also contained five human characters that walked around outside along predefined tracks (Fig. 4f). The participant's movements and interaction with objects as well as the events in the VE were controlled by the test leader using a joystick and a keyboard. The joystick was programmed to allow forward/backward movements, left/right movements and left/right rotation. It was also possible to make slow up/down movements. The speed of the movement and the rotation could be controlled with a lever on the joystick.

It has been shown that the speed of translational movements in a VE significantly affects symptoms of simulator sickness [48, 31] and so we chose rather slow navigation speeds. The walking speed in the VE could be varied between approximately two and five km/h and the maximum speed of the buses was approximately 30 km/h. The VE contained ambient sounds (city noises and birds singing) and the bus had engine, doors, stop buttons and ticket machine sounds. All the bus sounds were spatial, i.e. they seemed to come from the virtual object and became weaker with distance. The software used to develop the VE was *EON Studio 5.5* and *3D Studio Max 6.0*.

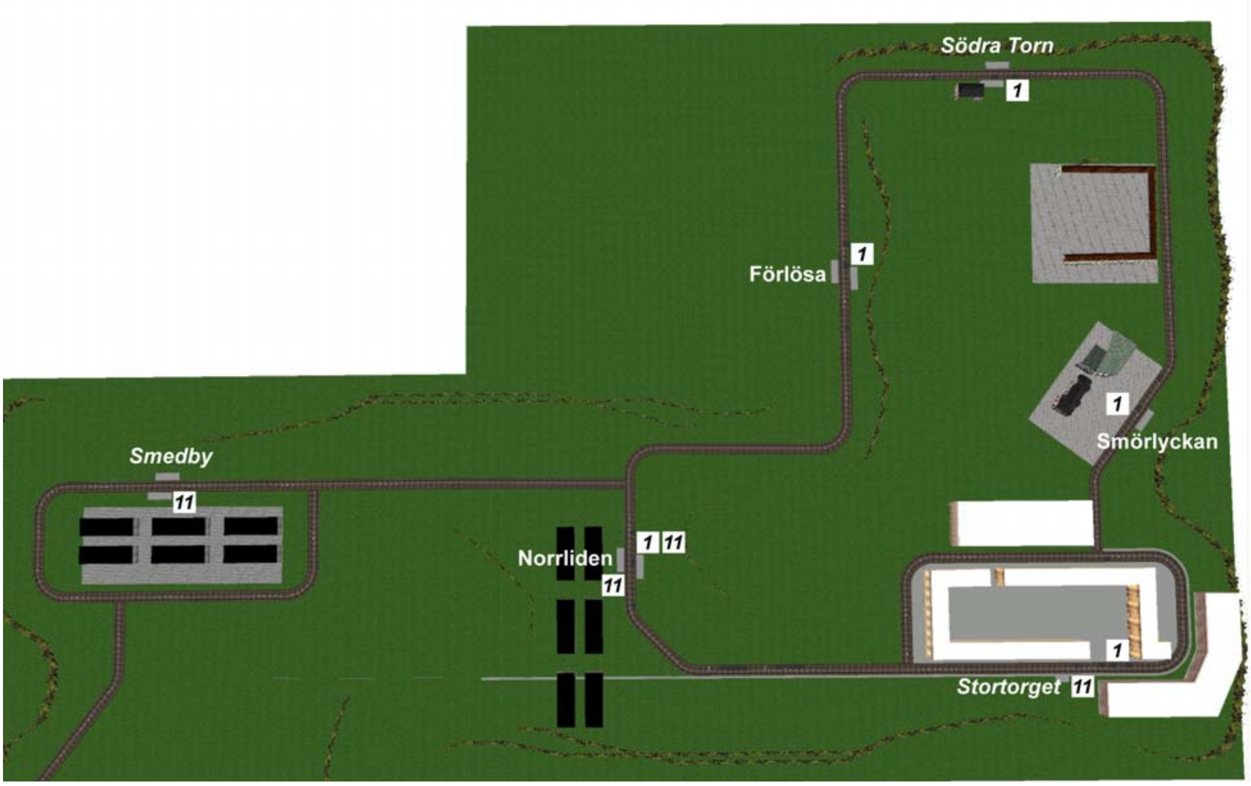


Fig. 3. Overview of the VE and its two bus lines. The numbers indicate the stops of each bus line. The end stations are italicised.

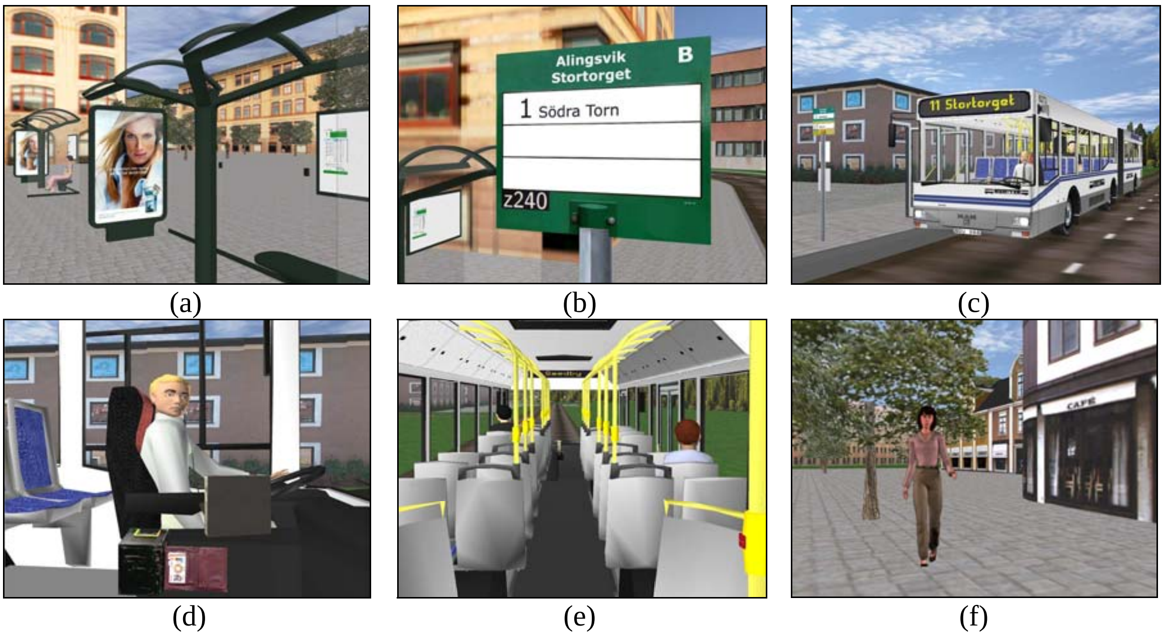


Fig. 4. Screen shots from the VE

2.2.2 Subjects

Purposeful sampling was used to select subjects for the experiment. According to Patton [36], the idea behind purposeful sampling is to select information-rich cases from which one can learn a great deal about issues of central importance to the purpose of the study. Seven people who had experienced a stroke between 2002 and 2005 participated. All had been assessed with *Cognistat*, a commonly used instrument for screening cognitive function [27]. They had also been assessed with a newly developed instrument targeting self-reported cognitive functional limitations [54]. Three subjects had no measurable cognitive impairment. They were included to learn how a person with personal experience of a stroke but without any measurable cognitive impairment would experience the VR methodology. The other four subjects were selected to have their most salient cognitive impairment in attention, memory, language or spatial ability, and little or no in the other cognitive domains (Table 1). The logic behind this sampling was our judgement that these four cognitive domains have the greatest effect on a person's abilities to handle the VR methodology. Furthermore, the cognitive impairment of the subject was not to be so severe that he or she could not travel independently by bus. The following two inclusion criteria applied to all 7 subjects:

- Did not easily become car sick (due to the risk for simulator sickness)
- Had adequate vision to watch TV

Table 1. The participants

Subject	Sex	Age	Most salient cognitive impairment
1	Male	68	None
2	Male	72	None
3	Female	58	None
4	Female	50	Attention
5	Female	50	Memory
6	Female	56	Language
7	Female	58	Spatial ability

2.2.3 Procedure

The subject sat on a chair in front of the projector screens during the trial. The test leader sat on a chair to the left of the subject with the joystick and keyboard placed on a little table in front of him (Fig. 2b). A second researcher was present during to assist the test leader with the observation equipment. The subjects performed actions in the VE by telling the test leader what they wanted to do. The subjects also had a laser pointer (Fig. 2d) that could be used to show intention by pointing at the projector screens. Before the experiment started, the subject's informed consent was obtained. The test leader then informed the subject about the scenario and instructed them in how to perform actions in the VE. The subject was also told that he had a wallet with a bus card inside and that the date and time in the VE was the same as in reality. The subject was given a piece of paper with written information about where to go with the two buses, so that subject performance would be independent of the ability to remember the instructions. If the subject got stuck, the test leader would provide help in three steps: 1) a verbal clue, 2) a verbal and a visual clue, 3) performing the task necessary for the subject to move on.

Directly after the virtual bus trip, the subject was asked to comment on his thoughts and feelings during the bus trip while watching the video material on a 28 inch TV. This technique is called retrospective think-aloud and is frequently used as a tool for uncovering cognitive processes in for example usability testing, [14]. Although it has been questioned [45], there is recent evidence that the retrospective think-aloud protocol can be valid and reliable [17]. The reason we excluded concurrent think-aloud, in which the participant verbalises his/her thought while performing the task, was that the act of verbalisation has been shown to interfere with task performance [45, 51]. This effect could be exacerbated in people who are extra sensitive to extraneous cognitive load due to cognitive disability. The test leader also asked questions from an interview guide while the subject was watching the video. The guide contained a battery of questions for each of the five research questions. The retrospective think-aloud session was video recorded in the same way as the virtual bus trip.

A trial run was conducted before the actual experiment in order for the test leader to practice and to make adjustments in the VR methodology. Four people participated, two able-bodied and two with stroke. The trial run resulted in some improvements of the VE and some changes in the experimental set-up.

2.2.4 Analysis

The video material was analysed using an observation schedule in which the bus trip was broken down into five steps (from the subject's home to the café). Observations were included from both the virtual bus trip and the retrospective think-aloud session. The observation schedule for each of the five steps was made up of five columns: one describing the subject's actions in the VE (e.g. "The subject enters the bus."), one for each of research questions 1-3, and one for miscellaneous observations (Table 2). There was also a place to jot down reflections on the observations. The data from the retrospective think-aloud session were transcribed using reformulation and concentration, and grouped according to the relevant research question in the observation schedule. In this way, the recordings from the observations and the think-aloud session could be easily analysed in parallel. The remaining two research questions regarding desirable but not necessary aspects of the VR methodology were recorded in two columns on a single sheet. All the data were then read through several times to provide an overview. Colour coding was used to create themes within and between the seven subjects.

Table 2. Observation schedule of step 1 of the bus trip (with pseudo results)

Step 1: Walking from the apartment to the bus stop of bus number 11

	What actions is the subject performing?		**How does the subject understand and perceive the VE?**		**How does the communication work between the subject and the person controlling the interaction with the VE?**		**What signs of discomfort does the subject show?**		**Misc.**
	Observation	Reflection	Observation	Reflection	Observation	Reflection	Observation	Reflection	
The virtual bus trip	S. walks to the bus stop. Walks up to the timetable and studies it.		S. doesn't see the bus when it's arriving.	This is probably due to the attention deficit of S.	S: "Ok, I'll walk to the bus stop." T.L.: "Would you like to point out where you want to go, please?" S.: "I want to go there" [pointing at the bus stop with the laser pointer].		When the viewpoint starts to move S. says, "Oh!" She shows no signs of discomfort, however.	S. is a bit surprised?	In the beginning S. sits silently for about 20 seconds.
Retrospective think-aloud	S.: "Then it took a little while before I realized that I had to check the timetable."		S.: "I heard the bus but I couldn't see it."		T.L.: "What was it like to describe what you wanted to do and point with the laser pointer?" S.: "In the beginning I was a bit unsure of what I had to do. Once I understood it, it became easier."				S.: "My first thought was, 'How do I get to the bus?'"

3. Results

Subject 1

Subject 1 had no cognitive impairments and reported taking the bus approximately 1-2 times in a three month period. He reported having a fair deal of computer experience, but no experience of interactive 3D computer graphics. Overall, he completed the bus trip without difficulties, and the only problem was that he had to turn the bus card three times before he could correctly insert it into the bus card reader.

How does the subject perceive and understand the VE?

Subject 1 did not seem to have any problems with this. However, he failed to detect the stop button on both buses during the trip. He also pointed out during the think-aloud session that he should have checked more carefully how to insert the bus card in the bus card reader: "There were small arrows (on the bus card) that I noticed after a while."

How does the communication work between the user and the person controlling the interaction with the VE?
Subject 1 used the laser pointer a bit in the beginning of the experiment but then stopped using it completely. When asked about this during the think-aloud session he could not explain why. However, his verbal communication was clear so it was easy for the test leader to understand what actions he wanted to perform. He commented during the think-aloud session that it took him a while before he grasped how things should be done in the VE, but that it went fine once he understood. When he was going to disembark bus number 11, he had problems verbalising in a clear way that he wanted to exit through the middle door. Still, it was easy for the test leader to understand since Subject 1 pointed behind him with the laser pointer. On a couple of occasions, he used verbalisations containing the words “there” and “here”, while at the same time pointing with his finger: “I assume that I should go over there [pointing at the bus stop] where the buses are coming.” This worked well and the test leader had no problems understanding what he was pointing at. When Subject 1 was going to pay with his bus card, and when he was going to push the stop button, he expressed what he wanted to do but also showed with very expressive hand gestures. For example, when he said that he wanted to take out his wallet, he made a movement that illustrated how he took out the wallet from his breast pocket. When asked about this behaviour during the think-aloud session he explained that the VE “looked realistic.”

On one occasion, when approaching a bus stop sign, Subject 1 said that he wanted to stop a couple of metres from it. However, the test leader moved the view closer to the sign anyway, perhaps because he thought the view was too far from the sign for Subject 1 to read it. During the think-aloud session the subject stated that he felt that he was in control but added that there was a noticeable time delay between his request to exit the bus and it actually happening in the VE:

> *S: When I said, “Now I’m standing up,” it took some time before something happened.*
> *TL: How did you perceive this delay?*
> *S: I was a bit unsure as to what would happen.*
> *TL: And when you got used to it?*
> *S: Once I understood, there was no problem.*

This delay was due to the fact that the test leader was too busy handling the bus to be able to move the view to the bus exit.

What risks for user discomfort does the VR methodology present?
Directly after the virtual bus trip, Subject 1 spontaneously commented that he felt dizzy. He made a grimace when bus 11 was doing a 90 degree turn and also commented spontaneously three times during the think-aloud session that he experienced the turning of the bus as very unpleasant.

What is the user’s subjective experience of the VR methodology?
The fact that Subject 1 used hand gestures when paying for the bus trip and when pushing the stop button could be indications that he experienced presence. Another indication is that he seemed to acknowledge the bus driver as a social actor. He returned the driver’s greeting on one occasion. On another, he was unsure if he was on the right bus and considered asking the bus driver. Subject 1 seemed to have a rather positive attitude to the VR methodology and described it as being “surely really good” during the think-aloud session.

How does the user reflect upon what he experienced in the VE?
Subject 1 had no problems to think-aloud about the bus trip afterwards. He pointed out that the bus stop names were not printed on the bus stop sign of bus 1: “Being an inexperienced bus traveller, I didn’t know if the bus was going to Smörlyckan or not.” He also commented that he would have liked to get a transfer ticket (which he did not get) when he paid for the first bus trip.

