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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.

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

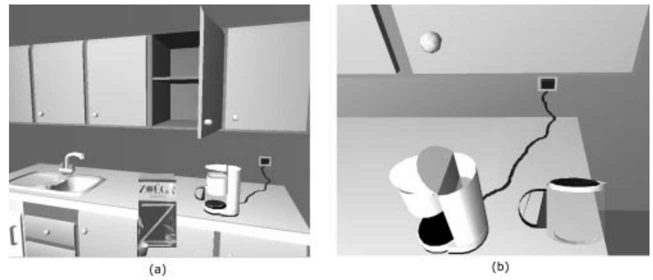

Figure 1. *The coffee brewing VE: a) Overview; and b) The viewpoint is close to the kitchen counter.*

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;

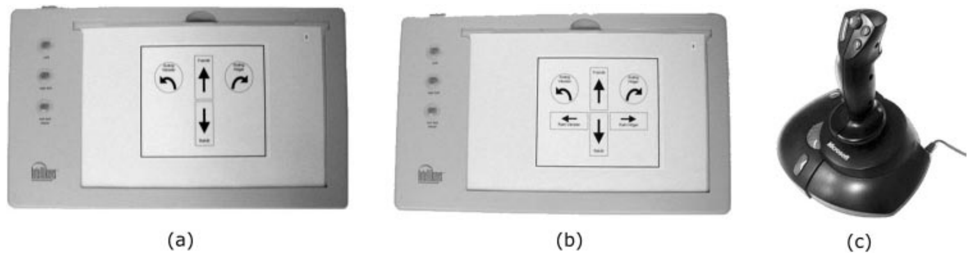

Figure 2. *The IntelliKeys keyboard with a) Two DOFs and b) Three DOFs respectively and c) The Microsoft Sidewinder joystick.*

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

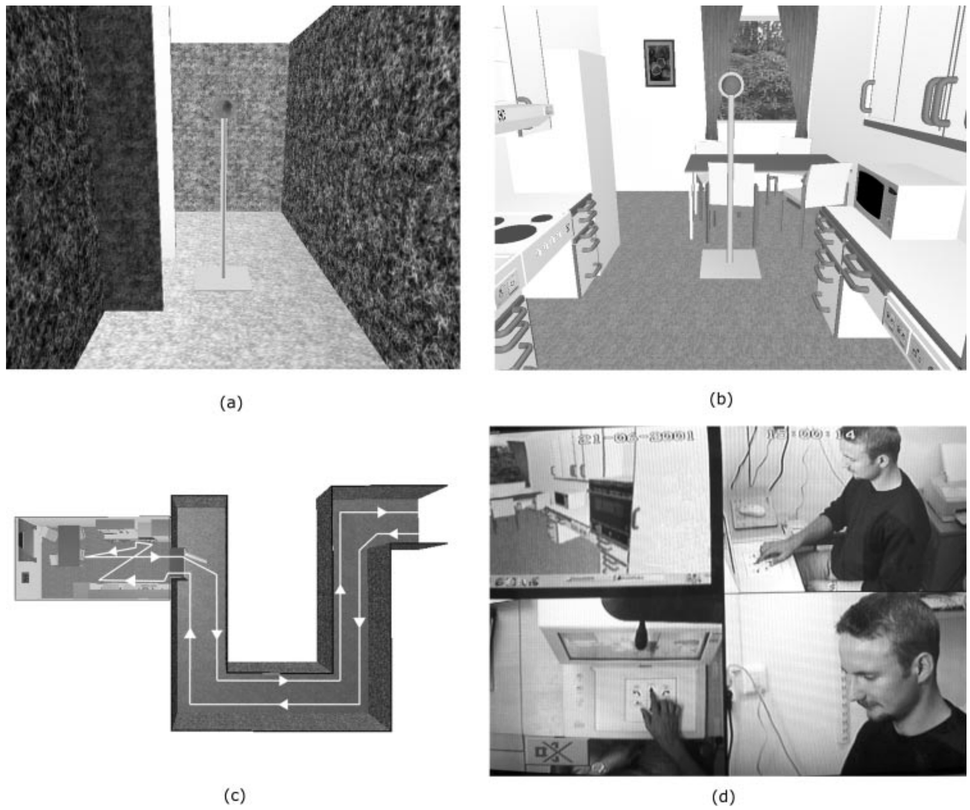

Figure 3. *a) The virtual corridor, b) The virtual kitchen, c) The path of the navigation task, and d) The video signal from the quad mixer.*

