Gaze control and cognitive load in active vision - Task specific strategies in normal and visually impaired subjects

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…the visual field is an "island of vision in the sea of darkness" (Traquair, 1931)

General Introduction

The visual sense and the function of shifting the direction of gaze

The seeing sense endows animals with a great advantage because it allows them to obtain information concerning the nature and location of objects in their environment without the need for direct or close physical contact, as required by more proximal senses like touch, taste, and smell. The direct physical stimulus for visual perception is light of differing wavelengths reflected by two groups of photoreceptors (i.e. rods and cones). Subsequent neural networks responsible for processing the perceived visual information are located in the retina, the lateral geniculate nucleus of the thalamus, and several primary sensory and higher association areas of the cortex. In humans, vision is arguably the major sensory input to the brain, by virtue of the fact that about half of all afferent fibers projecting to the brain - over one million - originate from the eyes. Additionally, there are about 120 million rods together with six million cones in the retina forming circa 70% of all exteroceptor cells in the human body.

The visual world contains more information than can be perceived and processed during a single glance. Furthermore, the visual system is restrained by the physical limitations of the eye, as well as the cognitive limitations of attention and memory. To overcome the problem of being confronted massively with a huge amount of visual information without losing the ability to monitor a large field of view (FOV), the retina of human beings evolved to differ in spatial resolution across regions. The peripheral areas with comparatively coarse visual resolution allow us to gain a broad view over the visual surrounding and thus enable us to perceive and process sudden stimulus changes in the outer visual field related to fast stimulus movements. To obtain and process detailed visual information, a region providing the highest spatial resolution and therefore processing capability, termed fovea, has to be actively aligned with the object of interest. The retina's differently developed spatial resolution is based on varying densities of photoreceptors (primarily cones, whereas rods are more evenly distributed over the retina) and their neural connections onto receptive fields. There, the cones reach a peak density of about 164,000 cones/mm^2 (Putnam et al., 2003) within the foveal region allowing for the highest visual acuity in the eye (cp. figure 1). The cone density declines steadily in all directions (Wertheim, 1894) from the fovea with a slightly elevated density distribution along the horizontal axis compared to the vertical one. The only exception in the distribution of photoreceptors is a small island (termed "blind spot") where neither cones nor rods are present, and thus no visual perception can occur. This island corresponds to the optic disc where all axons leave the eye to form the optic nerve.

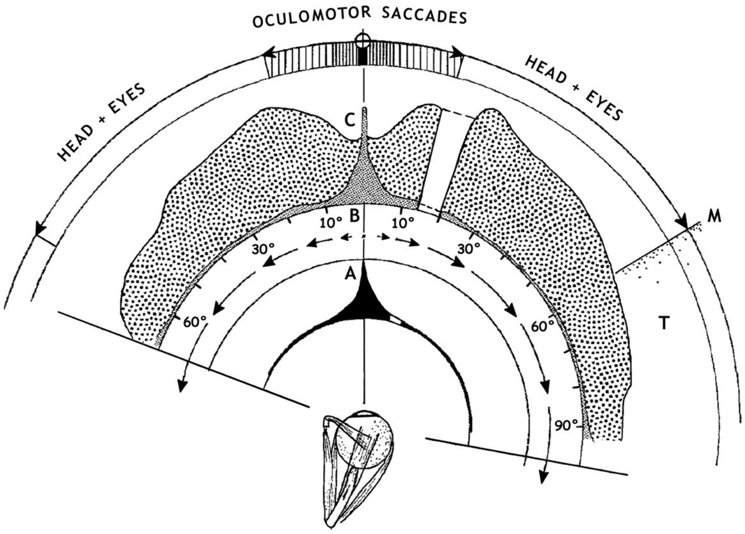

Figure 1: The visual field of a human's right eye at the horizontal meridian (modified according to Trevarthen, 1968). A - Relative visual acuity. B - The retinal displacement vectors for objects at equal distance from the eye when this moves forward along its axis (flow field vectors). C - Relative frequencies of rods (large dots) and cones (small dots). M - Anterior border of the monocular temporal crescent.

