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Navigating through a virtual city: Using virtual reality technology to study human action and perception ★

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Abstract

The introduction of virtual reality technology in the field of human perception and behaviour research has spawned many new research initiatives. The paper outlines the motivations of researchers in this field to start using virtual environments for their studies by presenting two such studies conducted in our laboratory. First, we discuss how we are building a large virtual model of the city of Tübingen and how we are using it for our research on human navigation behaviour. Second, we present data on the phenomenon that observers tend to underestimate the perceived speed of their movement through a virtual environment, and we discuss what implications these results have for the design of virtual environments. © 1998 Elsevier Science B.V.

Keywords: Virtual reality; Human behaviour; Perception; Navigation; Biological cybernetics

1. Introduction

The continuing improvements of high-performance graphical supercomputers and display technology over the last decade allows us to create increasingly convincing virtual environments. It is only very recently that scientists have started to realise that this is an almost optimal setting for their studies of human perception, cognition and behaviour. Being able to run experiments under realistic and well-controlled conditions creates many unique research opportunities, and an increasing number of scientists is now starting to explore this new field. The very nature of their research, trying to understand human perception and behaviour, guarantees potential profits for the whole virtual reality community. After all, many questions relating to the perceptually optimal usage of virtual reality technology still remain unanswered.

The Virtual Environments Laboratory at the Max-Planck-Institute for Biological Cybernetics in Tübingen has been founded to conduct systematic research in this specific area. Traditionally, biological cybernetics is a subfield of biology that studies the complete cycle of action and perception in organisms, i.e., how do they acquire sensory information, then process and store it, and finally retrieve this information again to generate behaviour. On its turn, such behaviour (like moving through the world) influences the sensory information available to the organism and therefore closes the action–perception loop. The introduction of virtual environments in the subfield of biological cybernetics that studies human behaviour yields a much more refined and comprehensive control of the elements of the action–perception cycle that lie outside the organism. This opens up a whole new spectrum of research possibilities.

★ Color pictures available. See http://www.elsevier.nl/locate/future

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In this paper we give an introduction to this specific usage of virtual environments by presenting some of the work done in our group. We discuss our motivations for using the technology and we explain two research projects in more detail. The first project, called Virtual Tübingen, is part of our research on human navigation. The goal is to construct a highly realistic virtual model of the centre of Tübingen, which will then be used to study human navigation and orientation behaviour. We discuss the process of building this model and explain how we are starting to use it for our research. The second project is an experimental study by Hartwig Distler from our group on the perception of one's own velocity when moving through a virtual environment. The results have direct implications for the design of virtual environments, and for driving simulators in particular.

1.1. Why use VR for human action and perception research

Investigating human action and perception in complex environments imposes high demands on the experimental platform. The most important requirements are:
- precise control over the presented stimulus (required for reproducible experiments),
- easy manipulation of scene parameters (needed for more systematic research),
- interactivity of the subject with the environment (closes the action–perception cycle),
- capability of displaying complex, multi-sensory scenes (provides a realistic setting).

Whereas the commonly used experimental platforms such as oscilloscopes, computer graphic displays, and the natural environment all violate one or more of those requirements, the advent of virtual environments offers us the means to satisfy these demands. We hold the view that this new experimental platform, though much more demanding in terms of equipment and skills, will eventually provide us with a highly valuable and more direct way of probing and understanding human perception, cognition and behaviour [2,5,9].

1.2. Research in the virtual environments group

The Virtual Environments Laboratory conducts research on human spatial abilities in real and virtual environments. We currently concentrate on four major topics: Motion in Three Dimensions (course control in car-driving; perception of one's own movement through a scene), Navigation & Orientation (exploring new environments; how do we integrate spatial information from different sensory inputs; cognitive maps), Spatial Encoding of Scenes (recognising scenes from new viewpoints; recognising changes in scenes; the role of auditory cues in scene recognition), and Grasping (how do the haptic and visual senses collaborate when grasping objects). For all these studies we use virtual environments.

A major concern about research investigating human action and perception in virtual environments is whether the results that are obtained can be transferred to natural environments. An applied version of the same question is commonly asked by people who use virtual environments for training purposes: how effective is training in a virtual environment for behaviour in the real world? One way of answering this question is to run at least part of the experiments in a natural environment as well. If the results gained in both environments are consistent with each other, further experiments can be performed in the virtual environment taking advantage of the advanced features. This view generates the need for virtual environments that are modelled after a corresponding real environment. The Virtual Tübingen model (see Section 3) is being created to satisfy this demand. By comparing navigation and orientation behaviour in the real city and in its digital counterpart we can establish an important relationship between studies conducted in the natural environment and those conducted in virtual environments.