Subject 2
Subject 2 had no cognitive impairments and reported never taking the bus. He had no computer experience at all and no experience of interactive 3D computer graphics. He managed to carry out the

bus trip and the only problem that appeared was that he needed three attempts to put the bus card in the bus card reader.

How does the subject perceive and understand the VE?
Subject 2 did not seem to have any problems with this. However, he did not detect the stop button during the first bus trip even though it was fully visible on the left screen.

How does the communication work between the user and the person controlling the interaction with the VE?
Subject 2 initially described his actions too vaguely, for example, when he entered bus 11: "Going in there. Then I pay with the plastic card. Then I have bought a ticket, registered my card and then I sit down." After having been informed by the test leader again he quickly understood how to perform actions in the VE. He used the laser pointer throughout the whole experiment, often in combination with short sentences containing the words "that", "here" and "there." However, on a couple of occasions he pointed with the laser pointer without using its laser function, which made it difficult for the test leader to understand what he was pointing at. Subject 2 also made hand gestures on two occasions to demonstrate his actions when turning his bus card and pressing the stop button. When he had paid his ticket on bus 11, he forgot to say that he wanted to put away his wallet. When he said that he wanted to exit bus 11, it took some time before something happened, but he showed no signs of being disturbed by this. When asked during the think-aloud session if he felt he was the one controlling his actions, he answered affirmatively.

What risks for user discomfort does the VR methodology present?
Subject 2 showed no signs of discomfort during the experiment.

What is the user's subjective experience of the VR methodology?
Subject 2 returned the bus driver's greeting when entering the bus, which could be an indication of presence. However, he did not answer when the bus driver said, "Thanks," after he had paid for his ticket. The fact that he used hand gestures is also a possible indication of presence. When asked during the think-aloud session if he reached out for the stop button spontaneously he answered affirmatively. Subject 2 seemed to have a positive attitude to the VR methodology. He commented twice during the think-aloud session that it was a "comfortable trip" and also said that it was a good and stimulating experience.

How does the user reflect upon what he experienced in the VE?
Subject 2 had no problems commenting on his experience of the bus trip during the think-aloud session. On one occasion he commented that there was no information in the bus card reader describing how the bus card should be rotated. He also pointed out twice that there was no zebra crossing at Stortorget.

Subject 3
Subject 3 had no cognitive impairments and reported taking the bus approximately 1-2 times in a three month period. She had some computer experience but no experience of interactive 3D computer graphics. She managed to complete the bus trip and only had a slight problem paying for the first bus trip: she failed at first to correctly insert the bus card in the bus card reader, but succeeded on the second attempt.

How does the subject perceive and understand the VE?
On two occasions, Subject 3 seemed to have problems with this. She did not see bus 11 as it arrived at the bus stop at Smedby even though it was clearly visible on the left screen. During the think-aloud session, she commented that she could hear it but not see it, and that she could not explain why. She also commented that she had some problems perceiving the inside of the bus: "When I had to turn around in the bus when disembarking… it felt strange. I didn't understand what it actually looked like." On one occasion, Subject 3 used the laser pointer just as she would her finger to help her keep her place when reading the time table.

How does the communication work between the user and the person controlling the interaction with the VE?
Subject 3 had no problems communicating her intentions to the test leader. She expressed herself clearly and used the laser pointer throughout the experiment. When she was paying with her bus card, she also showed with hand gestures how she wanted to turn it. The few communication problems noted were actually due to the test leader who failed twice to notice that Subject 3 pointed with the laser pointer and hence misunderstood her intentions. Interestingly, despite her seemingly effortless communication Subject 3 reported that it was difficult to understand how to behave at the beginning of the bus trip.

Subject 3 commented during the think-aloud session that she felt that it was a bit difficult to reach the timetables: "Normally I would walk all the way up so that I could see them, but here I felt that I didn't control (the movements) quickly enough." This was because it took some time for the test leader to move the view to a comfortable distance from the timetables, something he did slowly to avoid simulator sickness. Another example of slowness appeared when Subject 3 said she wanted to stand up to walk to the exit door; it took a while for the test leader to perform this action. This did not seem to bother her, though, and during the think-aloud session she said she felt that she had control over her actions once she "Got the hang of it."

When Subject 3 was looking for the Smedby bus stop, the test leader unconsciously helped her:

> *S: Bus number 11 it says there.*
> *TL: Yes [with neutral intonation].*
> *S: Then I assume that I should stay here at the bus stop and wait for the bus. TL: Yes [with positive intonation].*

Subject 3 was thinking aloud and the test leader appeared to confirm through his intonation that her reasoning was correct.

What risks for user discomfort does the VR methodology present?
During the think-aloud session Subject 3 commented that she felt slight discomfort: "You know, it felt like I was actually moving with the bus… also physically."

What is the user's subjective experience of the VR methodology?
On two occasions, Subject 3 commented that it felt strange and mentioned a feeling of insecurity four times during the think-aloud session: "It's a feeling of unreality I have all the time. I get a bit unsure of things I wouldn't normally think about if I was in a real environment." She commented that she did not think like she usually does when out in the real world, and described the VE as unreal and deserted.

Subject 3 showed some signs of experiencing presence in the VE. During the second bus trip she asked the bus driver a question with a voice that sounded like she was speaking with a real person. She also answered the bus driver when he said "Hi" and "Thanks." Another clear sign of presence was that Subject 3 was a bit unsure on how to enter bus 1, since she experienced that the entrance was very high, even if the VE did not impose any restrictions on movements. Her use of hand gestures could also be a sign of presence.

Overall, Subject 3 seemed to have a positive attitude towards the VR methodology. During the think-aloud session she said that the concept of the VR methodology is good, but that the user probably has to do it several times to be able to participate fully. She also mentioned that it is important that the user understand what is expected of him/her.

How does the user reflect upon what she experienced in the VE?
Subject 3 could think-aloud about the bus trip without any problems. She commented that she had problems inserting the card in the bus card reader: "It could have been because I didn't see the arrows (of the bus card). I was concentrating on the magnetic strip, since I am used to it."

Subject 4

Subject 4 had no cognitive impairments according to Cognistat, but her occupational therapist judged her to have impaired attention. According to the instrument targeting self-reported cognitive functional limitations, she had difficulties in the following areas: orientation to time; orientating in the room; remembering planned activities; remembering heard, read or seen information; mental calculations; reading and writing; focused attention; ability to do things simultaneously; verbal comprehension; ability to talk and express herself; concentration. She reported that she takes the bus a couple times a month. Her computer experience was almost nonexistent and she had no experience of interactive 3D computer graphics. Overall, Subject 4 managed to complete the bus trip, but failed twice before correctly putting the bus card in the bus card reader.

How does the subject perceive and understand the VE?

Broadly, Subject 4 had no problems with this, but could not detect the stop button onboard bus 11, even though it was fully visible on the left screen. During the think-aloud session she explained that she only looked for it on the right side of the bus: “The left side did not exist for me.” During the think-aloud session she commented that she had problems reading the time tables and therefore used the laser pointer to help her keep her place when reading them.

How does the communication work between the user and the person controlling the interaction with the VE?

On the whole, Subject 4 managed to communicate her intentions well, but had some problems in the beginning. She sat quietly and passively for 20 seconds. After getting information from the test leader she sat quietly for a little while longer. She commented during the think-aloud session that she was thinking: “Oh my, how should I go about getting to the bus stop?” In the beginning she also described her actions too vaguely, but ceased to do this after having been informed by the test leader. On several occasions, she used sentences containing the words “here”, “there” and “that” as she pointed with the laser pointer, for example, when walking up to a time table at Stortorget: “Now I want that one closer to me [pointing at the timetable]. And that I want large... [pointing at the list of bus stops in the timetable].” Subject 4 made hand gestures when inserting the bus card in the bus card reader. When asked during the think-aloud session if she felt that it was herself or the test leader who had control over her actions, she answered that she felt like somebody else was in control when she had to handle the bus card.

What risks for user discomfort does the VR methodology present?

Subject 4 related during the think-aloud session that she felt dizzy on one occasion when the bus was turning.

What is the user’s subjective experience of the VR methodology?

Subject 4 commented several times that she was very concentrated during the experiment: “You cannot just enter the bus by habit, pressing the button and so on. Here, you suddenly had to think more.” Furthermore, she had a very concentrated facial expression during the whole bus trip. When the test leader asked how it was to think back on the bus trip and talk about it she answered: “Then I was so concentrated, now I can see more clearly. And I see some of my mistakes, how I was thinking. […] Now it’s concrete, now I know.”

On two occasions during the think-aloud session, Subject 4 commented that she “was inside it,” which could be interpreted as a sign of presence. Another was that she showed signs of anxiety when she could not find the stop button onboard bus 11. During the think-aloud session she explained that she felt a bit of panic for not getting off the bus. The hand gestures she made could also be an indication of presence.

In general, Subject 4 seemed to have a positive attitude to the VR methodology and commented during the think-aloud session that she experienced its purpose as important.

How does the user reflect upon what she experienced in the VE?

Subject 4 thought aloud about her experience in the VE in a satisfactory way. She revealed that she felt panicky when she could not find the bus 11 stop button, and that she just wanted to get off the bus.

When she reached the stop for bus 1 at Stortorget, she was unsure if bus 1 was going in the direction of Smörlyckan and explained that she was confused when she saw "Södra Torn" (the other end of bus line 1) written on the bus stop sign. She pointed out that it would have been easier to understand if "Smörlyckan" had been written somewhere on the sign. She also commented that all the signs in the VE should have been larger.

Subject 5
Subject 5 had cognitive impairment in three areas according to Cognistat: severe memory impairment, mild spatial ability impairment and mild similarities (logic) impairment. According to the instrument targeting self-reported cognitive functional limitations, she had difficulties in the following areas: orientation to time; remembering planned activities; remembering heard, read or seen information; reading; ability to do things simultaneously; concentration. She takes the bus regularly, but always in company since she cannot manage on her own. She reported that she has some computer experience and has played 3D computer games a couple of times. She managed to complete the bus trip but needed three attempts before she was able to correctly put the bus card in the bus card reader. She failed to find the right bus stop for the transfer since she misunderstood the bus stop sign, whereupon the test leader had to intervene by giving her a verbal clue.

How does the subject perceive and understand the VE?
Overall, Subject 5 had no problems with this except on two occasions. When bus 11 arrived at the bus stop, she showed no signs of seeing it even though it was clearly visible on the left screen. She was unable to detect any of the stop buttons aboard bus 11, but commented that she knew that there was a stop button somewhere close to her.

How does the communication work between the user and the person controlling the interaction with the VE?
On several occasions, Subject 5 expressed herself too vaguely. A good example was when she wanted to push the stop button on bus number 1:

> *Bus voice: Smörlyckan.*
> *S: Mm, I'll take that one.*
> *TL: What do you want to do?*
> *S: I want to exit the bus at Smörlyckan now.*
> *TL: How do you want to do that?*

Despite repeated reminders from the test leader, Subject 5 continued to describe her actions vaguely. She tried to use the laser pointer only twice when she wanted to press the stop button. She asked if it was the button of the laser pointer she had to press, which indicates that she had not understood its purpose. She also had problems pressing it. Despite these difficulties, her communication with the test leader worked acceptably. When asked during the think-aloud session what it was like to convey her actions, she answered that the test leader "Got what I meant." A strategy she used on several occasions was a sentence with the word "there" in combination with pointing. This worked satisfactorily, even though she was pointing without using the laser pointer. However, on a couple of occasions it was hard for the test leader to see what she was pointing at. Subject 5 also used hand gestures when she was explaining how she wanted to rotate the card, which made it easier for the test leader to understand her intentions. When asked if she felt that she or the test leader had control over her actions in the VE she answered, "Why, nobody else had control over what I did!"

What risks for user discomfort did the VR methodology present?
On one occasion when the view rotated 90 degrees, Subject 5 exclaimed: "Oh, how awful this is!" and closed her eyes for a second. When the test leader brought this up during the think-aloud session she explained: "It was an animated image. One experiences it differently in real life."

What is the user's subjective experience of the VR methodology?
Broadly, it seemed like Subject 5 experienced a certain degree of presence in the VE. A graphic example of this is when she just had paid with her bus card:

> *TL: Do you want to put away your bus card?*
> *S: No, first I sit down. I always sit down before I put down my card, so I won't fall. I can do that when I am sitting down.*

Even though she was sitting safely on a chair in reality, she wanted to find a virtual place to sit as quickly as possible, just as she would have done on a real bus. She answered the bus driver when he talked to her. Her use of hand gestures was also an indication of presence. However, when asked how the virtual bus trip felt compared to a real one she answered that it felt artificial. Furthermore, she described the VE as very calm. In general, Subject 5 seemed to have a rather neutral attitude to the VR methodology. She commented that, "It's the right thing to do," but also added that, "It mustn't remain in the computer world because then it won't be of any use."

How does the user reflect upon what she experienced in the VE?
Subject 5 managed fairly well to think-aloud about the virtual bus trip while watching the video material. However, on two occasions she did not remember events from the virtual bus trip that the test leader asked her about. When paying on bus 11 she explained that she always tells the bus driver where she wants to go:

> *S: I still haven't understood if it matters if I say where I have to go.*
> *TL: You say that you want to go to Smörlyckan?*
> *S: Yes. But I have never understood….they just say 'Ok, fine!'*
> *Bus driver: Ok!*
> *S: Yes, just like him!*

She also commented that she never understands how much money is taken from the bus card and that she sometimes forgets to press the stop button.

Subject 6
According to Cognistat, Subject 6 had mild cognitive impairment in three areas: comprehension (language), repetition (language) and memory. According to the instrument targeting self-reported cognitive functional limitations she had difficulties in the following areas: orientating in the room; remembering heard, read or seen information; focused attention; ability to do things simultaneously; ability to talk and express herself; concentration. She reported taking the bus very seldom. She has some computer experience but no experience of interactive 3D computer graphics. All in all, Subject 6 managed to carry out the virtual bus trip in a good way but failed three times to correctly insert the bus card in the bus card reader on bus 11. On one occasion she also had problems reading a timetable.

How does the subject perceive and understand the VE?
Subject 6 had no problems with this.

How does the communication work between the user and the person controlling the interaction with the VE?
In the beginning of the experiment Subject 6 seemed a bit unsure as to what she was expected to do: "Am I supposed to talk or..?" After this initial confusion she started to communicate her intentions in a clear way by combining verbalisations and pointing with the laser pointer. She also made hand gestures when paying on both buses. On a couple of occasions it was cumbersome for her to point with the laser pointer and make hand gestures at the same time. She also forgot to say that she wanted to put her wallet away when she had paid for her ticket on bus 1. She repeatedly used sentences containing the words "here", "there" as she pointed with the laser pointer, which proved to be an effective way for her to communicate her intentions. When asked how she experienced her movements

in the VE, Subject 6 answered that they were a bit slow and that it took time to do things compared to in the real world.

What risks for user discomfort does the VR methodology present?

On no less than six occasions, Subject 6 made non-verbal sounds like "Phew" and "Gee" which could be signs of discomfort. This occurred both when she was walking around and when she was sitting on the bus. She brought this up during the think-aloud session:

> *S: I was a bit dizzy.*
> *TL: Would you like to develop that a bit?*
> *S: A somewhat unpleasant feeling. But it's not like I feel nauseous.*

Subject 6 also pointed out on two occasions that she sometimes felt that the bus was driving on the pavement, which she experienced as unpleasant.