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

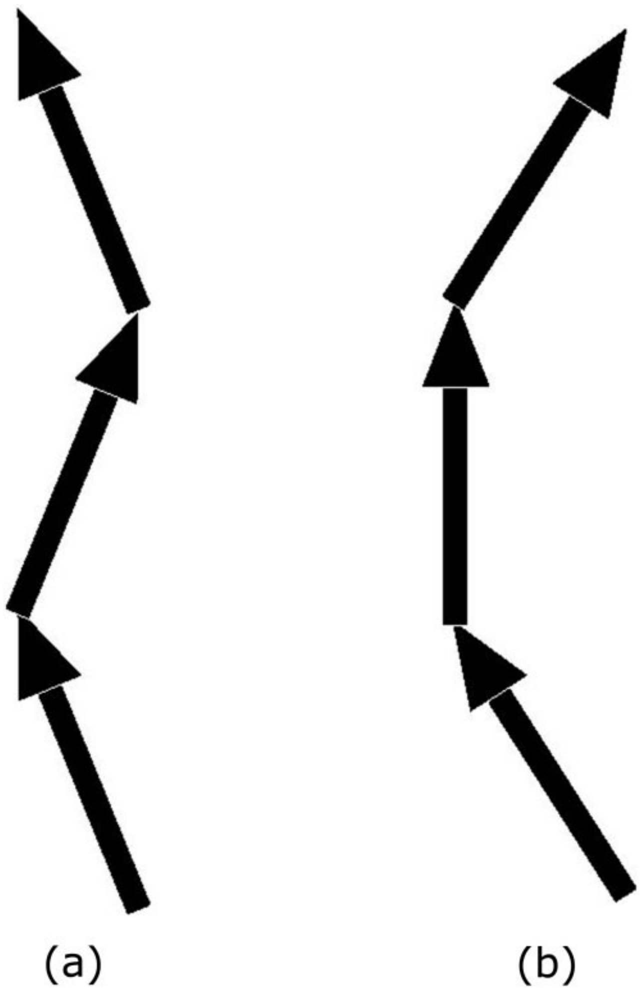

Figure 4. *a) The movement changes from clockwise rotation to counterclockwise rotation and is therefore registered as a direction change. b) The movement has only clockwise rotation and hence is not registered as a direction change.*

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)