Perceptual systems are constantly sampling selected portions of the surrounding environment. In vision, rays of light originating from the attended stimulus regions are imaged onto the retina and transduced into electrical signals that are processed by the nervous system. Ultimately, these signals are used to form visual percepts based on these perceived stimuli. In order to maintain fidelity, a perceptual database (Boothe, 2002) must be updated whenever important changes occur in the visual surrounding. To maintain an updated perceptual database, the line of sight (i.e. direction of gaze) has to be oriented continuously to new informative regions of the visual surrounding. Such a visually sampling system was termed an active vision system[1)] (Aloimonos et al., 1987) which contains stimulus triggered bottom-up and cognitively driven top-down processing of a given stimulus material. To shift the gaze (gaze ≡ eye-in-space = eye-in-head + head-in-space) towards new informative regions, rapid movements of the eyes (i.e. saccades) as necessary in combinations with much slower movements of the head are executed (e.g. Freedman & Sparks, 1997; Guitton, 1992; Klier et al., 2003; Phillips et al., 1995; Tomlinson, 1990). Gaze shifts tend to occur at a rate of around three to four times per second with visual information extracted from the environment primarily when the direction of one's gaze is relatively stable (related to the object of regard). These periods of stability are called fixations. Humans employ varying amounts of head movement in association with saccadic shifts in gaze. Head

[1)] Ballard (1991) preferred the term "animate vision" for such an active system. He wished to avoid possible confusion with active sensing, a term preempted in the computer vision world (Marr, 1982).

movements are unlikely for very small gaze shifts, but their probability increases as the saccade amplitude grows. One prominent hypothesis states that a consequence of head movements is the reduction of postsaccadic eye eccentricity thus allowing one to maintain the eye within a customary ocular motor range (COMR; Stahl, 1999) that is considerably narrower than the full-scale ocular motor range of approximately ± 55° in humans (Guitton & Volle, 1987). The COMR in human subjects was investigated with ± 22° (Stahl, 1999). In other words, head movement tendencies can be quantified by the width of the eye only range, the slope of the eye-head range, and the width of the region within which the eye was likely to be found at the conclusion of the completed gaze-shifting behavior - the COMR. The magnitude of head movements in head-free subjects reveals for a large intersubject variability (Borel et al., 1994). However, subjects invariably move their heads to some extent (Kowler et al., 1992; Pelz et al., 2001). Differing results are published by Freedman et al. (1996) and Fuller (1992) who claimed head movements were not a regular feature of gaze shifts until approximately 20°. Regarding to this discrepancy Pelz et al. (2001) argued the magnitude of head movements is probably a function of the particular constraints of the experiment, with small head movements almost always accompanying gaze shifts in natural tasks.

To process and generate vision related behavior, an indispensable cognitive resource is the visual domain of working memory[2)] (cp. Baddeley, 1978, 1992, 2003). This theoretical framework refers to the neural structures and processes used for temporary storage and manipulation of visual information. One of the most impressive characteristics of this memory structure is its severe storage capacity limitation. Specifically, visual working memory can maintain information about approximately three to four objects at any given time, and this information appears to be coded in the form of integrated object representations, rather than as a collection of disconnected visual features (e.g. Irwin & Andrews, 1996; Luck & Vogel, 1997). Irwin (1991) suggests that only information which has been the focus of attention will be retained across saccades and that this has the capacity limits associated with visual working memory. In their "just-in-time processing hypothesis", Ballard et al. (1992) claimed that subjects choose not to operate at the maximum capacity of working memory when free to select their own strategy. Instead, they seek to minimize reliance on working memory by acquiring information incrementally during the task. Finally, gaze changes can performed rapidly and the visual environment can be understood as external memory where the acquisition of visual information, achieved by gaze movements, is delayed until the point in time when it is needed. Thus, it seems unlikely that anything like a complete viewer-independent reconstruction of the visual scene is built up from successive gaze locations, as is often thought to be the job of vision (Marr, 1982).

[2)] There have been numerous models proposed regarding how working memory functions, both anatomically and cognitively. Of those, the theoretical framework assumed by Baddeley (1978) has received the distinct notice of wide acceptance.

Patients with homonymous hemianopia and their visual field restrictions

Each eye perceives a part of the visual space that defines its visual field. The visual fields of both eyes overlap extensively to create a binocular visual field. The total visual field is the sum of the right and left hemifields and consists of a binocular zone and two monocular zones (cp. figure 3). Just like the visual field is divided into two hemifields, the retina is divided in half, relative to the fovea, into a nasal and a temporal hemiretina. Each hemifield is projected onto the nasal hemiretina of the ipsilateral (i.e. on the same side) eye and the temporal hemiretina of the contralateral (i.e. on the opposite side) eye. The axons of ganglion cells exit the eyes via the optic nerve, partially cross at the optic chiasm, and form two optic tracts, so that the right and left hemifields reach the left and right hemispheres. Each optic tract receives information from the opposite hemifield, combining inputs from the ipsilateral temporal hemiretina and the contralateral nasal hemiretina. The retina projects to four subcortical regions in the brain: the lateral geniculate nucleus, the major subcortical center relaying visual information to the primary visual cortex; the superior colliculus, which controls orienting eye movements; the hypothalamus, which regulates the circadian rhythms; and the pretectum, which controls the pupillary light reflex (cp. figure 2).