Sometimes the differences between the natural and the virtual environment manifest themselves quite clearly. For instance, it is a well-known fact that the perceived velocity with which one seems to move through a virtual environment is often underestimated. Such cases should not be considered arguments against the usage of virtual environments for our type of research. Instead, they provide an easily accessible experimental handle for studying the influence of certain simulation parameters on human perception and behaviour. Section 4 describes an experimental study by Hartwig Distler from our group, in which he investigated the phenomenon of underestimated speed more carefully. Among the factors that turn out to play a role in this effect are the spatial frequency content and contrast of the depicted virtual world, as well as the size of the field of view. He concludes the section with a discussion of factors designers of simulations should take into account when they want to avoid such problems.

2. Simulator set-up

In 1997 a new Virtual Reality laboratory was built in our institute, in which we now perform most of our experiments (also see Fig. 1). The lab features a large curved projection screen (half-cylinder of 7 m diameter and 3.15 m height). A very fast graphical supercomputer (Silicon Graphics Inc. ONYX2 3-pipe InfiniteReality, 10 processors, 2.5 GB main memory) is used to compute highly detailed images that are then front-projected onto the curved projection screen, in stereo if required. Proper softedge-blending hardware (Panoram Panomaker II) is used to merge the three individual images produced by the Electrohome Marquee 8000 projectors together to one 3200×1000 pixels image. For an observer seated in the centre of the cylinder, this image covers a visual angle of 180° horizontal by 50° vertical. Alternatively, experiments can be conducted using a HMD (Virtual Research V8) or high-resolution computer monitors. Depending on the type of experiment we make use of several interface devices. In driving studies we use a force-feedback steering wheel and simple controls to give the subject a natural interface for driving. The torque exerted at the steering wheel is computer-controlled and is based on a car dynamics simulation. In several of the navigation studies we use a bicycle simulator consisting of a modified exercise bicycle originally distributed by Tectrix and Cybergear. The VRbike allows one to actively steer and pedal through the virtual city [9]. The bicycle tilts as you steer through the world, just as a real bicycle would do. The design of the VR-bike allows for a realistic simulation of the physical aspects of bicycle riding. For instance, the inertia of the bicycle is simulated by two fly-wheels connected to the pedals. The pedal resistance is computer-controlled and can be used to simulate going uphill or downhill, or driving on roads with different friction coefficients. Finally, for the grasping experiments we make use of a pair of Phantom force-feedback devices. These devices allow us to control the forces present at thumb and index finger when grasping a virtual object.

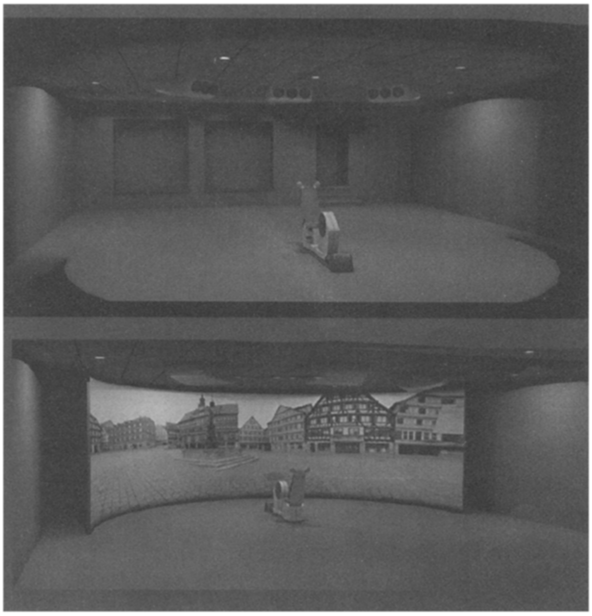

Fig. 1. Impression of the virtual reality laboratory. The upper picture shows the projectors attached to the ceiling above the VRbike. The lower picture displays the VRbike directly in front of the projection screen, on which a panoramic image of Tübingen can be seen.