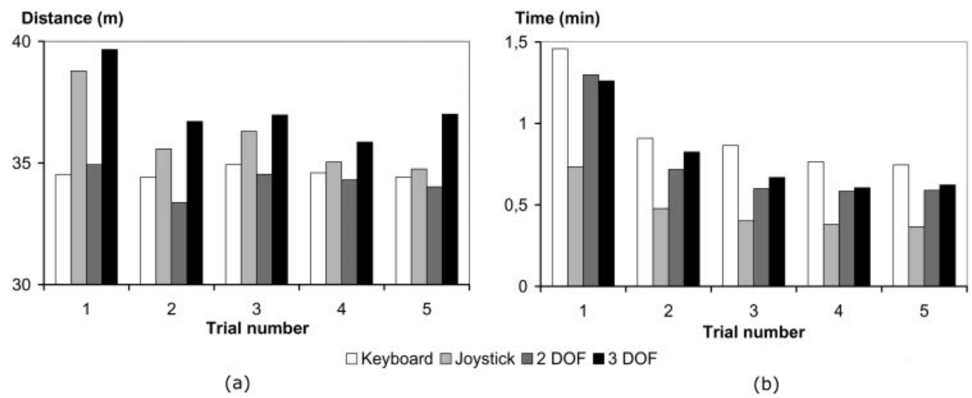

Figure 5. *a) Median distance and b) Median time in the corridor, trial 1–5.*

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-

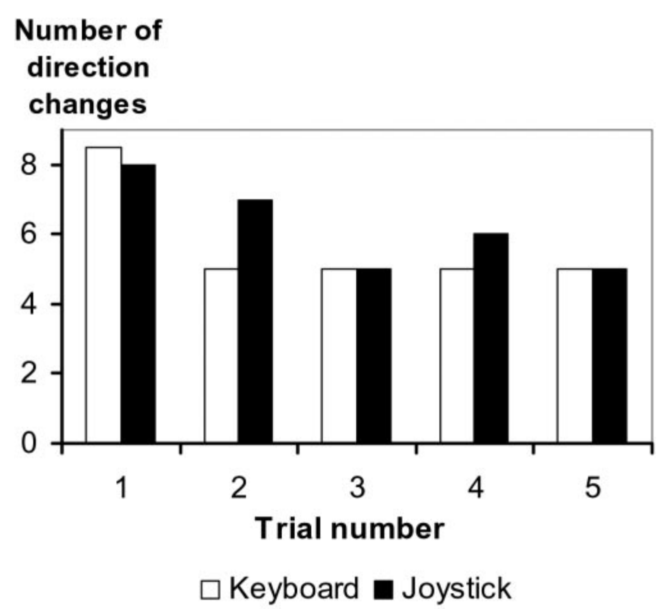

Figure 6. *The median number of direction changes in the corridor for keyboard and joystick, trial 1–5.*

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)

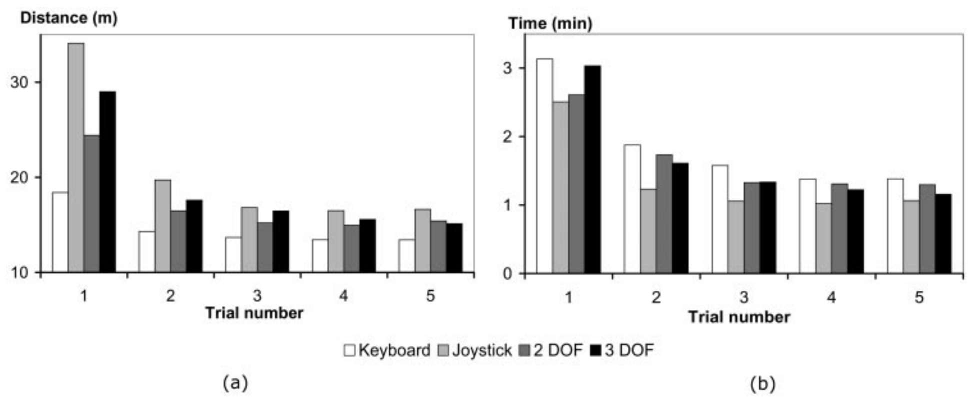

Figure 7. *a) Median distance and b) Median time in the kitchen, trial 1–5.*

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.

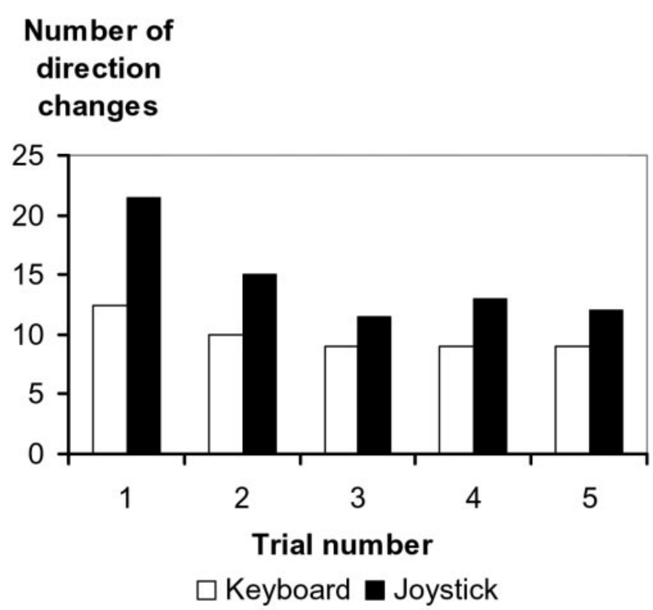

Figure 8. *The median number of direction changes in the kitchen for keyboard and joystick, trial 1–5.*