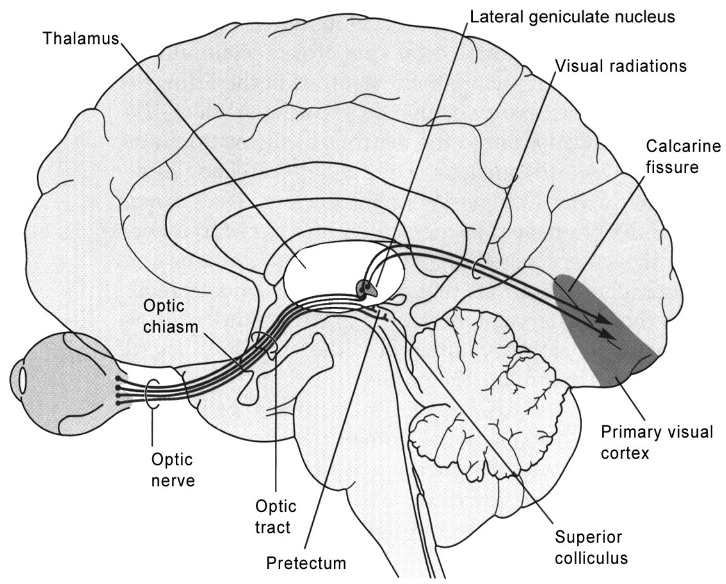

Figure 2: Projections from the retina to the visual areas of the thalamus (lateral geniculate nucleus), the midbrain (pretectum and superior colliculus), and the primary visual cortex (modified according to Kandel, Schwartz & Jessell, 2000).

Patients with a lesion affecting their posterior visual pathway (cp. figure 3) may develop homonymous visual field defects (HVFDs). There, homonymous hemianopia (HH) is a HVFD in which, for both eyes to the same extent, half of the visual field is blind (*homonymous*: same; *hemi*: half of the visual field; *anopsia*: blindness). Quadrant-anopia, that is, a homonymous loss of vision in a quarter section of the visual field of both eyes, is associated with a lesion of an optic radiation. If the Meyer's loop is lesioned, the vision loss is superior, if the parietal path is lesioned, the vision loss is inferior (cp. figure 3). Beside visual impairments, hemianopia is often associated with other cognitive dysfunctions like aphasia and visual hemineglect. The main reasons for developing HVFDs are brain injuries (i.e. lesions) secondary to stroke, surgery, or trauma, which can lead to arterial infarctions (70%), tumors (15%), and hemorrhages (5%). About 45% of stroke survivors have HVFDs (Gray et al., 1989) and approximately 31% of stroke survivors admitted to rehabilitation were found to have HH (Rossi et al., 1990). Males between 50-70 years of age are most frequently affected, reflecting the fact that HH is primarily a consequence of vascular disease (Huber, 1992; Trobe et al., 1973). Forty per cent of patients with HVFDs involve lesions in the occipital lobe, 30% in the parietal lobe, 25% in the temporal lobe, and 5% in the optic tract and lateral geniculate nucleus (Huber, 1992; Smith, 1962). Prospective studies of the natural course of vascular retrogenicular visual field defects show that spontaneous restitution (e.g. axon sprouting) in the blind hemifield takes place within the first six months after the event and that the average visual field gain is about 16% (Hier et al., 1983; Messing & Gaenshirt, 1986) in perimetry.

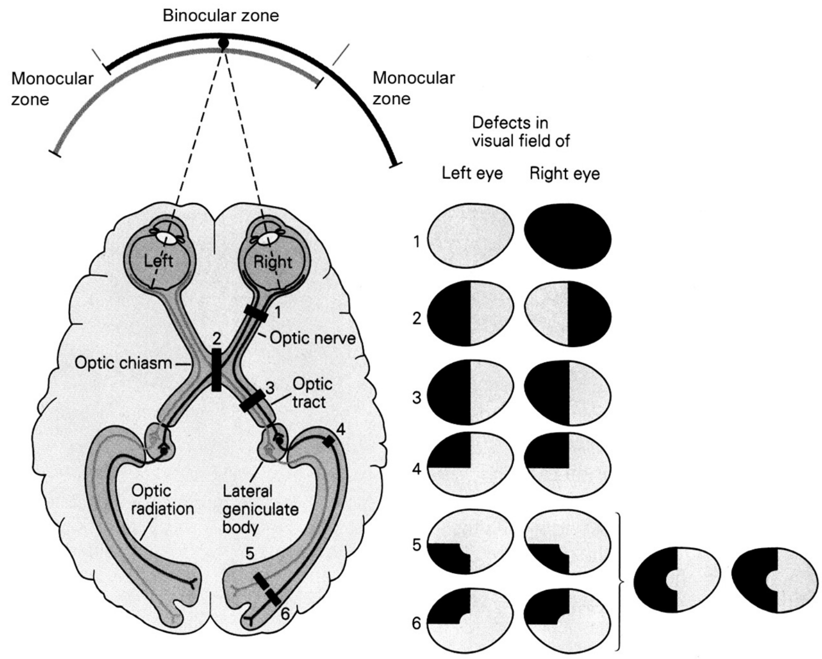

Figure 3: Scotomata produced by lesions at various points in the visual pathway (modified according to Kandel, Schwartz & Jessell, 2000). The numbers along the visual pathway indicate the site of lesions. Visual deficits which result from these lesions are shown in the visual field maps on the right as black areas. The visual filed losses labeled from 3 to 6 are assigned to homonymous hemianopia whereas numbers 1 and 2 refer to a non-homonymous deficit in vision.