What is the user's subjective experience of the VR methodology?

Subject 6 showed clear signs of experiencing presence in the VE. She commented that she experienced the VE as a "recording" in the beginning, but that it became "more and more real" during the experiment. The clearest indication of presence was when she asked the driver of bus 1 a question. She used a very formal voice and sounded like she was talking to a real person that she had never met before. Another indication was the following comment from the think-aloud session: "Why, I knew that the bus driver knew where I had to go!" When entering bus 11 she also said: "I can sit close to the bus driver so that I can talk with him if something goes wrong." Furthermore, the hand gestures she made could be an indication of presence. During the think-aloud session, Subject 6 pointed out that the bus felt deserted and that there should have been more passengers. On one occasion she described the VE as being "a bit empty."

Subject 6 showed a very positive attitude to the VR methodology and described it in the following way: "Extraordinary! I think it could help a lot of people."

How does the user reflect upon what she experienced in the VE?

Subject 6 had no problems to think-aloud about her experience in the VE. She commented when entering bus 1 that she wanted so sit behind the bus driver since it made her feel safe. Interestingly, when she tried to get to the right bus stop at Smedby, her reasoning emerged clearly from her descriptions of her actions:

> *S: Then I have to figure out what side I should wait on, so I guess I have to go to the bus stop. Now I don't know where I am, so I guess I have to go there [points at the stop for bus 11]. Now I have to stop. "Stortorget" it says there. Then I have to stay here until the bus arrives. But I don't know when it will arrive so we have to go there [points at the timetable].*

Subject 7

Subject 7 had a moderate spatial ability impairment according to Cognistat and also a mild memory impairment. According to the instrument targeting self-reported cognitive functional limitations, she had difficulties in the following areas: outdoor spatial orientation; remembering planned things; remembering heard, read or seen information; planning; mental calculations; reading; focused attention; ability to do things simultaneously. She reported that she takes the bus very seldom and does not like doing so. She has some computer experience but no experience of interactive 3D computer graphics. She managed to complete the bus trip but needed three attempts to correctly insert the bus card in the bus card reader. On one occasion she also had problems reading a timetable.

How does the subject perceive and understand the VE?

Subject 7 commented that it was hard to see the numbers of the buses. She also pointed out that reading the timetables was different compared to real life since she could not use her finger to help her keep her place. Instead, she used the laser pointer like a virtual finger, which seemed to facilitate her reading to some extent.

How does the communication work between the user and the person controlling the interaction with the VE?
In the very beginning of the experiment, Subject 7 sat quietly and passively for approximately 20 seconds. During the think-aloud session she said that she, “Sort of didn’t know what was going on,” and that she felt very unprepared as to what would happen even though she had been informed in advance. Once she got started, she described her actions too vaguely but gradually provided more detailed descriptions after being instructed by the test leader. She used the strategy of combining sentences containing the words “there” and “here” with pointing with the laser pointer several times during the experiment, which proved an effective way for her to communicate her intentions.

When waiting for bus 1 at Stortorget, Subject 7 stood with her back to the road for several minutes. The test leader brought this up during the think-aloud session:

> *TL: Why do you think you didn’t turn around before?*
> *S: I actually don’t know. I would have done it in real life, for sure. [...] It feels a bit strange and artificial to say, ‘Now I turn towards the bus.’ It’s not ideal that I have to tell you that I want to turn around.*

When Subject 7 told the test leader that she wanted to exit the bus, it took 10 seconds before something happened since the test leader was busy controlling the bus. Subject 7 showed no signs of being disturbed by this, and when asked if she felt that it was she or the test leader who controlled her actions, she answered that she felt that she decided herself.

What risks for user discomfort does the VR methodology present?
On a couple of occasions, Subject 7 showed signs of discomfort by saying “Phew” or by leaning her head back and shutting her eyes. During the think-aloud session, she described that she felt dizzy “when there were movements” and very dizzy when the bus was turning. She compared it to the experience of standing up in a real bus and also pointed out that it was good that she was sitting down since she probably would have fallen to the ground otherwise.

What is the user’s subjective experience of the VR methodology?
Directly after the experiment, Subject 7 commented that she experienced the VE as realistic. The test leader brought this up during the think-aloud session:

> *TL: Just after you finished the bus trip, you said that you experienced it as real. Could you go into detail about this, please?*
> *S: Yes, I was worried about all these things to keep track of. The change of bus, whether I would make it in time or not, keeping track of the time, putting myself on the right side of the street. That was a bit stressful: “Is this right? Am I on the right bus? Did it say 1 or 11?”*
> *TL: If you compare this with the experience of taking a real bus, what similarities and differences did you perceive?*
> *S: I think this was very realistic. […] I took the bus to Copenhagen some months ago, and then I partially got the same sensation as now.*

The fact that Subject 7 experienced the same sensation as when riding a real bus is an indication that she felt present in the VE. Another it that she answered the bus driver when addressed by him. Subject 7 commented that during a real bus trip the acceleration and breaking would frighten her very much, but that she did not have to think about this during the virtual bus trip since she knew deep inside that she was sitting safely on a chair and that nothing bad could happen.

Subject 7 seemed to have a rather positive attitude to the VR methodology. However, she pointed out that there is no getting away from the fact that it is an artificial world and not reality.

How does the user reflect upon what she experienced in the VE?
Subject 7 managed to think-aloud about the virtual bus trip in a good way. She said that during real bus trips she has problems turning the bus card right and difficulties choosing between two bus stops opposite each other. She also pointed out that she lost track of things in the VE when she had to divide her attention between the timetable and her wristwatch. When asked if the same thing could have happened to her in real life she answered affirmatively. Furthermore, she commented that there was very little space between the columns in the timetable making them hard to read.

Subject 7 made several comments about her emotional experience of events from both real bus trips and from the trip in the VE. She pointed out that the act of inserting the bus card is very stressful and commented that she would have been afraid of the acceleration and braking during a real bus trip. Furthermore, she said that keeping track of everything during the virtual bus trip caused her worry and stress. She also commented that she became very nervous and spastic in her left side when she was waiting for bus number 1.

4. Discussion

The results suggest that the VR methodology contains the crucial aspects addressed in research question 1-3. To a large extent, it also includes the desirable, but not necessary, qualities of research question 4 and 5. All seven subjects managed to complete the bus trip in the VE. Only on one occasion did the test leader have to intervene, which was when Subject 5 could not find the right bus stop. Several problems in performing the bus trip, mainly due to the portrayed environment and not to the VR methodology, could be observed. The three most apparent problems were: inserting the bus card in the card reader, finding the right bus stop for the transfer and reading the timetables.

How does the subject perceive and understand the VE?
Broadly, the subjects had problems perceiving or understanding the VE on just a few occasions. Four subjects were unable to find a stop button even when at least one was clearly visible on the projection screens. For Subject 4, it could very well be due to her attention impairment. The other three subjects, however, did not have attention problems and it is more likely that the difficulty lies in the VR system. The absence of binocular depth cues could have made it more difficult for the subjects to discriminate the stop buttons from the background due to difficulties to discriminate differences in depth [20]. This can be solved by providing binocular depth cues by using a stereoscopic display, thus enhancing the user's depth perception. The disadvantage is that the effects of such a display might be unpredictable in some people with impaired visual perception.

Subjects 1 and 3 commented that they did not initially see the arrows on the bus card. The VR system projectors were rather outdated and had relatively low resolution (800 x 800 pixels) and brightness (800 ANSI Lumens). It was a bit hard to perceive details on objects unless the view was very close. This problem will most likely diminish with the use of modern projectors, capable of projecting images with considerably higher resolution and brightness. Subjects 6 and 7 had problems reading the timetables, and it is possible that this was also due in part to the low resolution and brightness of the projectors. Nevertheless, the main reason for Subject 7's difficulties was most likely her spatial problems. She commented that it was different reading the virtual timetable compared to a real one since she could not use her finger to facilitate the reading. However, she and two other subjects used the laser pointer as visual aid when reading the timetables, which might have partially compensated for the absence of a finger.

In summary, all subjects appeared to understand and perceive the VE sufficiently well. Some difficulties were noted which eventually could be by remedied by using modern projectors and a stereoscopic display.

How does the communication work between the user and the person controlling the interaction with the VE?
All subjects managed to communicate their intentions to the test leader in a satisfactory way, but all of them experienced initial difficulties. These disappeared rather quickly, but indicate that the VR methodology would benefit from including an initial training session. The fact that Subjects 5 and 7 seemed to have problems remembering or understanding the test leader's instructions also speaks in

favour of such an introductory training. It could be integrated into the rest of the bus trip, for example, by starting out in the user's virtual flat. The task of the user would be to prepare for the bus trip by shutting down the radio, turning out the lights and carrying out other such virtual activities.

One strategy used by five subjects was sentences containing words like "here", there" and "that" combined with pointing with the laser pointer. This proved an effective way to communicate since the subjects did not need to provide precise descriptions of their actions. An interesting comparison can be made with a study by Oviatt [35] in which speech-only input to an interactive computer map was compared with speech and pen based input. The author found that "The combined use of pen and voice actually was faster, less error-prone, and input involved less complex linguistic expressions," and suggested that this was largely due to "people's difficulty articulating spatially-oriented descriptions." This suggests that the combination of verbal communication and pointing with a laser pointer is a suitable interaction technique in this context, since it reduces the need for accuracy in the user's expressions, thereby reducing his/her cognitive load. Basically, the user does not even need to know the name of things: "Put that [pointing at the bus card] there [pointing at the bus card reader]" would do fine. People also seem to prefer multi-modal over uni-modal interaction, especially in spatial tasks [35]. All together, this indicates that our suggested interaction method would be particularly suitable for users with language impairment. The two subjects who used the laser pointer very little or not at all also took advantage of this strategy, but pointed with their finger instead. This suggests that any type of pointing is an intuitive way of interacting with a VE. The problem that arose when Subject 5 used her finger was that it was difficult for the test leader to understand exactly what she was pointing at.

Another strategy used by five of the subjects, was hand gestures that described the actions they wanted to perform. The gestures made it easier for the test leader to understand how the subjects wanted to do things, such as rotating the bus card. It has been suggested that the more present people feel in a VE, the more likely they will behave like they would in the corresponding real environment [20]. Hence, a high degree of presence can facilitate the communication between the user and the person controlling the VR system since the user is likely to make hand gestures. On one occasion, the laser pointer limited Subject 6 in making hand gestures. Subject 5's problems pressing the button of the laser pointer could be due to flawed ergonomics. Despite these drawbacks, the laser pointer facilitated the communication of the subjects to the extent that it should be part of the VR methodology.

Four of the subjects' descriptions of their actions were too vague. Three of them started to offer more detailed descriptions when instructed by the test leader, but Subject 5 continued to describe her intentions in very general terms to the end of the bus trip. It is quite possible that her memory problems caused her to forget the instructions she received before the experiment. The test leader asked her to be more specific with phrases like, "What do you want to do?" and "Please describe how you want to do that." This actually worked satisfactorily even though Subject 5 did not use the laser pointer. Nevertheless, there might be a risk that the person controlling the VR system unconsciously helps the subject when encouraging him/her to describe his/her actions. The test leader gave hints to Subject 5 a couple of times. The test leader also unconsciously helped Subject 3 on one occasion through his intonation, which shows how important it is that the person controlling the VR system communicates in a very neutral manner.

Three of the subjects felt their actions were performed slowly in the VE, which was a bit confusing. The problem was due to task overload of the test leader and the time it took him to execute the movements smoothly. This slowness could make it harder for some people with cognitive disabilities to understand the "rules" of the VE. One solution would be to let two test leaders control the VE: one handling the navigation, the other the events in and the interaction with the VE.

Five of the seven subjects felt they were in control of their actions even though they did not give direct input to the VR system. This indicates that our proposed interaction method in general make the users feel in control.

To sum up, all subjects managed to communicate their intentions on what they wanted to do in the VE in an acceptable manner, even if some initial difficulties were noted. The laser pointer seemed to facilitate the subjects' verbal communication by reducing the need for accuracy in their verbalisations.

What risks for user discomfort does the VR methodology present?

Four subjects reported feeling dizzy. They also showed signs of discomfort by sighing or shutting their eyes. The majority of the symptoms appeared when the view was rotated, above all when the bus was turning. This is consistent with the findings of Lo and So [29] that rotational movements in a VE significantly increase simulator sickness symptoms. Even if the movements of the virtual buses were carefully designed, the buses turned faster than a real bus would, since they did not have any inertia. It is probably a good idea to make them turn quite slowly to minimise the risk for simulator sickness symptoms, at the expense of realism. Another possible source of simulator sickness is the fact that the subjects did not have direct control over the movements in the VE [33, 49]. Very few indications of simulator sickness were observed when the subjects were walking around in the VE, however. Furthermore, when the apparent advantages of letting somebody else control the input device are taken into account, this potential drawback seems acceptable.

Subject 3 did not report dizziness or nausea but mentioned feeling as if she was also physically moving with the bus, which evoked a slight feeling of discomfort. This indicates that she might have experienced vection, i.e. the sense of actual self-motion in physically stationary observers [19]. Large fields of view are more likely to induce vection than narrow ones [4], and the vection experienced by Subject 3 should not come as a surprise. Vection is a double-edged sword since it might lead to increased presence as well as increased simulator sickness and/or postural sway [19]. Subject 7 commented that it was fortunate that she was sitting down or she probably would have fallen, and it is possible that other subjects also experienced vection and/or postural sway without reporting it. Considering this, it seems a very good idea that the user is seated when interacting with the VE.

In summary, none of the subjects experienced discomfort to a degree that they could not complete the bus trip. Nevertheless, dizziness was reported and the main cause seemed to be the turning of the buses. Accordingly, it seems a very good idea that the user is sitting down.

What is the user's subjective experience of the VR methodology?

All seven subjects seemed to experience a certain degree of presence in the VE. IJsselsteijn [20] makes a distinction between physical presence (the sense of being physically located in a VE) and social presence (the feeling of being together with someone in a VE). One of several ways to measure presence is to look for behavioural indicators. The idea is that the more a participant feels present in a VE, the more similar his/her responses will be to those he/she would exhibit in the corresponding real environment [20]. All subjects showed signs of experiencing physical presence through their behaviour and/or comments. In particular, the very spontaneous hand gestures made by Subject 1 when paying for the bus trip seemed to indicate physical presence. Signs of physical presence could also be seen in the verbalisations of the subjects. For example, Subject 3 said that she did not know if she could get on the bus, since the step seemed very high. Subject 5 expressed eagerness to sit down before putting her wallet away, even though she was already sitting safely on a chair. Interestingly, despite experiencing physical presence in the VE three subjects also described it as being "artificial", "unreal" or "like a recording." Indeed, the VE had an artificial appearance compared to a modern 3D computer game: the materials of the virtual objects were not photorealistic and the buses did not move in a completely realistic way. The sound also lacked realism. There were for instance no differences between the sound environments. Three subjects described the VE using adjectives like "calm", "deserted" or "desolate." Indeed, the VE had very little of the dynamics of a real environment. There were no cars, just a couple of virtual characters and relatively few sounds. Nevertheless, the VR experience seemed to induce a certain degree of physical presence in all the subjects. As for social presence, the subjects tended to refer to and treat the bus driver as a real person, despite the lack of realistic appearance and behaviour. This was particularly evident in Subjects 3 and 6, who addressed the bus driver in polite and well-articulated voices. It is likely that the ability to maintain a simple dialogue with the bus driver contributed largely to the fact that the subjects treated him like a real person. Garau et al. [16] investigated the responses of people to virtual humans in an immersive VE. The results suggested that, "on some level people can respond to virtual humans as social actors even in the absence of complex interaction," which means that fairly simple virtual people like the bus driver might be sufficient for this purpose.