3. Virtual Tübingen

3.1. Motivation

One of several long-term research directions of our lab is to study aspects of navigation. Until recently we have used artificial virtual environments for the experiments, i.e., we created a non-existent computer graphics town, called 'Hexatown', and studied how subjects explored this environment and what kind of spatial information they used to navigate through it. Using virtual environments for this kind of human navigation research turned out to be a fruitful approach [6,12,13]. The technology enabled us to perform systematic changes of the environment and allowed us to vary the level of subject interactivity (subject means: the observer in our experiments), both of which we cannot easily accomplish in natural environments. Some of these manipulations are:

- changing position, size and orientation of objects (e.g., moving buildings in the town),
- manipulating the appearance of objects and roads (colour, texture, etc.),
- modifying the layout of the scene (e.g., adding or removing roads in an urban model),
- use different metaphors for interacting with the environment.

To study navigation in larger and more complex environments, and to be able to address the similarities and differences between navigation in real and virtual environments, we decided to create a virtual model of the city in which we live: Virtual Tübingen. Having a virtual model of a real city allows for some rather elegant experiments. One of those experiments studies the transfer of knowledge between virtual and real environments, i.e., can we use our experience with a real city for navigating through a virtual model of it, and, perhaps more interestingly, how well can we learn to navigate in a real city by training ourselves in a virtual model of it? Apart from learning about human navigation, we hope to obtain indications on how to improve the type of virtual environments that we and many others use (also see Section 4).

We are aiming to model the centre of Tübingen, which is a 600 × 400 m area, densely packed with approximately 600 houses and other buildings. There are many obvious and less obvious reasons to choose Tübingen as a model for our virtual city. The first major reason relates to the observation that the centre of Tübingen has a rather complicated structure: there are considerable height differences, the streets often tend to be curved and have varying width, and the medieval buildings are all different and have complicated façades. This complexity is expected to contribute a lot to the degree of realism that we are aiming at and provides a much more interesting environment for running navigation experiments than highly regular cities offer (e.g., New York City). The second major reason is that we like to pursue a high degree of photo realism, which is possible using real pictures and very fast, high-quality texture mapping. The process of making pictures and having access to architectural data is of course much easier for the local town. Secondary reasons include the fact that modelling the local town makes it easy to find people who are well trained in navigating through the real version of Tübingen. That offers special benefits regarding the kind of experiments we are planning to do.

3.2. General approach

As is the case with any modelling project, the special application that we have in mind for the Virtual Tübingen model imposes some restrictions on the accuracy of it. We have to deal with two conflicting interests: the subject (the observer in our experiments) must be able to interactively move through the environment in real time, and this virtual environment must resemble its real counterpart as well as possible. The basic choice we have made is to use a relatively simple geometry for the buildings and to use photographs of the actual city as highly detailed texture maps. We expect the final model to have 100–200 k polygons and 1–2GB of textures. The need for real time interactivity means that frame rates of 30 Hz and possibly higher are desirable. This can be achieved by using high-performance computers and software techniques like visibility culling, level-of-detail management, and dynamic database loading. The most difficult problem to solve is that of the real time management of the huge amount of textures. Hardware architectures that support virtually unlimited quantities of texture memory are now starting to become available (like SGI's clipmapping on InfiniteReality Systems or SGI's unified memory architecture used for O2 systems [23]), but certainly need further improvements to make

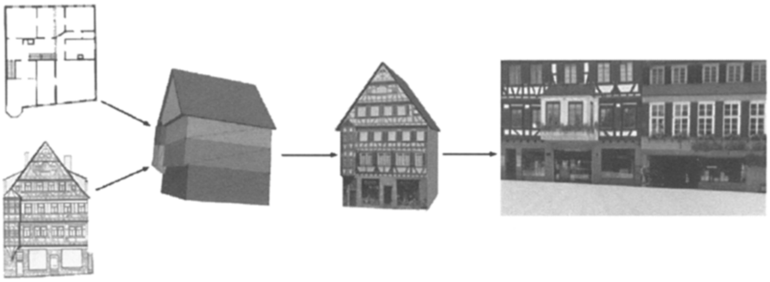

Fig. 2. Model construction process. We use architectural drawings to create simple polygonal models of the buildings. Textures are extracted from photographs taken in real Tübingen and are mapped onto the polygonal models to provide a detailed visual image.

implementing models like Virtual Tübingen more efficient.