HVFDs usually lead to visually related complaints and dysfunctions. The impact of the sensory deficit depends on size and localization of the lesion, impairing patients in visual information processing in many ways. Hemianopia usually leads to problems exploring the blind hemifield causing patients to perform hypometric, low amplitude saccades and handicaps them more or less severely in orientation and safety in everyday living. As a consequence, patients have difficulties in reading (e.g. Zihl, 1995a; McDonald et al., 2006), may bump into obstacles or persons on the affected hemifield (Zihl, 2000), have generally problems to comprehend a scene as a whole at a glance, and experience their vision as being too slow. In the past, a lot of research in the field of reading was investigated. Hence, it is well known that parafoveal field regions form a “perceptual window” for reading, subserving letter identification and playing a crucial role in both text recognition and guidance of eye movements in reading (Chedru et al., 1973; Zihl, 1995; Pambakian et al., 2000). Thus, parafoveal field loss affects reading at the sensory level, preventing patients from perceiving a word as a whole and impairing the visual guidance of eye movements in reading. As a consequence, the reading performance, i.e. correctly read words, is markedly reduced (Morris et al., 1990; Zihl, 1995, 2000). However, some hemianopic patients are able to compensate the visual limitation, at least to a certain extent, by performing additional, adaptive eye and head movements. And the disabilities, mentioned above, are related to the degree of this functional compensation (Kerkhoff, 1999). To compensate for HVFDs, patients need an appropriate ocular motor strategy for efficient use of the remaining areas of the visual system. Oculomotor compensation, that is, adaptive visual scanning behavior, can be assessed by recording eye movements (e.g. Zihl, 1995b, 1999, 2000; Zangemeister et al., 1982; Zangemeister & Oechsner, 1996). Ishiai et al. (1987) described one obvious adaptation used by some hemianopic patients. Whereas healthy controls look mainly at the center during viewing of simple patterns, hemianopic patients concentrate on their blind hemifield. This deviation of the fixation point towards the hemianopic side brings more of the visual scene into the seeing hemifield and could hint for a compensatory strategy (Gassel, & Williams, 1963). Meienberg et al. (1981) identified different compensatory strategies in HH patients when faced with simple visual targets which are presented in a predictable or unpredictable fashion. Overall compensatory effects identified in many studies showed, that some patients spend more (search) time in the stimulus half corresponding to their visual loss, generally perform more saccades but with decreased amplitudes when directed into the area of the visual loss, and differed therefore in their scanpath pattern as compared to healthy subjects (e.g. Zangemeister et al., 1982; Zihl, 1995b; Zangemeister & Oechsner, 1996; Kerkhoff, 1999; Zihl, 1999; Pambakian et al., 2000; Zihl, 2000; Tant et al., 2002). All studies concerning the oculomotor compensation clearly showed that, independently of the severity of the visual loss, HVFD patients can to some extent adapt their gaze movement behavior to overcome the visual restrictions.

Aim of the thesis

Oculomotor scanning in patients with homonymous visual field defects (HVFDs) and healthy subjects was investigated several times over the last decades. A major weakness in the majority of these studies was that only small parts of the patients' remaining visual field was stimulated due to the use of small computer monitors as stimulus providing devices. Furthermore, mostly regional and artificial stimuli were used to measure only basic compensatory components of the hemianopics' eye movement behavior. During my work, summarized in this thesis, I was interested in the patients' compensatory eye and head movements in cognitively varying tasks of daily living that inherently demand different adaptive gaze functions. Furthermore, my goal was to assess whether patients showing identical degrees due to their impaired visual field size (quantified by perimetry) can vary in their performance on the visual tasks. To achieve this, I developed three different paradigms to be completed by HVFD patients and healthy controls in an experimental toolbox. The first experiment was a re-examination of the dot counting paradigm previously introduced by others (e.g. Zihl, 1995b; Tant et al., 2002). Due to the large projection device available for my studies (cp. chapter one) I could enlarge the dot counting stimulus field up to 60° x 40° (in the original version it was 40° x 32°; Zihl, 1995b). The intention for including this paradigm into the toolbox was to reproduce and thus to verify my data with previously published results. Additionally, the dot counting paradigm with its cognitively simple kind due to the restriction of visual scanning to a process without any further identification function, conduced appositely as the first stage a of the experimental toolbox (cp. chapter four). As second stage, a comparative visual search paradigm as a more cognitively demanding scanning task was introduced. Unlike the dot counting experiment, head movements were permitted and even necessary for some experimental conditions, particularly in cases where there were large separations between the two stimulus fields (cp. chapter two and four). As the third and last stage, a crash avoiding traffic-related dynamic task was introduced to function as a highly challenging paradigm involving both lower and higher visual processes (cp. chapter five). In addition to the gaze performance measurements of visually impaired and unimpaired subjects, I was interested in their self-evaluation concerning their visual abilities in situations of daily living. These self reports allowed me to perform correlation analyses between the subjects' task and gaze performances and their subjective impressions.