A VR system such as the one used in the present study might be too cumbersome to use in an actual planning context. Its three projector screens are 3 x 3 metres each and the mirrors used to project the image also require a fair amount of space. However, modern VR systems can be made much more compact and it is likely that they will be even more so in the future. The question is if a VR system with smaller screens and smaller field of view can make the user feel engaged enough to reflect upon what he/she experienced in the VE. Several studies have shown that there is a relationship between the level of immersion of a VR system and presence [28, 46]. Furthermore, it is reasonable to believe that presence is a causal factor of engagement. The level of engagement in the VE most likely affects the extent to which the user can make associations to his/her previous knowledge and experiences. It is possible that smaller screens also could generate a sufficient degree of presence, but the horizontal field of view probably needs to remain large for several reasons. First, research has shown that the horizontal field of view correlates with presence, e.g. [28]. Second, a small field of view is likely to render the user's spatial orientation and navigation worse [41, 44], which might be a threat to the validity of the VR methodology since it is hard to judge if a disorientated user is the result of an insufficiently designed environment or the small field of view.

The user's attitude to a tool is an integral part of most definitions of usability, e.g. [21, 30]. Judging from their behaviour and comments, all subjects had a neutral or positive attitude to the VR methodology. It is important to consider possible effects of subject bias, however. Being in a sensitive life situation due to stroke, the subjects might have felt flattered by the attention from the research group, thereby unconsciously trying to help the experimenter obtain good results. Nevertheless, it is fair to say that all the subjects at least accepted the VR methodology.

To sum up, the VR system and the VE seemed to be able to engage the subjects in the bus trip. In addition, the subjects seemed to have a rather positive attitude to the VR methodology.

How does the user reflect upon what he/she experienced in the VE?

All seven subjects commented on their experience of performing the virtual bus trip, mainly during the retrospective think-aloud session but to some extent during the bus trip itself. The subjects' verbalisations included comments on problems they had during the virtual bus trip, things in the VE that could be improved and reflections over earlier experiences of bus trips. The retrospective think-aloud protocol in combination with the interview guide seemed to work sufficiently well. Nevertheless, Subject 5 had difficulties discussing some of the events since she did not seem to remember them, which illustrates that the retrospective think-aloud protocol might be problematic for people with memory impairments. Interestingly, the subjects' verbal descriptions of what they wanted to do also occasionally revealed how they reasoned in carrying out the bus trip. This was particularly evident in Subjects 6 and could be described as a sort of concurrent think-aloud. Results from a study by van den Haak et al. [51] suggest that concurrent and retrospective think-aloud are comparable in terms of quantitative output, but different in how this output comes to light. In concurrent think-aloud, more problems were detected through observations of the participants' behaviour, while the retrospective think-aloud identified more problems that were not observable, but could only be detected through the participant's verbalisations. Therefore, having both these think-aloud protocols as part of the VR methodology would be an advantage since they seem to complement each other.

Interestingly, three of the subjects also made comments about their emotional experience of the events in the VE. Most notably, Subject 7 explained several times during the think-aloud session that she became worried and stressed by all the things she had to keep track of during the bus trip. The affective dimension of design has gained considerable attention lately in several areas such as product design [25] and human-computer interaction [8]. The underlying assumption is that negative affects, like confusion, nervousness and anger, can make it harder to perform even easy tasks [34], and it is possible that this effect is enhanced in some people with cognitive disabilities. With this in mind, the VR methodology could make it easier for planners to understand the emotional experiences of people with cognitive disabilities related to public transport. This is supported by results from a study on personal safety issues at railway stations by Cozens et al. [9]. 47 respondents experienced a railway station environment through a VR system and were then asked about their personal safety concerns. The respondents were also asked for suggestions on improvements of the railway station that they felt could increase their perceived personal safety. The authors concluded that VR technology can make it possible to "better understand the experiences and perceptions of the users of built environment facilities as they might relate to crime and fear of crime."

Subject 4 commented that the VR methodology made it possible for her to see her own mistakes during the virtual bus trip, and Subject 7 mentioned that it could help her to build up her courage before performing a real bus trip. There is an increasing amount of evidence that less advanced VR systems such as desktop VR can also offer effective training for people with cognitive disabilities, e.g. [5, 53]. With some modifications it is thus possible that the VE could be used as a training tool in a brain injury rehabilitation context.

In summary, all subjects commented on their experience of performing the virtual bus trip. The comments also concerned emotional aspects. The retrospective think-aloud (combined with the semi-structured interview) worked satisfactorily, and somewhat surprisingly the subjects' descriptions of what they wanted to do revealed in part how they reasoned in carrying out the different steps in the bus trip.

5. Conclusions

In general, the VR methodology worked satisfactorily with regards to the crucial aspects addressed in research questions 1-3, which suggests that it can be a feasible methodology for allowing people with cognitive disabilities to communicate their knowledge and experiences. None of the subjects had any major problems perceiving and understanding the VE. However, four of them had difficulties detecting the stop buttons onboard the bus, possibly since the VR system did not provide any binocular depth cues. All subjects managed to communicate their intentions to the test leader in a satisfactory way. However, the verbal communication of some subjects was initially deficient, requiring encouragement from the test leader to make them verbalise their intentions more accurately. An efficient strategy used by several subjects was to combine words like "here", "there" and "that" with pointing with the laser pointer. This allowed them to use very simple verbal descriptions, which is likely to have reduced their cognitive load. Six of the subjects experienced some sort of discomfort, mainly dizziness. Most of the discomfort appeared when the bus was turning. Even though the discomfort was not severe enough to keep the subjects from completing the virtual bus trip, this problem must be considered.

The results suggest that the VR methodology also worked well with regards to the desirable, but not necessary, aspects addressed in research questions 4-5. All subjects showed indications of presence and engagement in the virtual bus trip. They all made reflections over their experience of the virtual bus trip, some of which addressed their emotional state during the bus trip. An unexpected advantage of the suggested VR methodology was that the subjects' verbal descriptions of what they wanted to do also occasionally revealed how they reasoned to perform the bus trip.

The results also revealed improvements in the VR methodology that should be considered:

- A short training session in the VE before the virtual bus trip.
- Make the VE more vivid to create a more realistic overall impression.
- Let two people control the VR system to minimise the risk that the participant's communication is misunderstood.
- Slow the buses down to decrease the risk for simulator sickness.
- Use modern projectors in order to achieve brighter images with higher resolution.
- Use a laser pointer with a button that is easy to press.

In a subsequent study, we will investigate if and how the VR methodology can be used to elicit the knowledge and experiences of professionals with expertise in the field of cognitive disabilities. A group of occupational therapists will perform a virtual bus trip while thinking aloud about accessibility issues with regards to people with cognitive disabilities. Four people with cognitive disabilities will then test the improved VR methodology by taking a virtual bus trip and thinking-aloud afterwards about accessibility issues. By comparing the knowledge and experiences collected from the end-users and the occupational therapists, we hope to learn even more about the nature of the VR methodology.

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A virtual reality methodology for eliciting knowledge about public transport accessibility for people with acquired brain injury

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IV

A virtual reality methodology for eliciting knowledge about public transport accessibility for people with acquired brain injury

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Abstract

Purpose. To evaluate a methodology based on virtual reality (VR) technology for eliciting knowledge about public transport accessibility for people with acquired brain injury (ABI).
Method. Four subjects with ABI and four occupational therapists each made a complete bus trip in a virtual environment. Think-aloud protocols were used to elicit their knowledge about public transport accessibility issues for people with ABI.
Results. All participants managed to handle the VR methodology and contributed knowledge about public transport accessibility for people with ABI. The most relevant knowledge from the ABI participants concerned concrete accessibility problems, emotional aspects and strategies. The direct observations of the ABI subjects led to the identification of some problems but revealed very little about what caused them. Instead, the causes of the problems came to light through the verbalisations of the ABI subjects. The most relevant knowledge from the occupational therapists concerned concrete accessibility problems and suggested solutions.
Conclusions. The concept of first carrying out actions in a virtual environment and then reflecting over these actions seems to be a very good way of eliciting knowledge about public transport accessibility for people with ABI. The knowledge elicited from people with ABI and from occupational therapists illuminates, in part, different aspects of public transport accessibility and hence is complementary.

Keywords: *virtual reality, acquired brain injury, design, planning, public transport, expert knowledge*

1 Introduction

By 2010, the Swedish public transport system should be accessible for all citizens, regardless of their physical and cognitive abilities, according to a decision taken by the Swedish parliament. Several different methods have been used to investigate the problems people with disabilities might encounter in a public transport system. For example, Iwarsson, Jensen and Ståhl [1] examined the use of the critical incident technique during participant observation to assess the accessibility of public bus transport. Such a methodology, however, is only applicable to existing environments. What if the public transport system is still in the planning stage? This would require a methodology not dependent on existing public transport. Carlsson [2] used focus group interviews to explore usability problems in public transport as perceived by 20 people with physical disabilities. Although attempts have been made to run focus groups with elderly people having age-related declines in cognitive abilities [3], such a methodology would probably prove too difficult for many people with cognitive impairments due to acquired brain injury (ABI). A desirable methodology would attempt to elicit knowledge about accessibility for this population by letting them directly experience the planned public transport system. Virtual reality (VR) technology provides a means for such a methodology since it allows the creation and visualisation of three-dimensional environments with which a user can interact.

1.1 Using VR to elicit the knowledge and experiences of people with cognitive disabilities

The use of VR to elicit the knowledge and experiences of people with cognitive disabilities is a largely unexplored area of research. The only known effort so far, with the exception of our own research, is a collaborative project between the University of Teesside and Durham University in the UK that studies the use of VR to allow people with dementia to test outdoor environment designs. The findings suggest that VR-based methodology can be useful in the evaluation of outdoor environments and for identifying improvements for people with dementia [4]. Our own research group has recently investigated the feasibility of a methodology based on VR technology that enables people with ABI to communicate their knowledge and experiences of public transport accessibility through their:

- actions and behaviour while performing the task in the virtual environment.
- verbal communication about their experience in the virtual environment [5].

The VR system was composed of three screens on which the virtual environment was projected. Seven people with stroke performed a complete virtual bus trip, including a transfer (Figure 1). The subjects performed actions in the virtual environment by verbally describing them to the person controlling the VR system and/or pointing with a laser pointer. We chose this interaction method since we wanted to make it as easy as possible for the subjects to perform actions in the virtual environment. Part of the VR methodology was also to elicit the subject's verbal communication about the virtual bus trip. This was done by letting the subject watch a video recording of the trip while thinking aloud about his/her experience. Overall, the results indicated that our suggested VR methodology is feasible for people with ABI. The proposed model for performing actions in the virtual environment worked satisfactorily. Moreover, the subjects could relate the virtual bus trip to their knowledge and experiences of public transport accessibility; they all made reflections over the virtual bus trip, some of which addressed their emotional state during the trip. Interestingly, the subjects' verbal descriptions of what they wanted to do revealed in parts aspects of how they reasoned when taking the bus trip. The experiment also revealed issues in need of improvement.

Figure 1. The user is transferring to the second bus in the virtual environment [5].

1.2 Using the VR methodology to elicit expert knowledge

Bengtsson et al. [6] have investigated the use of a 3D tool for the planning of production, working and residential environments, an activity usually involving many occupations. The authors argue that: 'The quality of the solutions would be increased if a better dialogue could be created, implying that a broader spectrum of knowledge, experience and skills be manifested in planning discussions'. In view of that, we decided to investigate if and how the VR methodology could be used to elicit the knowledge of professionals who are experts on people with ABI. Could occupational therapists, for example, provide a more complete image of the problems experienced by people with ABI in public transport? According to Schön [7], most professionals know more than they can put into words. An occupational therapist might find it difficult to share his/her knowledge and experiences of the accessibility problems of people with ABI through interviews or focus groups. To directly experience the environment and reflect over its accessibility through recollections of past cases might be a better approach. Could this be possible with the VR methodology? Picture the following scenario:

> *Eva has worked as an occupational therapist on a neurological unit for 10 years. She has been invited to the transport system authorities of Lund municipality to discuss the purchase of new city buses. Right now she is in the visualisation room with Lars and Katarina who are co-ordinating the project. A bus approaching Lund central station can be seen on three screens around her. 'Ok, so now I want to enter the bus' Eva says, whereupon Lars moves the view into the bus with a joystick. 'What strikes me at first is that there is no information on the card reader describing how to insert the bus card. A lot of my clients would find this difficult'. She inserts her bus card and then takes a seat. She looks around in the bus as it pulls away from the bus stop: 'The display that shows the name of the next bus stop is easy to understand but I am pretty sure a lot of people will have difficulties finding the stop buttons'.*
>
> *An hour later the meeting in the visualisation room is over. Eva has completed a bus trip in the virtual environment while making comments about the accessibility of the new city bus model for people with ABI. Katarina has taken notes that will be summarised in a document that will be discussed at the next meeting of the transport system authorities.*

We argue that the VR methodology can be used to elicit an occupational therapist's knowledge in at least two ways: 1) by making a virtual bus trip and/or 2) by watching a person with ABI make a virtual bus trip.

The purpose of the present study was to address the following three research questions:

RQ1: How does the VR methodology work for occupational therapists?

RQ2: How does the VR methodology work for people with ABI?

RQ3: What type of knowledge can be elicited with the VR methodology?

2 Method

As already described, the VR methodology was found to work satisfactorily in the pilot study but there were details that needed to be improved [5]. Initial difficulties for the subjects were observed, and so the improved VR methodology included a short training session allowing the subjects to become acquainted with the VR methodology before the virtual bus trip. The training session was integrated with the rest of the bus trip by taking place in the subject's virtual flat (Figure 2a) and lasted for approximately five minutes.

The training tasks included clearing the table turning off the radio, and picking up one's wallet. Another important lesson from the pilot study was that some of the subjects experienced dizziness, which is a symptom of simulator sickness [8]. Most of the dizziness appeared when the bus was turning and as a result, the speed of the buses was reduced by approximately 20%. Moreover, some subjects described the virtual environment using adjectives such as 'calm' and 'deserted', which pinpointed the need to make the virtual environment more vivid to create a more realistic overall impression. This was done by adding more passengers to the buses (Figure 2b) and more human characters walking around outside. Otherwise, the virtual environment was the same as the one used in the pilot study. It contained some built environment and two bus lines, bus 1 and bus 11, which went in loops (Figure 3). The buses and the bus stops were modelled after the city bus system of the Swedish town of Lund (Figure 2b). The buses were equipped with a card reader, a ticket machine (Figure 2c), a number of stop buttons and a display mounted over the aisle showing the name of the next bus stop (Figure 2d). The next bus stop was also announced by a pre-programmed female voice. The bus drivers (Figure 2c) were able to carry out some basic communication, which was controlled by the test leader.

The method for interacting with the virtual environment was the same as in the pilot study. It allowed the subjects to perform actions in the virtual environment by:

- verbally communicating their intentions to the person controlling the VR system and/or
- showing their intentions by pointing at the projector screens with a laser pointer.