There are several different ways in which one can construct virtual geometrical models of existing buildings. A common approach is to use photogrammetric methods, sometimes in combination with template matching. These techniques use the images taken from one or more viewpoints to infer the geometry of a building (e.g., [16] or [7]). Because these methods operate on pictures or video sequences they often have the advantage that the necessary textures are obtained (and mapped) along the way. Another approach, which is the approach that we have taken, is to make use of architectural drawings. We have chosen this method because it allows us to control the simplifications of the geometry in a consistent way (e.g., the walls on all floors are flat and vertical). Furthermore, creating the necessary textures in a separate process allows us to control the quality of those textures in a consistent manner.

3.3. Geometry processing

For the construction of 3D-models of the buildings we use architectural drawings provided by the city administration. We have separate floor plans for each floor of almost every building, as well as drawings of the front and back of those buildings. This multitude of drawings is rather useful because the houses in Tübingen are quite irregular; e.g., it is very common for the upper floors to stick out a little relative to the lower floors. The construction of the geometry proceeds as follows. We digitise the drawings using a graphics tablet and manually select the relevant points (corners) on each of these drawings. The front and back views are used to indicate the height of each floor and the roof. After having digitised the drawings in this way we use a purpose-built software tool that generates a polygonal 3D-model of the building. A problem that becomes apparent at this stage is that the drawings carry no alignment markers. This means that they have to be aligned manually (shifting and rotating) using some assumptions about the actual spatial relationships between the different floors. The complete process usually takes between 15 and 30 min per building. We then use a commercial modelling tool like Multigen to refine the geometry, which takes another 25–45 min for a normal building. At this stage we have a triangulated model of the building that typically consists of 100–200 polygons (also see the left part of Fig. 2).

3.4. Texture processing: CorTex

Most of the realism in *virtual* Tübingen derives from the actual photographs of *real* Tübingen, which serve as texture maps. Because the majority of buildings are actually houses grouped together in blocks (rendering the side walls largely invisible), we concentrate on texturing the front of a building. Thus we need at least one texture for each floor. In the centre of Tübingen there are many places where the houses are typically 20 m high while the streets are only 5 m

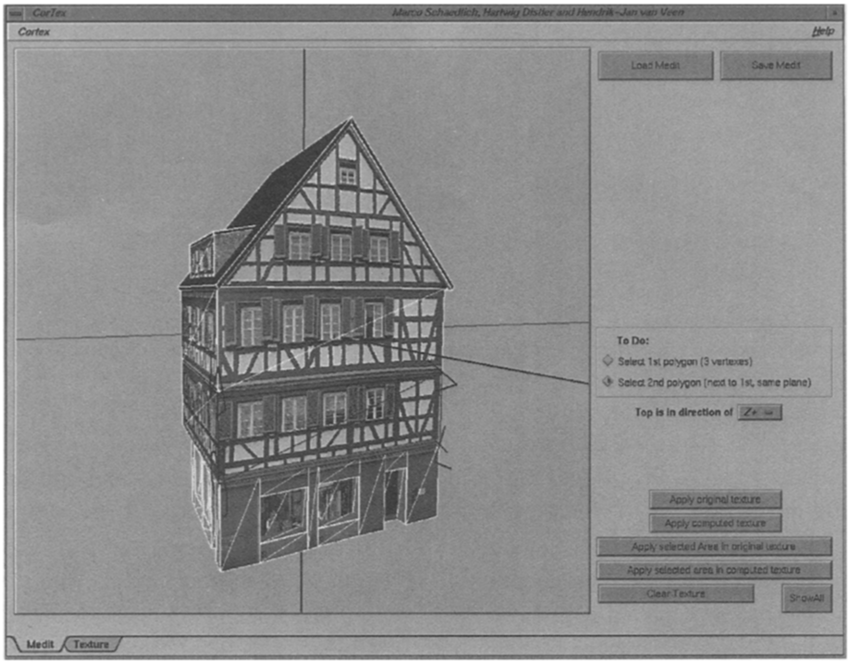

Fig. 3. A snapshot of the 3D model handling tabbed deck of CorTex. All textures of the house of interest have already been mapped. The red lines and the numbers in the second floor of the model depict two selected polygons.