The entire PhD-project was accomplished in co-operation and could only be realized with the assistance of the external partners Prof. Dr. U. Schiefer and E. Papageorgiou of the Centre for Ophthalmology (University of Tübingen), whom I would like to thank for their help in patient recruitment. All clinical visual field investigations were accomplished by these partners preceding my experiments.

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Results

Chapter one: Image correction and engineering considerations for a curved projection device

Aim of this subproject, main results and my own contribution

To investigate the HVFD patients' ability to perform various compensatory visual tasks with varying degrees of difficulty, the entire residual FOV should optimally be stimulated. The best way in order to provide a large field display to a subject combined with equal gaze distances to all points of the projection plane is the use of a curved screen. Concerning the experimental investigations, virtual rather than real stimuli should be applied. The usage of virtual reality is advantageous because stimuli can be generated in a highly standardized and easily manipulable manner, even while the experiment is running. In the projection setup, the subject is sitting comfortably in front of the screen and can move its head and eyes in a natural manner. Furthermore, such a projection device enables the possibility to simultaneously record both head and eye movements of a subject while performing the tasks. Afterwards the data collected from the head and eyes can be combined with the particular experimental situation to generate a real time simulation of the subjects' gaze position for each distinct time point.

I was mainly involved in performing the calculations and assembly of such a curved projection screen which was combined with the existent tracking systems (eye and head tracker) that is set up in our virtual reality lab. Together with Dr. H. Dahmen I developed the geometrical algorithms for the software image distortion/correction functions. In collaboration with Dr. S. Gillner I implemented the geometrical algorithms in C++ to integrate these image distortion functions into the experimental software. Afterwards I integrated all the components together into a complete projection setup and performed experiments, mostly those related to psychophysics, to evaluate and calibrate the system.

Our findings concerning the production and setup of such a projection device in conjunctions with psychophysical evaluations have been submitted for publication (together with Dr. S. Gillner and Dr. H. Dahmen) in the journal of Behavior Research Methods.

Manuscript

Title: Image correction and engineering considerations for a curved projection device

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Running Head: Projection device applicable for psychophysical investigations

Abstract:

In our laboratory we designed a cone-shaped, seamless and wide projection screen for psychophysical experiments in virtual reality (VR), in order to investigate the integration of head and eye movements in scene perception and navigation tasks. Our goal was to establish a low cost projection unit with a large field of view (FOV) in horizontal and vertical direction, where no edges would disturb the visual sensation. Here we present the engineering and computational considerations in order to establish such a setup in combination with psychophysical evaluations and some results from different implementations.

Introduction:

Virtual reality (VR) has been an integral part of research in the fields of cognitive science, visual perception or social psychology since the 1990's (Kalawsky, 1993). When applying this technology, stimuli can be presented either using head-mounted devices or they can be projected on more or less elaborated projection screens varying in qualities such as size, shape, and field of view (FOV). There are numerous possibilities concerning the design of such a screen: it can be planar, curved or angled, it can vary in terms of the FOV, it can be small and therefore rather close to an observer or it can be large, providing an increased distance to the subject. Furthermore, the image resolution, frame rate, image contrast and brightness may influence the quality of a projected image (e.g. Nichols & Patel, 2002).

But what are the critical attributes for a projection screen used for experiments in the field of visual perception and behavior? We specifically addressed this question and tried to investigate this topic in more detail. In particular, we designed a projection screen useful for psychophysical VR experiments by integrating also eye and head movement measurement.

There are numerous studies, supporting the theory that photorealism of a simulation might be one critical factor for being immersed, that is, the feeling of being "inside" a virtual world (for a review see Sanchez-Vives & Slater, 2005). In this review, the authors claimed that a high-resolution display and a wide FOV are indispensable to achieve a deep feeling of immersion. However, if immersion is an essential prerequisite for natural behavior is still unclear. Bailenson, Blascovich, Beall, & Loomis (2001) could show that photorealism of a VR simulation of acting persons did not influence the interpersonal distance which could be an indicator for the so-called social immersion. In the condition where the virtual agents showed a more realistic behavior, subjects held the same interpersonal distance as observed in real world experiments.