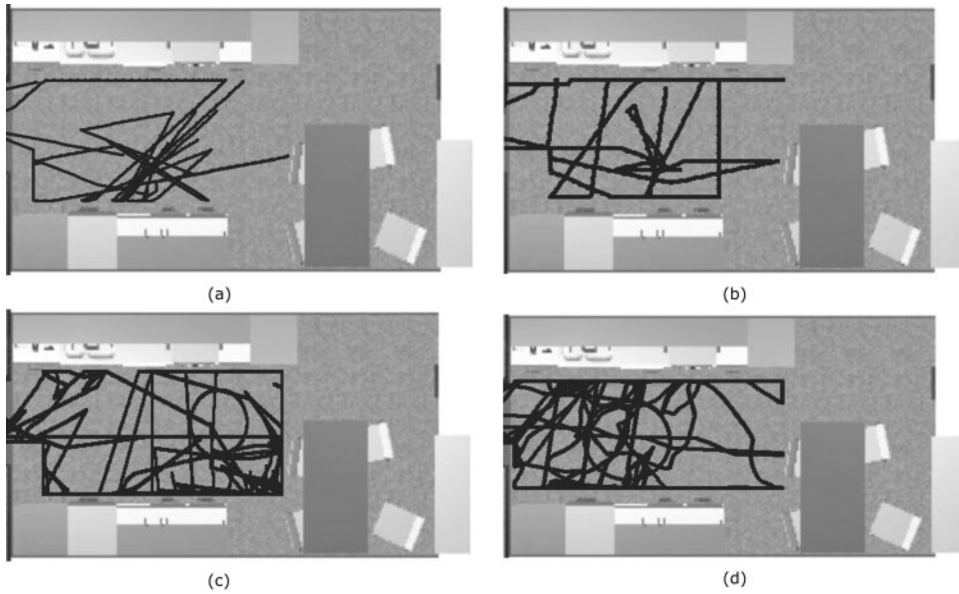

Figure 9. *The first trial's navigation path in the kitchen for the subjects who were judged to have the worst performance in each group: a) Keyboard two DOFs; b) Keyboard three DOFs; c) Joystick two DOFs; and d) Joystick three DOFs.*

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

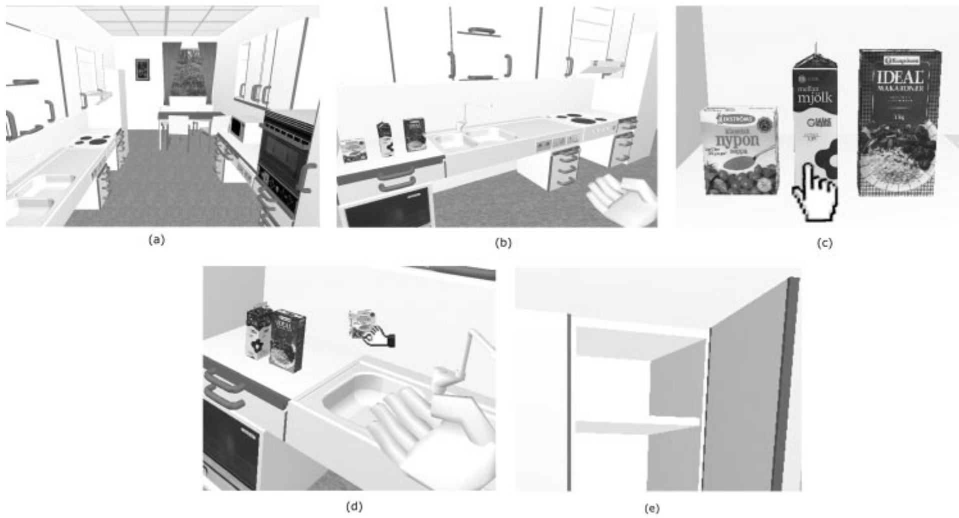

Figure 10. *The kitchen VE: a) Overview of the VE; b) The virtual hand; c) The three packages soup (soppa), milk (mjölk), and macaroni (makaroner); d) Dragging an object (the soup); and e) The top shelf of the cupboard, the destination for the soup.*

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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