wide. This causes some problems with shadowing and obstacles, but it also means that even with a wide-angle lens one cannot photograph a house from the front, which causes considerable perspective distortion. We have written a modeller called CorTex (Correcting Textures) that allows us to map the scanned (and distorted) images in a perspectively correct way onto the polygonal model without knowing the camera parameters. This is possible because the walls of our polygonal buildings consist of flat quadrangles. Mapping flat areas correctly only requires one to establish the correspondence between four pairs of points in the image and the polygonal model, which is easily done by hand (we implemented an algorithm given in [15]). CorTex was developed in C++ integrating functions of OpenGL, RapidApp, and the ImageVision Library from Silicon Graphics. It consists of two tabbed decks. The first tabbed deck is assigned to handling the geometry of the house, whereas the second tabbed deck is assigned to image processing (see Figs. 3 and 4). This fast mapping procedure allows for the automatic and consistent control of texture resolution and thus supports multiple levels-of-detail. At the highest level-of-detail a building has several megabytes of texture attached to it.

3.5. Current status

At the moment roughly 350 buildings have been modelled, and due to the recent completion of CorTex only about 10% of these houses have been textured yet (see Fig. 5). A snapshot of part of the model in its current stage is depicted in Fig. 6.

3.6. First experiments

Although the model is still under construction we have initiated the first experiments. Since we are interested in a comparison of human spatial behaviour in real and virtual environments we have started to conduct spatial orientation experiments in the real city. Subjects who had lived in Tübingen

Fig. 4. A snapshot of the texture processing tabbed deck of CorTex. The image being shown is a typical perspectively distorted photograph. Four points on the second floor have been marked in preparation for the perspective correction process.

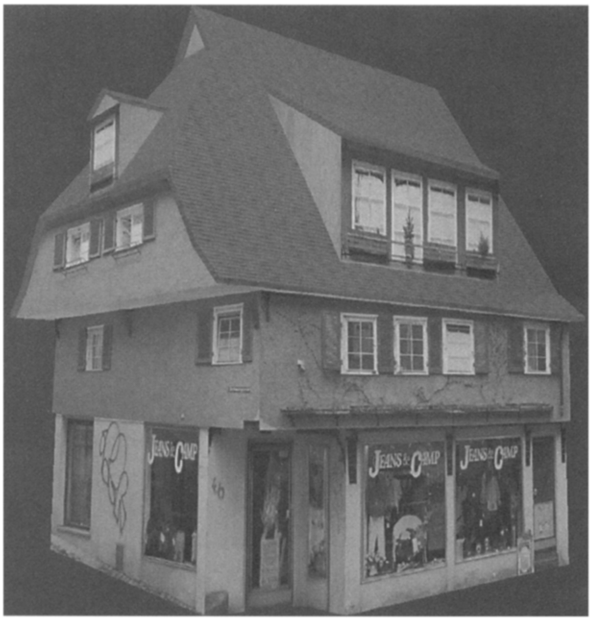

Fig. 5. An example of one of the completed houses in Virtual Tübingen.

Fig. 6. Bird's eye view of the partly modelled central market square in Virtual Tübingen. The texture on the ground plane is the cadastral map of the area, which is being used for positioning the buildings relative to each other.

for at least two years, and who were therefore expected to have a detailed mental representation of the city, were asked to point to invisible (occluded) landmarks in the city, like churches and the city hall. We then brought these subjects to our lab and set them in front of the projection screen on which we projected panoramic images (real photographs) of the city. These images were taken at the same location as where subjects had to point to landmarks in the real city, thus creating the impression of being at that location again. Once more, subjects were asked to point to where they thought the landmarks would be. The first preliminary results [21,27] show that the accuracy with which subjects are able to indicate the correct direction of hidden landmarks is quite high, with a minor decline in performance in front of the projection screen: the mean absolute pointing error was 12° instead of 10° in the real city (averages over seven subjects). Apparently, subjects do not get disoriented in front of the projection screen, which is a rather promising result. In the next stage subjects will eventually perform the same experiment again while cycling through Virtual Tübingen.

4. Perception of velocity in virtual environments

4.1. Background

The study described in this section was initiated after we noticed the following problem when we started using our bicycle simulator to cycle through some of the predecessors of Virtual Tübingen. Participants in our experiments reported that the same pedalling effort leads to different results in the natural and virtual environment. The experienced difference was due to an underestimation of their cycling velocity [9]. To compensate for this subjective impression, subjects started pedalling faster and/or increased the gear. Not being used to the increased physical effort, subjects felt tired and exhausted before they finished the experiment. Since in most cases data of subjects who do not finish the experiment cannot be used, which is rather inefficient, we decided to systematically investigate what the causes of the underestimation of velocity might be.