The above mentioned considerations lead to the conclusion that the main goal should not be to design a VR application equipped with the best possible image quality, which might be pleasant but expensive, but also to consider the properties that are important for the certain task. Hence, the requirements for our projection device have been (i) to construct a projection unit which is capable of psychophysical VR experiments including eye and head movement measurements and (ii) to construct a low-cost projection unit. In this paper we report on the implementation of a curved multi-projection screen with a special focus on these features. Furthermore, we discuss the problems that arise when designing such a projection unit and present our solutions.

(1) Screen shape - curved or cornered? The CAVE™ (Cave Automatic Virtual Environment; Cruz-Neira, Sandin, & DeFanti, 1993), which consists of two or more planar projection fields in a cubic arrangement, has the disadvantage of edges in the projection field. This may be advisable in order to illuminate a rectangular room, but it is not appropriate for all other shaped environments. We would therefore recommend the use of a curved projection screen for psychophysical experiments. However, another challenge arises thereby: by projecting onto non-planar surfaces the displayed image will be deformed. Geometrical transformations have to be calculated in order to correct the distortion in such a way, that objects displayed on the screen will appear in the actual relationship. These considerations are especially important in utilizing the setup for psychological investigations. For cinema screens a solution was presented in Moriya, Utsugi, Beniyama, & Takeda (2003). In this study the authors focused mainly on practical considerations meeting the demands of the movie makers rather than on correct transformations due to geometrical requirements. Therefore, their solutions cannot be transferred to a setup intended for psychophysical experiments, because the exact image correction depends on the viewer's actual position in relation to the screen. To overcome this problem one could track and calculate the viewer's actual position, in order to continuously generate new deformations for the presented images (Raskar, Welch, Cutts, Lake, Stesin, & Fuchs, 1998). An overview for setups with several projectors on curved surfaces is given in Raskar, Cutts, Welch, & Stuerzlinger (1998). Hereby, the authors used projective texturing for the process of image warping.

(2) What is an adequate screen size? The trade-off between screen size and the pixel resolution of video projectors is an important question arising in the design of appropriate projection devices. Concerning the application of a small-sized projection screen, the number of all pixels is distributed only over a narrow area. However, in preliminary experiments with projection screen prototypes of different dimensions, we ascertained that smaller projection screens, spanning the same FOV, induced unsatisfactory viewing comfort. The discomfort might be reasoned by the fact that the observer has to accommodate to the projection surface in a very short distance, but the simulated VR objects may appear in a distance of several meters (e.g. Sanchez-Vives, & Slater, 2005). In this case, sensory information of the visual input on one hand and the distance information obtained by the vergence and accommodation systems might conflict (Kenyon, DeFanti, & Sandin, 1995). In summary, a screen should be more than 1.5 m away from an observer in order to reduce this accommodation conflict.

(3) Should the screen be tilted or not? Projectors are placed above a curved projection screen, in order to avoid overshadowing of the projected image due to the position of the observer within the light beam. However, in this case, the problem of a trapezoid image distortion occurs. Tilting the curved screen (changing the shape from a cylindrical to a conical one) can prevent the trapezoid distortion. Furthermore, the combination of a curved shape with a tilt, leading to a cone sector, still has the advantage of being easy to construct because of the developable surface.

(4) What is an appropriate FOV? Not only the horizontal but also the vertical FOV is of importance for psychophysical experiments. We choose values inspired by the human binocular visual field, which has an extension of approximately 170° horizontally and 110° vertically. For our screen we achieved a FOV of 150° in horizontal and 67° in vertical direction. In terms of driving and walking tasks it was demonstrated, that the majority of eye movements are directed to the ground or to the street (Land, & Hayhoe, 2001; Patla, & Vickers, 2003). In these tasks, the lower part of the visual field was more involved than the upper one. For this reason we chose for our projection device an asymmetric vertical FOV, where the lower part is larger than the upper part (FOV above the horizon = 43° and below the horizon = 24°).

It is possible to widen the image of a single video projector by using wide angular lenses or special mirrors, in order to obtain a larger FOV. Thus, the illuminated area of this projector can be spanned over the whole FOV, but it also leads to a decrease of spatial resolution. Another solution to illuminate a large FOV without losing pixel resolution is the employment of more than one projector. In this case the edge-blending problem in the overlapping areas of two adjacent projector illuminations has to be solved (e.g. Chen, Clark, Finkelstein, Housel, & Li, 2000; Li, & Chen, 1999).