It is of utmost importance that the user be able to perform actions in the virtual environment as easily as possible. Interacting with a virtual environment inevitably increases the cognitive load on the user [9]. For people with ABI this extraneous cognitive load might decrease their ability to concentrate on the task at hand. As a result, it could be hard to tell if a problem was one of accessibility to the portrayed environment (e.g. problems locating the right bus stop) or if it was related to the VR interface itself (e.g. problems navigating the viewpoint). This would seriously compromise the validity of the VR methodology. A more practical reason for making the interaction as easy as possible is the time constraints of an actual planning situation: it must be possible to use the VR methodology without extensive training.

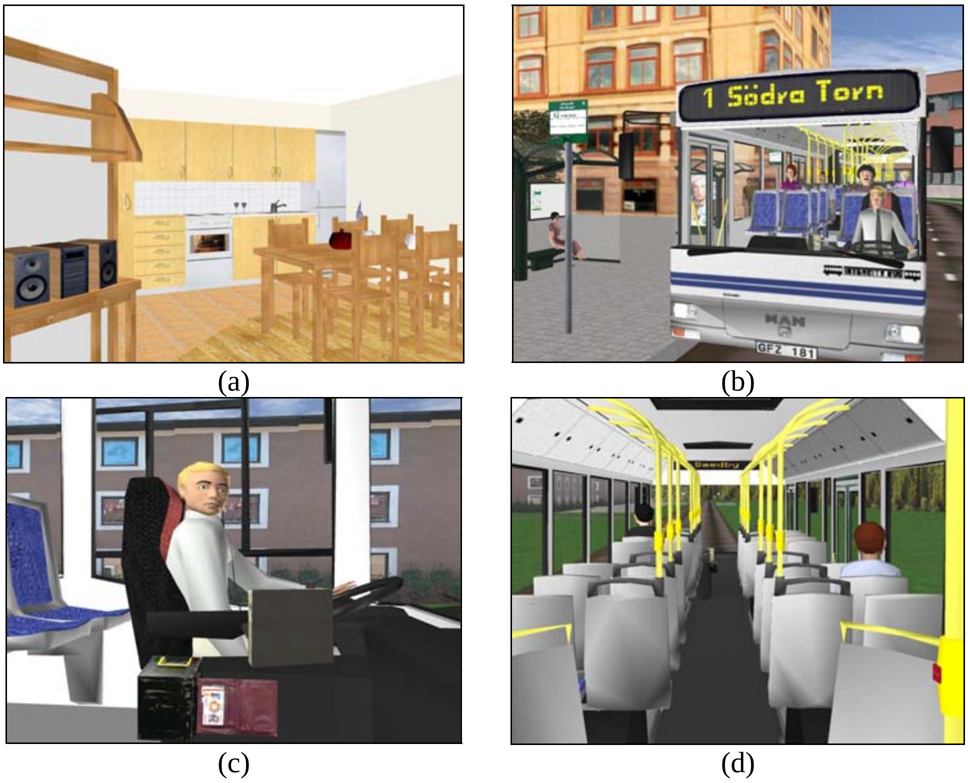


Figure 2. Screenshots from the virtual environment

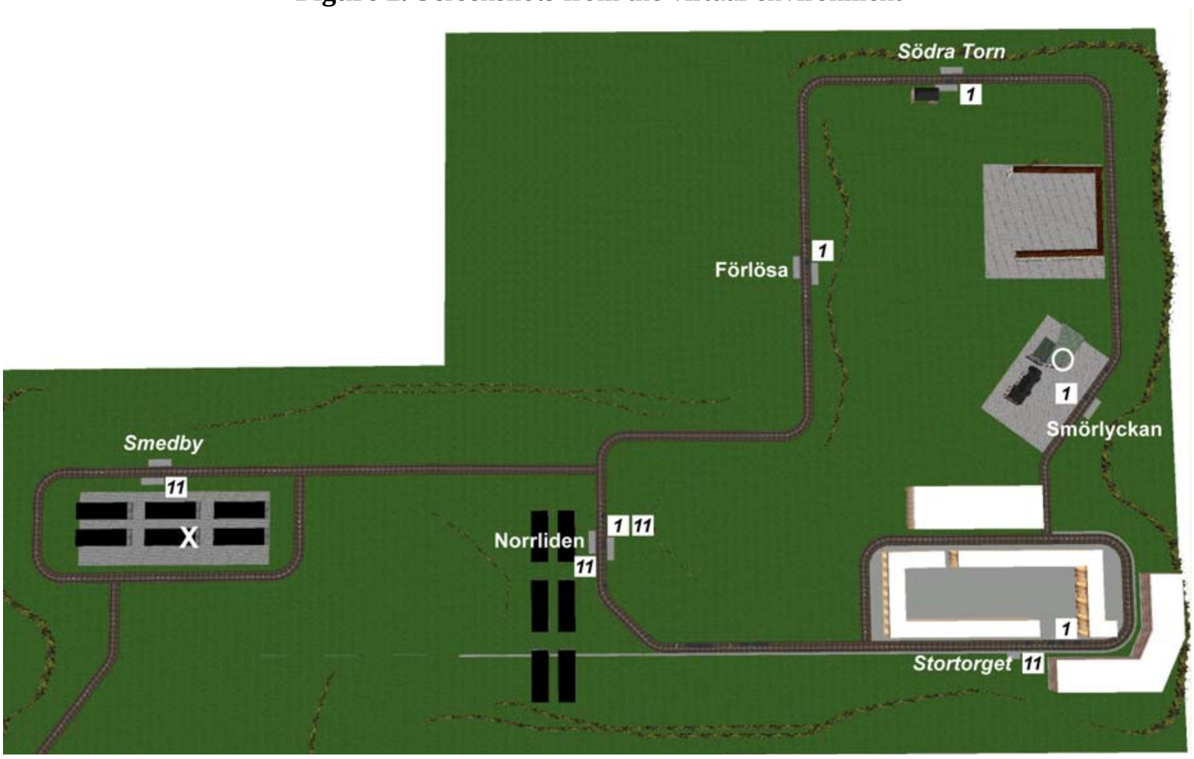


Figure 3. A bird's-eye view of the virtual environment. The subject's virtual flat is marked with an X and the café with a circle. The numbers indicate the stops on each bus line and the names of the end stations are italicised.

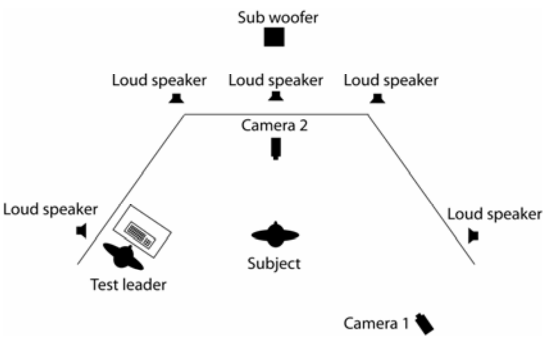
2.1 Material

The VR system was of the back-projection type and covered approximately 180° of the user's horizontal field of view (Figures 4a-b) by projecting the virtual environment on three projector screens, each 3 x 2.25 metres. In the pilot study, it was observed that the subjects sometimes had difficulties perceiving details due to low brightness (800 ANSI Lumens) and resolution (800 x 800) in the rather outdated *Barco* CRT projectors. They were therefore replaced for the present study with *NEC WT610* projectors with higher brightness (2500 ANSI Lumens) and resolution (1024 x 768). Just as in the pilot study, a surround sound system was used to add realism.

The participant’s actions in the virtual environment were controlled by the test leader using a joystick. The joystick was programmed to allow forward/backward movements, left/right movements and left/right rotation. It was also possible to make slow up/down movements. The speed of the movements and the rotation could be controlled with a lever on the joystick. The test leader could also control the events in the virtual environment, such as the bus stopping and starting, with a keyboard.

The laser pointer used by subjects in the pilot study was found to be ergonomically flawed. Therefore, an ergonomically designed laser pointer was used in the present study (Figure 4c).

(a) The VR system



(b) Schematic view of the VR system

(c) The laser pointer

(d) The subject taking the bus trip

(e) The retrospective think-aloud session

Figure 4. The experimental setup

Two video cameras were used to document the experiment (Figure 4b). A video quad mixer was used to mix the two video signals to one (Figure 4d-e). Wearable microphones recorded the utterances from the test leader and the subject.

2.2 Subjects

Four people with acquired brain injury (ABI), two with stroke and two with traumatic brain injury (TBI), and four occupational therapists were selected for participation. The subjects with ABI were chosen using purposeful sampling [10]. They were selected to have their most salient cognitive impairment in language, attention, memory or spatial ability, and little or none in the other cognitive domains (Table 1). The assumption behind this sampling was that these four cognitive domains have the greatest effect on a person's ability to handle the VR methodology. Furthermore, the cognitive impairment of the subject was not to be so severe that he/she could not travel independently by bus. The following three inclusion criteria also applied to the ABI subjects:

- At least six months since brain injury to make sure that the subject had some experience of how his/her impairments affected daily living.
- Did not easily become car sick due to the risk for simulator sickness.
- Had adequate vision to watch TV.

The subjects were all assessed with *Cognistat*, a standardised instrument for screening cognitive function [11] and with an instrument targeting self-reported cognitive functional limitations [12].

Table 1. ABI Subjects

Subject	Sex	Age	Type of brain injury	Most salient cognitive impairment	Misc.	Bus experience
1	F	38	Stroke	Language	Broca's aphasia and speech dyspraxia. Difficulties speaking fluently, understanding speech and reading.	One time/week
2	M	41	Stroke	Spatial ability	–	Two times/week
3	F	58	TBI	Attention	Moderately impaired vision.	Three times/month
4	M	44	TBI	Memory	–	Five times/week

The four occupational therapists had baccalaureate degrees in occupational therapy. Our inclusion criteria specified more than three years experience of working with people with ABI (Table 2).

Table 2. Occupational therapists

Subject	Sex	Age	Experience working with people with ABI (years)	Computer experience
5	F	29	3.5	Quite good. Played computer games when younger.
6	F	30	5.5	Internet and mail.
7	F	27	3.5	Internet and word processing.
8	F	28	6.0	Internet and word processing.

2.3 Procedure

The procedure before the experiment was the same for both subject groups. First, the subject's informed consent was obtained. Then he/she was asked to sit on a chair in front of the VR system while the test leader took his place at a table with a joystick and a keyboard (Figure 4b). The subject was then informed about the scenario:

> *You want to take the bus from your flat to a café. You will do this by taking bus 11 to the city centre and then transfer to bus 1. You will get off bus 1 at Smörlyckan where you will find the café. The date and time is the same as in the real world. You have a wallet with a bus card inside. First, however, you want to prepare for the bus trip by clearing the table, turning off the radio and picking up your wallet.*

The subjects were also told that they could perform actions in the virtual environment by telling the test leader what they wanted to do and/or pointing with the laser pointer at the projector screens. The subjects were then given a memory note with written information about which buses to take so that their performance would be independent of their ability to remember the instructions. The experiment consisted of three phases that were different for the two subject groups (Figure 5):

I. The virtual bus trip

The occupational therapists were requested to think aloud about aspects related to accessibility for people with ABI while making the bus trip. This is called a concurrent think-aloud protocol and is extensively used in for example usability testing [13]. The occupational therapists could ask the test leader to pause the simulation. This made all the events in the virtual environment come to a halt but the subject still could move around in and interact with it. The purpose of the pause function was to provide the subjects with time to reflect over something without being disturbed.

The subjects with ABI were not asked to think aloud while performing the bus trip since concurrent think-aloud can interfere with task performance [14,15]. This effect is likely to be exacerbated in people with impaired cognitive abilityy. If a subject with ABI got stuck during the virtual bus trip, the test leader provided help in three steps: 1) a verbal clue, 2) a verbal and a visual clue, 3) performing the task necessary for the subject to move on.

II. The subsequent think-aloud session

Immediately after phase I, the subjects with ABI were asked to think aloud about what they were thinking and feeling during the virtual bus trip while watching the recorded video material thereof (Figure 4e). This is called a retrospective think-aloud protocol and has the advantage of not interfering with task performance since the verbalisation occurs afterwards. Retrospective think-aloud has been criticised by Russo et al. [14] but recent research suggests that it can be valid and reliable [16]. If the subject fell silent he/she was encouraged by the test leader to think aloud. The reason why the subjects with ABI were not requested to think aloud about accessibility (as were the occupational therapists) was to avoid the risk for misunderstandings since not everybody shares a similar definition of this concept.

The four occupational therapists were shown the video material of one ABI subject's virtual bus trip (Subject 1) who was judged to have the greatest difficulties to use the VR methodology and they were asked to once again think aloud about public transport accessibility for people with ABI. We reasoned that this would encourage the occupational therapists to reflect on aspects not addressed during their own virtual bus trips. Another reason why we wanted to evaluate this procedure was that we considered it to be feasible in an actual public transport planning process.

III. The semi-structured interview

The experiment was concluded with a semi-structured interview. An interview guide with a battery of questions was used during the interview.

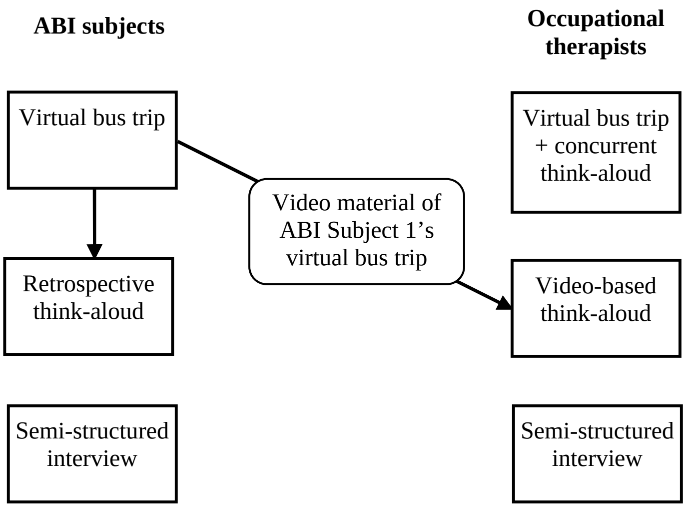


Figure 5. The two procedures

2.4 Analysis

The video data from the experiment was analysed using observation schedules, which broke down the bus trip into six steps: a) preparing for the trip in the virtual flat, b) locating the bus stop of the first bus, c) riding on the first bus, d) transferring to the second bus, e) riding on the second bus and f) finding the café. Each step had space for data from each of the following analysis points:

- Aspects of how the user understands and perceives the VE.
- Aspects of the communication between the user and the person controlling the VE.
- Aspects of user discomfort.
- Aspects of public transport accessibility with regards to people with ABI.

Observations from the virtual bus trip as well as the think-aloud data and the data from the semi-structured interview were recorded and grouped according to the relevant analysis point. In this way, the data from the different sources could be easily analysed in parallel. The think-aloud data and the interview data were transcribed using reformulation and concentration. The observation schedule also had space for another two analysis points on a single sheet:

- The participant’s subjective experience of the VR methodology
- Miscellaneous

3 Results

3.1 Research question 1: How does the VR methodology work for occupational therapists?

In general, the four occupational therapists handled the VR methodology well. They had no problems at all to understand and perceive the virtual environment and they also managed well to communicate to the test leader what they wanted to do. Three of the occupational therapist used the laser pointer throughout the whole experiment, often in combination with the words ‘here’, ‘there’ and ‘this’ as demonstrated by the following excerpt from Subject 5’s virtual bus trip:

S5: Then I put myself over here [points at the bus stop sign with the laser pointer].