As it turns out, the phenomenon that participants of a simulation underestimate the velocity of the simulated egomotion is a common experience shared by most designers of driving simulators. When such a driving simulator is used to teach or improve people's driving skills, a misperception of velocity can become very dangerous when trainees transfer their driving behaviour to the real driving situation. Other types of simulators might be less effected by such a misperception of velocity, but in general a better velocity percept will help to improve the quality of the simulation.

After excluding any methodological errors by carefully revisiting the physical model of our bicycle, it became clear that the underestimation of velocity was due to the insufficient simulation or absence of certain velocity cues. As has been shown by Ohta et al. [19], velocity perception in our natural environment is a multi-modal percept. This means that perceived velocity does not only depend on the visual sense, but is influenced by acoustic and tactile (vibration) cues as well. Although it is known that we have a reasonable percept of velocity in the absence of visual stimulation, very little is known about how visual, acoustic, and tactile information are integrated in the process of perceiving velocity. Nevertheless, for the reason that the predominant source of information in our bicycle simulator is visual information, we decided to concentrate on studying the influence of visual cues on perceived velocity in more detail.

Although there is a considerable amount of research studying time-to-contact [4,20,24], including studies in virtual environments [1], until very recently just a few studies have investigated velocity perception in natural [11,22] and virtual [10,17,18] 3D environments. In contrast to this, an extensive literature on 2D velocity perception exists. Common to most of these studies is the usage of simple stimuli such as dots, lines, and gratings moving in the (2D) image plane. This psychophysical research has shown that especially spatial frequency [3,8] and contrast [14,25,26] of the visual stimulus have significant effects on perceived velocity: increasing spatial frequency and contrast can, to a certain extent, increase the perceived velocity. Distler et al. [10] replicated the results of the above studies using an open loop driving simulation.

Although it is rather difficult to determine the spatial frequency and contrast of a 3D pattern, they were able to show that the perceived velocity of egomotion (i.e., a 3D motion percept) can indeed be increased by increasing the spatial frequency and contrast of the depicted pattern. Larish et al. [17] provided evidence showing that the optical edge rate and not the optic flow rate is the predominant information source for perceived velocity. Larish defines optical edge rate as "the rate at which local discontinuities cross a fixed point of reference in the observer's field of view". Based on the results of these studies, Levine et al. [18] conducted an experiment in a driving simulator investigating the influence of roadside delineation poles on perceived velocity. By manipulating the position of the poles they were able to show that the farther away the poles are from the road, the smaller the perceived velocity in the driving simulator is. In the next sections we present results on the influence of another important factor, namely the size of the field of view.

4.2. Field of view and perceived velocity

During a major upgrade of our simulation environment we increased the size of the horizontal field of view (HFOV) from 50° to 180°, while the vertical field of view was increased from 40° to 50°. First tests of the new set-up revealed that although we were displaying the same scenes as in the previous set-up the perceived velocity of egomotion was improved. To systematically study the influence of the size of the HFOV we conducted the following experiment.

4.3. Experimental method

In a two alternative forced choice (2-AFC) paradigm participants observed two successively presented driving simulation sequences (presentation time: 2 s) simulating vehicles moving at different velocities on surfaces with random dot textures (dot density: 20%). The choice for a dot density of 20% is based upon results of our previous experiments investigating the influence of spatial frequency and contrast [10]. The two presentations were separated by a 1.5 s presentation of a homogenous background. The HFOV of one presentation (the standard stimulus) was always 73° and its simulated velocity was 7 m/s (25.2 km/h). We tested four different HFOV's (37°, 73°, 107°, 180°) of the other presentation (the test stimulus). The simulated velocity of this stimulus was adjusted by an adaptive staircase procedure. Standard and test stimulus were presented in randomised order. Four subjects viewed the scene from the viewpoint of the car driver and judged which driving simulation (first or second) depicted the faster moving vehicle. The experimental procedure described above allows us to determine the point of subjective equality (PSE) as a function of the HFOV. PSE is defined as the simulated velocity necessary to perceive the egomotion at a certain HFOV as fast as the simulated egomotion at the standard HFOV.