(5) Considerations concerning the optical path: Attention should be paid to placing the projectors in such a way that potential observers do not disturb the path of rays by sitting within the projector's optical path. It is possible to hang the projectors below the ceiling, which may entail a trapezoid image deformation. Another solution might be a back projection, where the projectors are placed behind the screen. However, this creates the demand for an expensive back projection foil in order to enable a homogeneous illumination.

Methods:

1.1. Hardware

A simulated view of our setup is illustrated in figure 1 and a schematic, dimensioned representation can be seen in figure 2. As projection wall we chose a 150° pre-formed foam plastic cone segment with a lower radius of 1.29 m and an upper one of 1.83 m. The cone radius in eye height of a sitting subject (1.2 m) is 1.62 m. The tilt of the wall is 15° and the height is 2.0 m. The resulting asymmetric vertical FOV for the viewer is 67° (upwards: 24° and downwards: 43°) and the horizontal one is 150°.

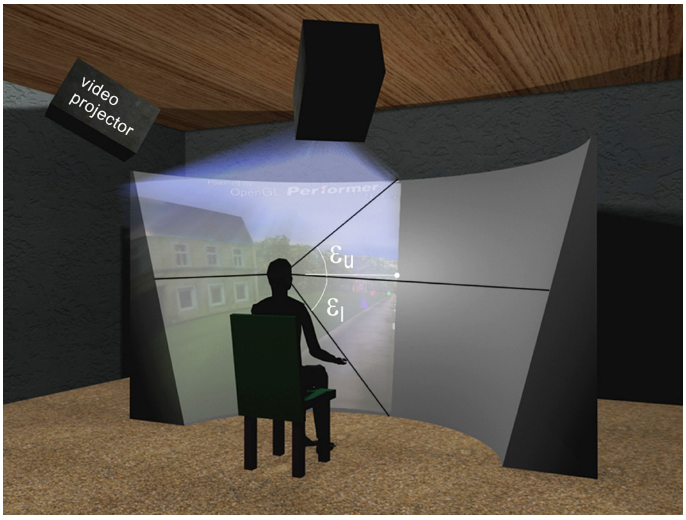

Figure 1. Simulated picture of the experimental VR setup in our laboratory. Here, the illumination with only one video projector onto the curved projection screen is shown. In the final setup both projectors are used. From the observer's position (eye level: 1.2 m; distance to the screen: 1.62 m) the setup enables an asymmetrical vertical FOV with ε_u = 24° and ε_l = 43°.

All rendering, experimental and distortion programming-routines are proceeded on a personal computer (Intel® Pentium® 4, 2.6GHz; RAM: 2x 512MB) with Linux RedHat 9.0 as operating system. As graphic card a NVIDIA® Quadro4® 980XGL (128MB DDR SDRAM) with a dual monitor connection is used.

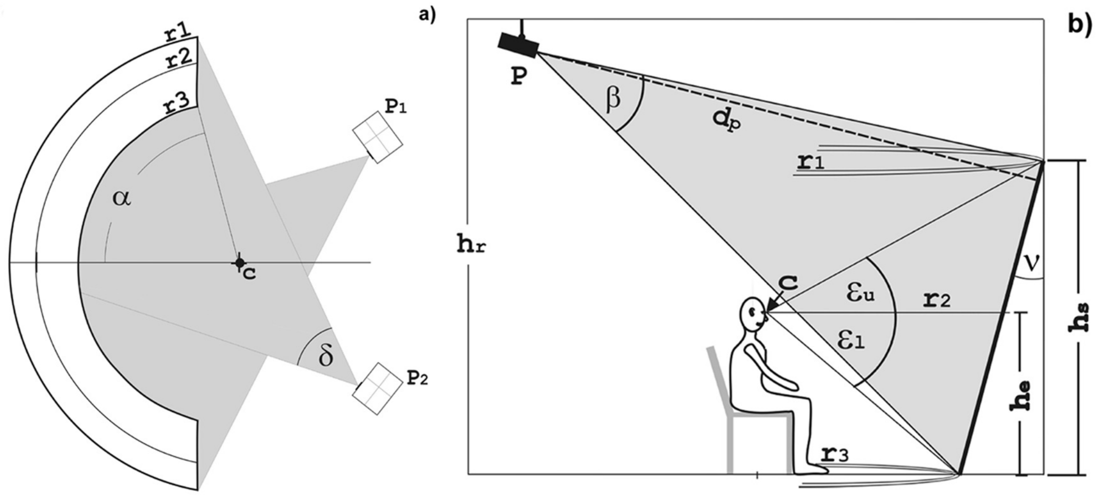

Figure 2. Technical information of the projection setup. (a) View from above (b) View from the side. α = angle of the cone segment/2 = 75°, c = center of the cone segment, r1 = upper radius of the cone segment (1.83 m), r2 = radius in eye height (1.62 m), r3 = lower radius of the cone segment (1.29 m), ε_u = upper vertical FOV (24°), ε_l = lower vertical FOV (43°), ν = tilt of the projection screen (15°), β = vertical frustum of the projector (35°), δ = horizontal frustum of the projector (47°), h_e = height of subject's eyes (1.2 m), h_s = height of the screen (2.0 m), h_r = height of the room (2.9 m), P, P1 and P2, = video projectors, d_p = optical axis of the projector which hits the screen perpendicularly (note: resulting from the asymmetric course of beam, 10% of all rays are above and 90% are below of the optical axis).