Subject 8 only used the laser pointer on one single occasion towards the end of her virtual bus trip. Some small issues regarding performing actions in the virtual environment appeared. During the interview, Subject 5 revealed that it took her some time to understand that it was possible to take a closer look at objects. Moreover, on a couple of occasions Subjects 5 and 7 asked the test leader if certain actions, such as talking with people at the bus stop, were possible.

Subjects 5 and 6 showed signs of discomfort during the virtual bus trip. Subject 5 commented that she felt very dizzy but also added that she did not feel nauseous. In the middle of the experiment she said that she felt better and that she started to get used to the discomfort. For Subject 6 the discomfort culminated when she was turning around to sit down on bus 1. She told the test leader to pause the VR simulation and explained that she could hardly look at the screen.

All four occupational therapists managed to think aloud in a satisfactory manner during the virtual bus trip and the video-based think-aloud session. Subjects 6 and 8 were completely self-motivated whereas the other two each needed questions from the test leader to think aloud on a couple of occasions. Subject 6 commented during the interview that thinking aloud while watching the video of Subject 1 was like analysing or assessing a patient. Subject 8 expressed that she was unsure whether she was making relevant comments. There were differences in how the occupational therapists used the pause function. Subject 5 paused the virtual bus trip just once whereas Subjects 6 and 7 paused it sporadically. Subject 8 used the pause function almost every time she had something to say. Interestingly, during the semi-structured interview all four occupational therapists pointed out, even though not asked about it specifically, that it is better to think aloud during the bus trip than afterwards. Subject 5 related during the interview that she probably would have felt the urge to think aloud even if not asked to do so.

In general, the occupational therapists revealed a positive attitude to the VR methodology during the interviews. Nevertheless, they also pointed out issues that might be problematic. On one occasion Subject 5 mentioned that being in the virtual environment felt like being inside a computer game and also made her feel ‘a bit clueless’. She pointed out several times that her movements in the virtual environment were slow, which she perceived as unrealistic. Other things she found unrealistic were the roads, the way in which the buses turned and the fact that the bus card could not be suitably placed back in the wallet: ‘[…] one cannot put the card properly in the wallet, which might be disturbing. You might think that you will drop it’. Subject 6 also touched upon the issue of the virtual environment being different from the real world during the interview:

> *S6: It’s a different thing compared to taking the bus in the real world, I would say. One has to think more every moment and since I am not quite sure what will happen, I have to think more about each step. […] It’s a little bit like doing something for the first time, because when I do it in the real world I might not think so much about (it)… Then I do it spontaneously but now I have to think about each step…*
> *TL: Would it be an advantage or a disadvantage that you have to think more about what you’re doing?*
> *S6: In this context it’s an advantage. […] I have some patient cases that I have experienced which I try to think about in every step and connect to this.*

Moreover, Subjects 5 and 6 commented during the virtual bus trip and the interview that the virtual environment was calm and quiet and empty of people and cars. During the interview, Subject 8 pointed out that there was very little time between the virtual bus trip and the video-based think-aloud session. She thought it could be good to allow some time for reflections between the two tasks.

3.2 Research question 2: How does the VR methodology work for people with ABI?

Overall, the subjects with ABI managed well to understand and perceive the VE but some occasions of difficulties could be observed. Subject 3 had problems finding the radio in the virtual flat. The test leader told her that the radio was behind her whereupon she actually turned her head to look behind her as if she expected to find the radio there. A similar situation occurred just shortly thereafter. While at the bus stop of bus 1, Subject 2 did not perceive bus 1 appearing on the right screen. During the interview he explained that this was because he was too focused on the timetable.

In general, all four ABI subjects managed to communicate their intentions well enough to complete the virtual bus trip. There were problems, however, especially for Subject 1 who had difficulties clearly verbalising what she wished to do. On several occasions, it was difficult for the test leader to understand what she wanted. However, on all these occasions the test leader was able to discover her intentions by posing a question, as illustrated by the following excerpt when she was searching for the outer door of the virtual flat:

S1: There [points at the hallway]. The door [points at the toilet door]. Open [points at its door handle].
S1: Again [points at the outer door].
TL: Again..?
S1: Eh… Close the door [points at the toilet door].
TL: You close the door.
S1: Now [points at the outer door].
TL: You want to try that door instead?
S1: Yes. Open.

The excerpt also demonstrates her main strategy throughout the whole experiment, namely pointing with the laser pointer in combination with one or several keywords. On seven occasions she pointed at the screen without turning the laser pointer on, but the test leader was able to understand what she wanted to do anyway. Another strategy she used on several occasions was to make gestures, especially when she was inserting the bus card in the bus card reader. Despite her problems to provide clear descriptions, she commented during the interview that she thought it was easy to communicate what she wanted to do. Subject 3 also communicated her intentions in a less than optimal manner. On many occasions throughout the bus trip, she just pointed at the projection screens without saying anything. When she was supposed to move or rotate the card, she moved the laser point over it as if she believed she could control it with the laser pointer and she confirmed this during the interview. Despite this, the communication between Subject 3 and the test leader worked sufficiently well, as demonstrated by the following excerpt:

[Subject 3 points at the bus card with the laser pointer without saying anything and then drags the laser point to the card reader.]
TL: Do you want to put it there?
S3: Yes.

A strategy that Subject 3 used on several occasions during the virtual bus trip was to use words like ‘here’, ‘there’ and ‘this’ while at the same time pointing with the laser pointer. During the interview she revealed that she found the method for interacting with the virtual environment to be very good. She also commented that being able to show with the laser pointer is very good if the user has problems explaining what he or she wants to do. Subjects 2 and 4 used very clear verbal descriptions in combination with pointing with the laser pointer throughout the experiment. Just like Subject 3 they combined words like ‘here’, ‘there’ and ‘this’ with pointing with the laser pointer. However, Subject 2 did this to a much lesser extent than Subjects 3 and 4. During the interview, Subject 2 described the method for interacting with the virtual environment as ‘not so difficult’. He also revealed that he thought it was only possible to point at the middle screen and not on the two side screens. Despite this, he actually did point at the side screens on several occasions during the bus trip, and he seemed a bit surprised when the test leader explained to him that it was possible to do so. Subject 4 commented that the interaction method worked very well.

On several occasions during the virtual bus trip, Subject 1 showed signs of experiencing discomfort. From the video material it seemed the discomfort mainly appeared when the view was rotating and Subject 1’s own comments during the interview confirmed this. However, her comments about the nature of the discomfort were difficult to interpret and slightly contradictory. Nevertheless, she used the word ‘dizzy’ twice, and also confirmed when the test leader asked her if she felt dizzy on two occasions. On several occasions she also mentioned the chair she was sitting on while at the same time grabbing its armrest. Her reason for doing this was unclear but the following excerpt from the interview suggests that she appreciated that she had the armrest to hold on to:

S1: Hold [grabs the armrest].
TL: Did you want to hold on to the chair?
S1: Yes. Secure!
TL: So the chair was a good thing, giving you a stable point.
S1: Yes, yes.

Subjects 2 and 4 showed no signs of experiencing discomfort during the virtual bus trip but pointed out during the interview that they felt some dizziness on one occasion when the view was rotating. Subject 3 revealed during the interview that she did not experience any type of discomfort.

Subjects 3 and 4 described the virtual environment as very realistic and mentioned that the experience actually was like riding on a real bus. Subject 4 added that the virtual environment did not feel very real in the beginning but gradually became more realistic. He also pointed out that the projection screens sometimes moved due to gusts of wind, making the edges between the projection screens more visible, which broke the realism. He thought that a big, curved projection screen without joints would have given an 'even stronger experience'. Another thing he experienced as unrealistic was the movements of the buses, which he perceived as very slow. On several occasions, Subject 1 also made the same observation. She mentioned that the virtual environment was empty and that there were no sounds of other people on the bus. Subject 2 commented that the virtual environment felt a bit weird and unusual and that the real world is easier. Later he developed this line of reasoning:

S2: But then again… if I had done this a couple of times I probably would have gotten into it. The first time it is a bit… Well, one doesn't think in the right way, I guess.
TL: Do you mean that if you had the opportunity to get used to the virtual environment it would have become more like reality?
S2: Oh yes. It sure would.

All subjects with ABI thought the initial training in the virtual flat was a good idea. However, Subjects 1, 2 and 3 pointed out that it should have lasted longer. The four occupational therapists felt the same and made additional comments suggesting that the initial training was not adequate. Subject 7 thought that it would require more than one virtual bus trip before a person with ABI fully understood the VR methodology. Subject 6 commented that the initial training should include outdoor navigation since a great deal of the virtual bus trip takes place outdoors.

The interview revealed that all four subjects with ABI had a positive opinion of the VR methodology and seemed to believe that it can be useful. However, Subjects 1 and 3 were not fond of the idea of watching themselves during the retrospective think-aloud session, especially Subject 1 who expressed a strong aversion to this on several occasions. Subjects 3 and 4 were self-motivated during the retrospective think-aloud. Subject 4, anyway, pointed out that it was a bit difficult to think-aloud since he was so concentrated on observing his own behaviour. He believed that hiding the camera and the microphone during the retrospective think-aloud and having a dialogue about the virtual bus trip would be a better method: 'Like you and me watching TV together'. Subjects 1 and 2, instead, needed continuous reminders from the test leader in the form of questions to keep thinking-aloud.

During the interview, the occupational therapists were asked how they think a person with ABI can use the VR methodology. Subjects 5 and 6 answered that it most likely would be difficult for individuals with severe cognitive problems to use. Subject 7 commented that using the VR methodology probably requires relatively intact cognitive abilities, whereas Subject 8 believed that it depends on the individual. Subject 8 also commented that it is good that the VR methodology offers the opportunity to both describe one's actions and to point with the laser pointer since people with ABI might have different preferences as to what they find easy to use.

3.3 Research question 3: What type of knowledge can be elicited with the VR methodology?

The occupational therapists

In total, the four occupational therapists made 122 utterances regarding public transport accessibility (Table 3). The following excerpt from Subject 6 is a good example of what the concurrent think-aloud during the virtual bus trip was like. She has just entered the bus and is preparing to pay with her bus card:

> *S6: You can stop here. This is a bit of a problem… for many people. If you have spatial problems it's often hard to know the direction in which to insert the card. It should be possible to indicate it somehow. There should be better indications both on the card and on the machine, so you can put it in correctly and don't have to stand there getting nervous and stressed.[…]Everything is so dark. Here [points at the card reader] it melts into the background. I don't know if it's the seat or what, but everything is really black here. It's good with this yellow border here, however, but… I know that inserting the card correctly can be difficult. Mmm… maybe the machine should be another colour to make it stand out.*

The occupational therapists' utterances could be sorted into four groups:

- *Accessibility problems* that might occur in a public transport system (the virtual as well as a real one).
- *Suggested improvements* of the public transport system (the virtual as well as a real one).
- *Positive aspects* of public transport systems (the virtual as well as a real one).
- *The performance of Subject 1* when making the virtual bus trip.

Table 3. Utterances made by occupational therapists

Group	Data type	Subject 5	Subject 6	Subject 7	Subject 8	Total
Accessibility problems	Bus trip	6	11	3	14	34
	Video	5	5	5	6	21
Suggested improvements	Bus trip	0	9	0	15	24
	Video	0	2	0	8	10
Positive aspects	Bus trip	0	1	1	4	6
	Video	0	1	0	0	1
The performance of Subject 1	Bus trip	N/A	N/A	N/A	N/A	N/A
	Video	11	2	9	4	26
	Sum	*22*	*31*	*18*	*51*	*122*

Table 4 illustrates the utterances of Subject 8, who provided the largest number of utterances among the occupational therapists. Similar utterances have been grouped as 'themes'.

Table 4. Utterances of Subject 8

Themes	Occurrences	
	Bus trip	Video
Accessibility problems		
It is difficult to orientate since all houses look the same.	1	
The information on the bus stop signs is too small.	1	1

The bus stop signs are too high.	2	1
The timetables are difficult to read.	2	1
It is important that the timetables aren't too high or too low.	1	
Poor contrast between the card reader and the background.	2	
Patients can get very stressed when paying with the bus card if there is a queue.	1	
Patients might forget which bus stop has been announced over the loud speakers.	1	1
Poor contrast between road and kerb.	1	1
It might be difficult to judge the distance between the bus stop platform and the bus.	1	
It might be difficult to perceive height differences inside the bus.	1	
It might be difficult to reach the stop buttons.		1
Suggested improvements		
There should be an information system at the bus stop announcing when the next bus is coming.	2	1
The bus number should be posted in several places on the exterior of the bus.	1	
The card reader should be another colour.	1	
There should be clearer information on the bus card on how to insert it in the card reader.	1	1
It should be possible to insert the card in the card reader arbitrarily.	1	1
There should be two card readers to avoid the stress of people waiting behind you in the queue.	1	1
The bus should not leave until the boarding passengers are seated.	1	
There should be stop buttons in several different places in the bus.	1	
The next bus stop should be announced several times over the loud speakers.	1	1
There should be a zebra crossing at Stortorget.	1	
There should be information about what stops the bus will stop at, both onboard the bus and at the bus stops.	2	2
There should be special seats for people with physical or cognitive disabilities.	2	
If necessary, the bus driver should help passengers insert the bus card in the card reader.		1
Positive aspects		
The stop buttons have suitable colours that are easy to see.	1	
It's good that the name of the next bus stop is both printed on the display and announced over the loud speakers.	2	
It's good that city buses and regional buses are different colours.	1	
The performance of Subject 1		
The language problems of Subject 1 can make it hard for her to read and recognise numbers.		1
Subject 1 looks to the right even when the bus will be arriving from the left.		1
Subject 1 repeats the name of the bus stop 'Stortorget' to remind herself.		1
The bus trip makes Subject 1 nervous.		1

The occupational therapists' utterances regarding accessibility problems made during their own virtual bus trips tended to be the result of them reasoning about various aspects of public transport. In 14 of the 34 problem utterances, references were made to one or several types of consequences of cognitive impairment as illustrated by the following think-aloud excerpt from Subject 7:

> *S7: Let's pause here. Reading a timetable is not very easy if you have a cognitive disability. If you perhaps have a sight loss or attention deficit or something like that, then it is quite difficult to interpret all the numbers and minutes. And then you have to keep track of if it's Monday, Saturday or Sunday. That can be rather tricky.*

The utterances regarding accessibility problems made during the video-based think-aloud tended to be more focused on Subject 1: Eight of these 21 utterances were made in direct response to Subject 1 having problems during the virtual bus trip. In general, the occupational therapists believed that there were differences between the knowledge coming from the virtual bus trip that they took and the knowledge from the video-based think-aloud session. Subjects 5, 6 and 7 described the knowledge from the think-aloud session as ‘another type of understanding’, ‘more specific to the patient’s problems’ and as giving ‘a completely different perspective’. Moreover, Subject 6 described the matter in the following manner:

> *S6: I can only sit here and brainstorm about how I think people would experience it but when I see a patient in the (virtual) environment I am able to directly reflect on it… How was she thinking at that moment? Why did it end up like that? That can give you additional insight. You can also see people’s reactions. […] That is something I cannot imagine when taking the bus trip by myself.*

Subject 8, though, felt that she was commenting on more or less the same things during the virtual bus trip and the video-based think-aloud session.

In total, more unique themes, i.e. ones that only appeared either during the bus trip or the video-based think-aloud session, came to light during the virtual bus trip (41) compared to the video-based think-aloud session (15).