4.4. Results

There is a small, but significant influence ($F(3, 9) = 4.351$; $p = 0.0374$) of the HFOV on perceived

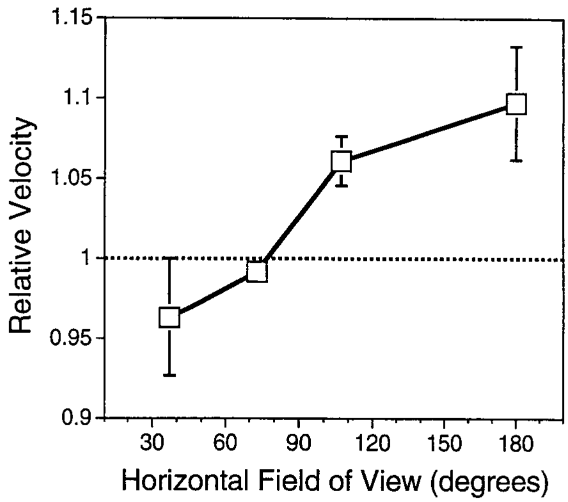

Fig. 7. The graph depicts the relationship between perceived velocity of egomotion and the size of the HFOV. The data are the average of four subjects who repeated the staircase three times. Perceived velocity is plotted as the quotient of the velocity of the standard stimulus (7.0 m/s) over the velocity of the test stimulus at the PSE. If the relative velocity has a value greater than 1.0, the test stimulus is perceived as moving faster than the standard stimulus and vice versa. If the size of the HFOV would not exert any influence on perceived velocity the relative velocity (dashed line) should have a value of 1.0. The size of the HFOV of the standard stimulus was 73°. The error bars correspond to one standard error of the mean.

velocity of egomotion (see Fig. 7). By increasing the HFOV from 37° to 180° the perceived velocity is increased by 13%. The results furthermore indicate that increasing the HFOV from 73° to 107° accounts for 50% of the increase in perceived velocity, while increasing the HFOV from 37° to 73° and from 107° to 180° has less impact on perceived velocity.

4.5. Discussion

The results of experiments studying the perceived velocity of egomotion in driving simulators show that perceived velocity depends on several factors. No single factor can account completely for the apparent misperception of velocity in virtual environments. As far as the visual aspects of driving simulations are concerned, three factors that can account for differences in perceived velocity in driving simulators have been investigated more carefully. First, perceived velocity can be increased by increasing spatial frequency and contrast of the depicted virtual world [10]. Second, by increasing the edge rate of a driving simulation the perceived velocity of egomotion can also be increased [17]. Third, we have shown in this study that increasing the size of the field of view has a small but significant impact on perceived velocity.

What do the above results mean for designers of driving simulators? In general it can be said that taking the results of all studies into account is the best solution for improving velocity perception in driving simulators. However, due to technical limitations (field of view, hardware texture mapping) or requirements of the application it is sometimes not desirable, possible or applicable to implement all the results. Size of field of view is clearly a technical limitation and is usually associated with high costs. In contrast, edge rate depends on the layout of the simulated scene. By adding small objects such as delineation poles next to the road the velocity percept can be improved substantially. Implementation of the third factor, spatial frequency and contrast of the depicted simulation, can be achieved by manipulating the texture maps of the roads and the surrounding environment in such a way that their spatial frequency content and contrast are optimal. However, to prepare the textures in an efficient way, the designer not only has to take into account aspects of projective geometry, instead she/he also needs to be aware of display parameters including gamma function, resolution and size of the display, as well as the viewing position of the participant.

5. Concluding remarks

In this paper we have outlined our motivations for using virtual environments for conducting research on human perception and behaviour by providing detailed information about two rather different studies carried out in our laboratory. Whereas the first study relies on the simulation of virtual environments such as Virtual Tübingen for the investigation of human navigation and orientation behaviour, the second study is concerned with a practical aspect of the simulation itself, namely the underestimation of perceived egomotion in simulators. In some respect these two studies are complementary, in the sense that we cannot study human spatial abilities using virtual environments without also studying the effects of those virtual environments on our perception and behaviour. Similar observations can be made about our work on grasping behaviour, where we find that studying grasping using virtual haptic feedback cannot be separated from studying how haptic displays can generate an impression of touching a solid shape. As we argued before, biological cybernetics seems to offer a useful experimental approach for studying these closed loops of humans interacting with their environment, be it a real or a virtual one.

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