The utterances in the group ‘Accessibility problems’ could be further divided into four categories (Table 5):

- Cognitive (e.g. difficulties understanding the timetable)
- Affective (e.g. paying with the bus card is very stressful with people waiting behind you)
- Social (e.g. bus drivers who are rude to individuals with communication problems)
- Physical (e.g. difficulties reaching the stop buttons)

As can be seen, a clear majority of the utterances were related to cognitive or affective accessibility problems.

Table 5. The four categories of accessibility problem utterances

Accessibility problem category	**Data type**	**Subject 5**	**Subject 6**	**Subject 7**	**Subject 8**	**Total**
Cognitive	Bus trip	7	11	3	13	34
	Video	0	5	3	4	12
Affective	Bus trip	1	2	0	1	4
	Video	3	0	2	2	7
Social	Bus trip	0	0	0	0	0
	Video	1	0	0	0	1
Physical	Bus trip	0	0	0	0	0
	Video	0	0	0	1	1

On a couple of occasions, very small details in the virtual environment triggered the occupational therapists to think aloud. A very illustrative example of this was when Subject 5 (occupational therapist) observed Subject 1 (subject with ABI) putting the bus card incorrectly in the card reader:

> *S5: No, it doesn’t work. That hateful sound…*
> *TL: Do you mean the sound of the card reader?*
> *S5: Yes, that chewing when you insert the card wrong. It increases the stress. It often chews several times. Not only twice but many, many times. […] At least four or five times before the card comes up again.*

The subjects with ABI

The idea behind the VR methodology is to allow a person with ABI to communicate his/her knowledge and experiences of public transport accessibility through his/her:

- actions and behaviour while performing the task in the virtual environment.
- verbal communication about his/her experience in the virtual environment.

Table 6 presents the observed problems of the subjects with ABI related to the activity of taking the virtual bus trip.

Table 6. Observed problems of ABI subjects when taking the virtual bus trip

Subject 1	**Subject 2**	**Subject 3**	**Subject 4**
Subject 1 has problems inserting the bus card correctly.	Subject 2 has problems reading the timetable.	Subject 3 has problems reading the bus stop signs.	Subject 4 has problems inserting the bus card correctly.
Subject 1 thinks she has taken the wrong bus since it's going in the direction she came from.	Subject 2 has problems inserting the bus card correctly.	Subject 3 has problems finding the card reader.	Subject 4 has problems seeing the bus stop display inside the bus.
	Subject 2 does not know where to catch bus 1.	Subject 3 has problems inserting the bus card correctly.	
	Subject 2 does not notice when bus 1 arrives.	Subject 3 does not find the stop button.	
		Subject 3 gets off the bus at the wrong stop.	

All in all, the subjects with ABI made 79 utterances about public transport accessibility (Table 7). The following excerpt from Subject 4's retrospective think-aloud session is a good example of what the think-aloud was like. Subject 4 is watching the video material of himself reading the bus stop sign and the timetable while waiting for bus 11:

> *S4: I need to be in control so I have to… I don't trust myself and therefore… I see now that I am looking at the memory note a lot, you know. What is written on the note should be up there on the sign. It should match…*
> *TL: Are you comparing, so to speak?*
> *S4: That's right, I am comparing. […] Then I looked at the timetable there, to check that it's correct…where I am…since I don't know…I am not familiar with this place. I don't know the order in which the Stortorget bus stop comes. And then I check the time at which the bus should leave.*

The utterances could be sorted into five groups:

- *Accessibility problems* that might occur in a public transport system (the virtual as well as a real one).
- *Suggested improvements* of the public transport system (the virtual as well as a real one).
- *Positive aspects* of public transport systems (the virtual as well as a real one).
- *Strategies* used by the subject in public transport systems (the virtual as well as a real one).
- *The subject's performance* when making the virtual bus trip.

Table 7. Utterances made by ABI subjects

Group	Data type	Subject 1	Subject 2	Subject 3	Subject 4	Total
Accessibility problems	Bus trip	1	0	1	0	2
	Video	6	5	8	4	23
	Interview	2	4	1	3	10
Suggested improvements	Bus trip	0	0	0	0	0
	Video	1	0	0	0	1
	Interview	1	0	0	1	2
Positive aspects	Bus trip	0	0	0	0	0
	Video	0	2	1	1	4
	Interview	0	0	0	0	0
Strategies	Bus trip	0	0	1	0	1
	Video	0	5	2	5	12
	Interview	0	0	0	0	0
The subject's performance	Bus trip	0	1	0	0	1
	Video	6	5	2	6	19
	Interview	0	2	0	2	4
	Sum	*17*	*24*	*16*	*22*	*79*

Table 8 illustrates the utterances of Subject 2 who provided the largest number of utterances among the subjects with ABI. Similar utterances have been grouped as 'themes'.

Table 8. Utterances of Subject 2

Themes	**Occurrences**		
	Bus trip	Video	Interview
Accessibility problems			
Most timetables have small text.		1	
The timetable was hard to understand.		1	
At first I did not see the arrows on the bus card.		1	
People waiting behind may get angry if you have problems inserting the bus card.		1	
Some bus drivers pull away from the bus stop very fast.		1	
Finding the right bus stop can be difficult if there are many.			1
It is difficult to take the right bus if many buses stop at the same bus stop.			1
You might miss the bus while reading the timetable.			2
His performance during the bus trip			
I was unsure exactly where to transfer.	1	2	
I did not see bus 1 arrive since I was too focused on the timetable.			1
I entered bus 1 without checking its number.		1	1
I had full control over when I had to get off bus 1.		1	
It was unnecessary that I read the timetable of bus 1 since it was the only bus stopping at the bus stop.		1	
Strategies			
If you know which bus to take, you only have to wait until it comes the next time.		1	
If you insert the bus card incorrectly in the card reader you simply have to turn it until it is in the correct position.		1	
You can ask the bus driver to not pull away until you are seated.		1	

It is easier to choose a seat in the bus that does not require you to take a step up.	1
Doing a trial run makes me feel less insecure.	1
Positive aspects	
Previously, I hesitated to take the bus, but lately I have discovered that it is not so difficult.	1
It is easy when there is just one bus line leaving from the bus stop.	1

Interestingly, 16 of the utterances made by the subjects with ABI were made during the semi-structured interview even if this was not the intention. Eight of the interview themes were unique, i.e. they only appeared during the interview.

The utterances concerning ‘Accessibility problems’ could be further divided in three categories: cognitive, affective and physical (Table 9).

Table 9. The three categories of accessibility problem utterances

Accessibility problem category	**Data type**	**Subject 1**	**Subject 2**	**Subject 3**	**Subject 4**	**Total**
Cognitive	Bus trip	0	0	1	0	1
	Video	3	3	6	4	16
	Interview	1	4	1	2	8
Affective	Bus trip	1	0	0	0	1
	Video	2	1	2	0	5
	Interview	1	0	0	1	2
Physical	Bus trip	0	0	0	0	0
	Video	2	1	1	0	4
	Interview	0	0	0	0	0

The language impairment of Subject 1 made it difficult for her to provide detailed descriptions during the retrospective think-aloud session. It became more like a conversation with the test leader as demonstrated by the excerpt below, which is about her trying to understand if bus 1 was the right bus or not. She seemed to get confused that bus 1 was going in the direction she just came from and that the sign on it was ‘Södra Torn’ (the end station) and not ‘Smörlyckan’:

> *TL: What were you thinking here?*
> *S1: Unsure. The bus… Hmm… [S1 asks TL to pause the video]. Café. Right way [points at the TV screen].*
> *TL: Aha. Did you think it was that way [points at the TV screen]? That you should have continued..?*
> *S1: Yes.*
> *TL: You went the other way. Did this confuse you?*
> *S1: Yes. Name. Right.*
> *TL: Do you mean the destination sign on the bus? It said ‘Södra Torn’. Did this make you unsure?*
> *S1: Yes.*

Miscellaneous

When asked about this during the interview, all four occupational therapists believed there were differences between the knowledge elicited from occupational therapists and that elicited from people with ABI. Subject 5, for example, commented as follows:

S5: When observing a patient who does this, you immediately gain empirical knowledge on how it might be, whereas when I comment on things, I generalise on the basis of my expert knowledge.

Subjects 6 and 7 commented during the interview that people with ABI often have problems expressing what the problem really is. Subject 6 described the issue as follows:

S6: But they generally have great difficulties describing what the problem actually is. They say it's difficult, or they say something really basic like 'I can't see' or 'I can't hear'. On the other hand, if you have some knowledge about cognitive problems you can sort out the cause of the problem, and perhaps you also know how to fix it.

Subject 6 also pointed out during the interview that it probably is difficult for people with ABI to make suggestions themselves on how to improve the public transport system.

4 Discussion

4.1 Research question 1: How does the VR methodology work for occupational therapists?

Broadly, the four occupational therapists managed to handle the VR methodology well. They quickly understood how the VR technology functioned and made many comments about public transport accessibility for people with ABI. Subject 6's comment that making the virtual bus trip felt a bit like doing something for the first time is very interesting. For some people with ABI, every bus trip might feel like the first one and it is therefore good if the VR methodology can help the occupational therapists simulate this mental state. Some problematic aspects of the VR methodology could be observed, however. For example, the virtual environment was perceived as calm and quiet and empty of people and cars. It is, of course, possible to create a more vivid virtual environment more similar to the real world but this would have required time and financial resources beyond the capabilities of this research project. The lack of life and movement is clearly a disadvantage since the overall experience is less persuasive. However, the opposite could be argued, that the lack of vividness is an advantage since it might make it easier for an occupational therapist to focus on accessibility aspects. In the present study some of the comments made by the occupational therapists regarded very small details. Subject 5 commented that the 'chewing' sound when the card is inserted incorrectly in the card reader can be very stressful for a person with a cognitive disability. Such a small detail might be hard to perceive onboard a real bus filled with people and sounds. Some hesitation regarding the actions that could be performed in the virtual environment was observed in the occupational therapists. This suggests that it is important that the training in the virtual flat is relevant for the actions performed during the virtual bus trip. One such task could be to read a reminder note on the refrigerator so that the user understands that it is possible to move in closer to objects.

In general, it went well for the occupational therapists to think aloud while making the virtual bus trip, which suggests that this is a feasible means of eliciting their knowledge. This is supported by the fact that they all spontaneously commented that it is better to think aloud during the bus trip than afterwards. Nevertheless, Subjects 5 and 7 occasionally needed to be encouraged by the test leader to do so and Subject 8 was not sure if her comments were relevant. One way to remedy these problems would be to allow the occupational therapist to become acquainted with the think-aloud protocol in the virtual flat before the actual bus trip starts. They could perform a number of daily activities while thinking aloud about the flat's accessibility for people with ABI. Thereafter they would receive feedback so there would be no doubt that they are making relevant comments during the bus trip. Subject 8 used the pause function in an efficient way and it seemed to facilitate her think-aloud process. Even if Subject 5 hardly used the pause function, and Subjects 6 and 7 only sporadically, the results suggest that it should be part of the VR methodology. One way to increase the occupational therapists' use of the pause function would be to encourage them to do so during the introductory training. Subject 8 suggested allowing some time for reflections after the virtual bus trip, before the retrospective think-aloud session. This is a good idea since the occupational therapist might want to summarise or make additional comments. Another idea would be that the test leader pause the virtual bus trip at regular intervals to allow the occupational therapist to sum up his/her thoughts and reflections.

4.2 Research question 2: How does the VR methodology work for people with ABI?

In general, the four subjects with ABI managed to handle the VR methodology sufficiently well. The only real problem to perceive and understand the virtual environment that could be noted was when Subject 3 turned around thinking that she could find the radio behind her. Understanding that it is the virtual environment moving and rotating in relation to the stationary user, and not vice versa, is not an apparent and easy task, especially for individuals with impaired visio-spatial ability. Even if Subject 3 quickly overcame it, this highlights the importance of initial training to allow the user to become acquainted with the 'rules' of a virtual environment.

Even if all four ABI subjects managed to communicate what they wanted to do sufficiently well, problems were noted. As expected, Subject 1 had the greatest difficulties due to her language difficulties. Even so, she found strategies that helped her to communicate what she wanted to do. Her use of keywords in combination with pointing with the laser pointer shows that this interaction method is very suitable for people with language impairments. Furthermore, her spontaneous use of gestures clarified her intentions, especially when she handled the bus card. Accordingly, the VR methodology should encourage the user to make use of gestures. This could be done by including tasks in the virtual training flat that 'forces' the user to do so. Subject 3 also had problems since she had misunderstood the purpose of the laser pointer. She thought it worked like a desktop mouse and that she could use it to move and rotate the bus card. This highlights the importance of clear instructions to help the user build a sound mental model of how the interaction with the virtual environment works. Subjects 2, 3 and 4 used a strategy similar to Subject 1's keyword strategy: They combined words like 'here', 'there' and 'this' with pointing at objects or places in the virtual environment. This strategy was also observed in our pilot study: Five of the seven stroke subjects applied it [5]. This enabled them to make simpler verbal descriptions and still communicate their intentions clearly, lowering the extraneous cognitive load the VR interface inevitably places on the user. A minimised extraneous cognitive load is very important for the validity of the VR methodology since it otherwise might be difficult to determine if the problems the user experiences are due to the VR technology or the activity to be performed. This problem has been noted by Blackman et al. [4] who used VR to investigate outdoor environments for people with dementia. The authors found that although the participants were able to use a joystick to navigate in the virtual environment, this presented more of a challenge for them than navigating in the real world. In the present study, the participants' subjective experience of the interaction method was also positive, which is an indication that they perceived it as an easy and natural way of performing actions.

Three of the ABI subjects, mainly Subject 1, experienced dizziness during the virtual bus trip. Subjects 2 and 4 reported that the dizziness only appeared on a single occasion. Two of the occupational therapists, Subjects 5 and 6, also reported feeling dizzy. Dizziness is a symptom of simulator sickness [8], which is believed to be the result of conflicting input to the visual and vestibular senses [17]. The risk for simulator sickness is clearly a disadvantage of the VR methodology that could create difficulties in a real planning process. The root of the problem seemed to be the movements of the virtual buses. The problem was also observed in our pilot study in which four of the seven stroke subjects reported dizziness [5]. Thus, the speed of the buses was lowered by approximately 20% for the present study. This did not help, however, and it is possible that the problem is, instead, the lack of similarity to real bus movements: Making a virtual bus move like a real one is not an easy task. Nevertheless, as software tools for developing virtual environments improve it will become increasingly easier to create virtual buses that obey the laws of physics and hence move in a more realistic manner. Moreover, there is some evidence that motion sickness susceptibility correlates with simulator sickness symptoms [18]. One way to deal with the problem would be to carefully screen the users for motion sickness before participation.

During the retrospective think-aloud session, Subjects 1 and 2 needed continuous reminders in the form of questions form the test leader to think aloud. It might be difficult for a person with impaired cognitive abilities to watch the video material and think aloud at the same time. Furthermore, he/she might be so focused on observing his/her mistakes during the virtual bus trip that he/she forgets to think aloud. Subject 4's suggestion of making the retrospective think-aloud more like a regular conversation might be the key to avoiding this problem. The fact that Subject 4 managed to make many comments during the retrospective think-aloud session is very interesting considering his memory problems (severe memory impairment according to *Cognistat*). He made several comments on how he was thinking during the virtual bus trip and seemed to make associations from his own comments in the video material. Even if a participant with severe memory problems has difficulties remembering how he/she was thinking and feeling during the virtual bus trip, he/she might be able to associate to other bus trips. Hence, there is no reason to exclude individuals with severe memory problems from using the VR methodology as long as they are able to handle it.

Even if the subjects pointed out things that were unrealistic or peculiar in the virtual environment, it seemed the VR methodology was good enough to partially create the illusion of a bus trip. All four subjects approved the idea of initial training but three of them believed it should be longer. This is supported by comments of Subjects 2 and 4 about the initial, gradually disappearing difficulties in accepting the virtual environment as a real one. Moreover, one of the occupational therapists thought it would require more than one virtual bus trip before a person with ABI would fully understand the VR methodology. The goal of the initial training should be that the participant understands how the VR methodology works and that he/she has overcome the initial disbelief of the virtual environment before the actual bus trip starts. How long this takes varies from individual to individual, but 10-15 minutes of initial training ought to be enough for most people. The content of the initial training must also be considered. Tasks similar to those the participant will solve during the virtual bus trip should be performed in the virtual flat. One such task has already been discussed: reading a reminder note on the refrigerator. One occupational therapist commented that the initial training should include some outdoor navigation. One such task could be to take out the rubbish before the bus trip starts. Another, already mentioned, would be to 'force' the user to make gestures to make him/her understand that this is an efficient way to communicate his/her intentions. This task could be to put the dishes in the dishwasher, requiring the participant to use gestures to show how to place the plates and glasses to make them fit.

The fact that all subject with ABI displayed a positive attitude to the VR methodology is a very encouraging result since acceptance in the end-users is crucial when introducing new technology. A positive attitude was also observed in the seven participants of our pilot study [5].

4.3 Research question 3: What type of knowledge can be elicited with the VR methodology?

In total, 13 problems were observed during the virtual bus trips of the ABI subjects. These observations showed what the problems were but revealed very little about what caused them. Instead, the cause came to light through the subjects' verbalisations. This demonstrates the importance of not only observing but also listening to what the participants have to say about their experience. In total, the subjects with ABI made 79 utterances related to public transport accessibility. The majority of them regarded accessibility problems, the subject's performance during the virtual bus trip and strategies. The utterances regarding strategies were unique for the ABI subjects and contain knowledge very useful for a planning process. Sheehan, Burton and Mitchell [21] investigated outdoor wayfinding in people with dementia by studying 13 dementia subjects on outdoor walks. The authors concluded that knowledge about the wayfinding strategies of this population is important when planning the built environment. In the context of public transport planning, supporting already existing end-user strategies can be a way to minimise the need to re-learn, which probably is particularly important for individuals with impaired memory.

About a fifth of the utterances about accessibility problems made by the ABI subjects regarded emotional aspects such as stress and insecurity. This was also observed in the pilot study: Three of the seven subjects made comments about their emotional experience of the virtual bus trip [5]. This knowledge may be just as relevant as that of cognitive accessibility aspects: It is crucial to understand in detail what triggers negative reactions in people with ABI when using public transport. Logan, Dyas and Gladman [22] found that in a group of stroke patients (n=24), 11 wanted to use transport but had lost their confidence. To focus on affective dimensions when planning a public transport system can be a way to make the traveller feel more relaxed and confident. An example of such a solution, based on the knowledge elicited from the subjects of the present study, is a multi-modal information system inside the bus that provides information to the traveller at regular time intervals about where the bus is now and where it is heading.

The language problems of Subject 1 bring up questions concerning the validity of her utterances. There were some things she wanted to communicate but never managed to explain clearly enough. Individuals with language problems may be one of the groups that will have the most difficulties contributing their knowledge through the VR methodology. Even so, they are a big population whose needs must be considered in public transport planning, especially since there is good reason to believe that many of them could use a public transport system designed to compensate for their language impairments. Even if it can be difficult to elicit detailed knowledge from this population, their holistic experience of a virtual public transport system is likely to be useful in a planning situation. For example, the facial expressions, body language and comments of Subject 1 clearly expressed that there were certain parts of the virtual bus trip that made her feel stressed and nervous. All four occupational therapists pointed this out during the video-based think-aloud session. Moreover, it is possible that there are ways to facilitate communication for people with language problems. You could let somebody close, who knows how to communicate with the subject, participate as a sort of interpreter during the virtual bus trip. The knowledge coming from the end-users might not only be useful as a pure information source for the planning process. Perhaps one of the most valuable contributions from the end-users has to do with empathy. In a real planning situation the public transport planners would be able to observe the problems, anxiety or stress of people with ABI when making virtual bus trips. To see this with their own eyes would make them more aware of the consequences of a badly planned public transport system and also more willing to consider the needs of individuals with cognitive impairments in the planning process.

The results suggest that people with ABI can contribute a great deal of knowledge to a real public transport planning process by means of a VR-based methodology. The most relevant knowledge from the end-users, i.e. people with ABI, probably concerns concrete accessibility problems, emotional aspects and strategies as illustrated in the left part of Figure 6.

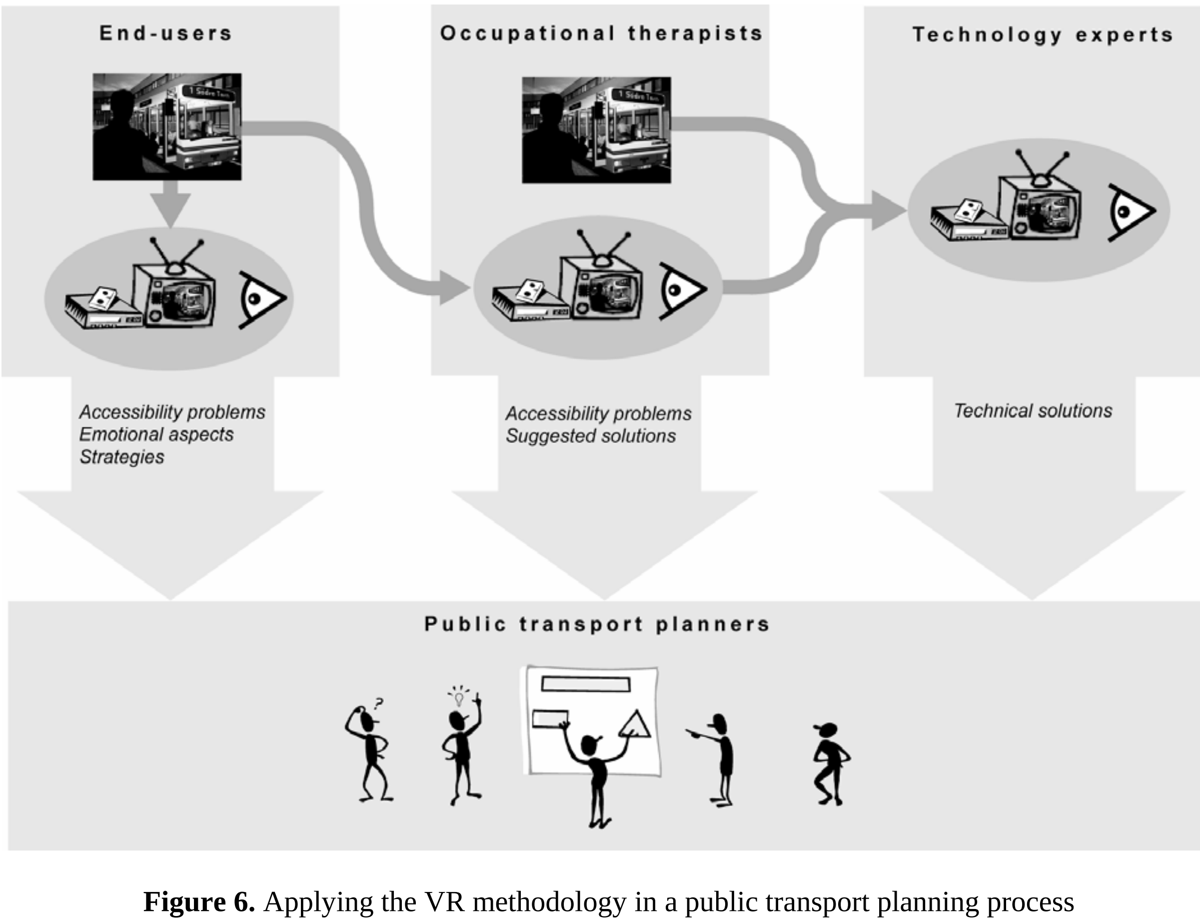


Figure 6. Applying the VR methodology in a public transport planning process

The occupational therapists made no less than 122 utterances related to public transport accessibility for people with ABI during the virtual bus trip and the video-based think-aloud session. More than a fourth of them were suggested solutions, which is a very positive result since it suggests that the VR methodology encourages occupational therapists' ability to analyse how things can be improved. A clear majority of the utterances regarded cognitive issues and only one utterance was made about physical accessibility. This suggests that the VR methodology makes it easy to focus on cognitive aspects of public transport, which is a positive result considering its purpose. A possible reason for this is the absence of proprioceptive and tactical stimuli in the virtual environment, which may decrease the participant's attention to physical accessibility issues. A fifth of the utterances touched upon affective aspects of public transport accessibility for people with ABI, such as stress and fear. Occupational therapists get to see their clients' anxiety and frustration at close range when they are trying to cope with everyday activities and the fact that the VR methodology seems able to elicit such aspects is a positive result.

The knowledge elicited from the occupational therapists during the virtual bus trip was somewhat different from the knowledge from the video-based think-aloud session. The virtual bus trip utterances regarding accessibility problems tended to rely more on generalisations based on different consequences of cognitive impairment. The video-based think-aloud utterances, instead, tended to be more focused on Subject 1. Furthermore, unique themes emerged in both sessions, i.e. themes that only appeared either during the virtual bus trip or the video-based think-aloud session. Moreover, the occupational therapists themselves believed that the video-based think-aloud session provided another type of understanding. Taken together, this suggests that both methods provide unique knowledge and should be part of the VR methodology in order to cover as many aspects as possible of public transport accessibility for people with ABI.

The occupational therapists were a relatively homogenous group: They were all women in their late twenties with approximately 3-6 years of experience working with people with ABI. How did this affect the results? It is reasonable to assume that a middle-aged occupational therapist with 20 years of experience or so would have more knowledge to share about public transport accessibility issues. However, experience of computers and computer games might make it easier for younger professionals to work with and accept the VR methodology. If the VR methodology was to be used in a real planning situation, a mixed group of occupational therapists would probably be the best solution.

Subjects 6 and 8 had the most experience of working with people with ABI. The fact that they made many more utterances than Subjects 5 and 7 suggests that experience may be an important factor for the ability to share knowledge about accessibility issues. This is supported by studies which have found occupational therapists' experiences to play a role in their clinical reasoning [19,20]. It is also reasonable to believe that the type of rehabilitation an occupational therapist has experience of can affect the sort of knowledge he/she can contribute. Subject 8 pointed out that occupational therapists with experience of home rehabilitation probably can furnish the most valuable information since they have seen their patients in numerous everyday situations outside the hospital environment.

The results suggest that the VR methodology makes it possible for occupational therapists to contribute with valuable knowledge about public transport accessibility for people with ABI. The most relevant knowledge from the occupational therapists is probably that concerned with concrete accessibility problems and suggested solutions (Figure 6).

One way to develop the suggested improvements and take them one step closer to actual implementation would be to use the knowledge of engineers with expertise in information technology. By letting them directly experience the problems that can occur for people with ABI and elaborate on the suggested solutions from the occupational therapists, they could suggest concrete technical solutions to the public transport planners as illustrated in Figure 6. Since the technology experts are familiar with the possibilities of modern information technology, they would also be able to suggest innovative solutions for long-term improvements. Such solutions could then be evaluated using the VR methodology to see how they work for the end-users and how they can be improved.

So far, very little research has been carried out on how VR technology can be used to produce knowledge about accessibility for people with cognitive impairments. The only work similar to the present study is a collaborative project between the University of Teesside and Durham University in the UK, which investigates the use of VR technology for evaluating outdoor environments with people with dementia. In a recently completed study, 38 participants with symptoms of mild to moderate dementia were rated as they performed walks in a virtual town centre [4]. The virtual environment was then redesigned based on the results from their walks and in the subsequent test the participant's performance on the walks improved. The study provides evidence that observations of individuals with cognitive disabilities made in a virtual environment can provide valuable knowledge to a design or planning process. The present study has investigated how another type of knowledge can be elicited by letting the end-users and occupational therapists think aloud. The different perspectives of these two groups produced five types of utterances: accessibility problems, suggested solutions, comments on performance, positive aspects and strategies. The fact that our suggested VR methodology elicits a broad spectrum of knowledge should be regarded as a strength since this provides a more complete image of public transport accessibility for people with ABI. Another strength of this VR methodology is that it combines objective observations with subjective verbalisations from two groups with different points of view on public transport accessibility. This data triangulation is an important support for the validity of the VR methodology.

5 Conclusions

The results of the present study, in combination with those from our previous research [5], suggest that a VR-based methodology can be used to elicit knowledge about public transport accessibility for people with acquired brain injury (ABI). However, the results also demonstrate the importance of carefully considering how such a methodology is used. First and foremost, we would like to emphasise the importance of eliciting knowledge from end-users, such as people with ABI, as well as people with expert knowledge about the end-users, such as occupational therapists. Both groups have their own perspectives and unique knowledge indispensable for public transport planning. We suggest using an interaction method that allows the participants to communicate what they want to do in the virtual environment by means of verbalisations and pointing with a laser pointer. We highly recommend using an ergonomically designed laser pointer such as the one used in the present study. Preferably, the VR system should be one that covers a large part of the participant's field of view. This creates a more realistic experience and makes it easier for the participant to orientate in the virtual environment. Of course, it is not realistic to use a VR system like the one of the present study since it is extremely bulky. There are, however, more compact VR systems available today with a large field of view that could be feasible for public transport authorities. For participants with ABI, the think-aloud session after the virtual bus trip should be conducted more like a normal conversation to make it easier for them to share their knowledge. As for occupational therapists, thinking aloud both while performing a virtual bus trip and while observing the virtual bus trip of a person with ABI seems to be a good way of eliciting a broad spectrum of knowledge. The occupational therapists' think-aloud process can be facilitated by allowing them to pause the virtual bus trip whenever they want. We also propose an initial training session before the actual bus trip starts so that the participant will understand how the VR methodology works and will overcome the initial disbelief of the virtual environment. The training should consist of tasks that teach the participant strategies for performing actions during the virtual bus trip. For occupational therapists, this initial training should be designed to allow them to practise thinking aloud. It is important to be aware of the risks for discomfort that VR technology involves in the form of dizziness or nausea. One simple way of decreasing these risks is to let the participant sit on a chair during the virtual bus trip. Moreover, participants should be screened for motions sickness before being allowed to participate. In our two studies we have mainly examined how impairments in memory, attention, spatial ability and language affect the usage of the VR methodology since we assumed that these four cognitive abilities have the greatest effect on a person's ability to handle the VR methodology. However, we consider the VR methodology to also be a plausible tool for individuals with other cognitive limitations, such as orientation problems or impaired executive function. Individuals with very severe cognitive impairments would probably find it too difficult to use the VR methodology, however. It might seem too difficult at first glance to let people with language impairments participate when using a VR-based methodology in a planning process. However, our research demonstrates that doing so can be fruitful. There is also the possibility of letting the participant bring somebody close to them who knows how to communicate with the participant and who would function as a sort of interpreter.

Further research should study the use of the VR methodology in a real public transport planning context. The aim of this research could be to study how public planners would be able to use the VR methodology and the knowledge it elicits. Another plausible objective would be to study how information technology experts can elaborate on the suggested solutions elicited from occupational therapists with the VR methodology.

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