The setup runs with two LCD video projectors (Sanyo PLC-XU46, each with 3 LCD panels; resolution: 1024x768 pixels). By shifting the lens courses, the beam is distributed asymmetrically in vertical direction. As a result only 10% of all rays leave the projector below the optical axis (see figure 2). The areas illuminated by the projectors overlap in the middle of the projection screen. This leads to higher light intensity in this area, which has to be adjusted with the so called edge-blending method. The traditional procedure for edge-blending projection devices is to alter the video signal or the image intensity according to the blending curve. Unfortunately, it cannot be applied in commodity LCD projectors, which have a fair amount of light leakage (Chen et al., 2000). We applied an optical edge-blending that operates directly on the light output from the projectors, hence bypassing the light leakage problem (cf. Chen et al., 2000; Li, & Chen, 1999). This method is based on aperture modulation. By placing an opaque object between the lens and the screen one creates a shadow gradient. As opaque objects we implemented two simple aluminum plates which are mounted just in front of the lenses of the projectors (cf. figure 3). With this arrangement one achieves a smooth shadow on both overlaying borders and the remaining illumination sums up to a light intensity equal to the non-overlap neighborhood. The advantage of using aluminum as a material is, that it does not heat up too much due to its high heat conductance.

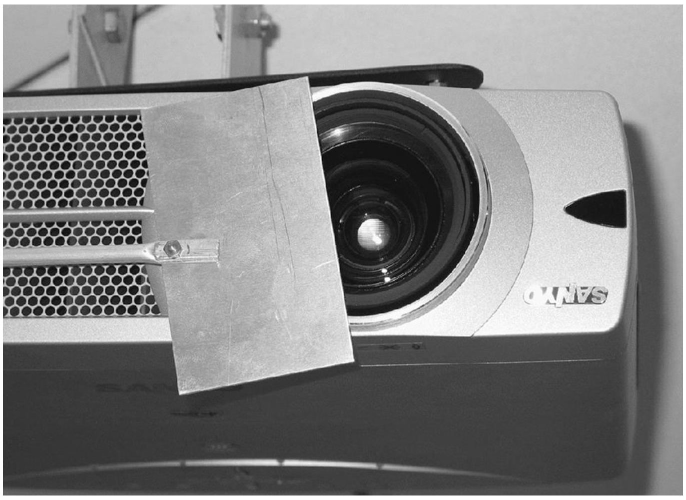

Figure 3. Optical edge-blending method that operates directly on the light output from the video projectors. An aluminum plate in front of the lens enables edge-blending. By mounting this plate very early in the optical path of the projector a smooth shadow could be achieved. Note that the projectors are turned upside down utilizing the asymmetrical vertical FOV.

1.2. The algorithm and implementation in OpenGL®

To overcome the problem of the image distortion we developed the following algorithm, adapted from Raskar et al. (1998). We implemented the routines with OpenGL® Performer™ (SGI®) and C++. The rationale of our procedure is as follows:

(a) View the 3D scene with *c* (*c* = 1, 2 ...) cameras (i.e. world cameras). These cameras need together the same FOV properties and over ground height as the observer in front of the projection screen (cp. section 1.1.).

(b) Render the whole image of all world cameras into the back-buffer of the graphic card.

(c) Map the back-buffer content into the texture memory. This mapping can be achieved with the following code fragments, which have to be included within the Performer's draw process for the world cameras. Care must be taken that this draw routine is called at first - that is before calling the draw routine for the projection cameras (see below).

```
Texture → subload(PFTEX_SOURCE_FRAMEBUFFER,
NULL, 0, 0, 0, 0, 0, sizeTexX, sizeTexY);
pfClear(PFCL_COLOR || PFCL_DEPTH, &clr);
pfDraw();
```

(d) Calculate the uv-coordinates needed for the warping process of the texture (cp. section 1.3.). The grid point number of this frame defines the resolution of the resulting image.

(e) Map the texture onto a virtual model of the projection screen (see figure 5).

(f) Define n virtual projection cameras (n = number of video projectors used in the setup) to capture the virtual projection screen. These cameras should be placed at the same virtual positions and share the same optical properties (e.g. asymmetrical FOV) as the video projectors in the real world.

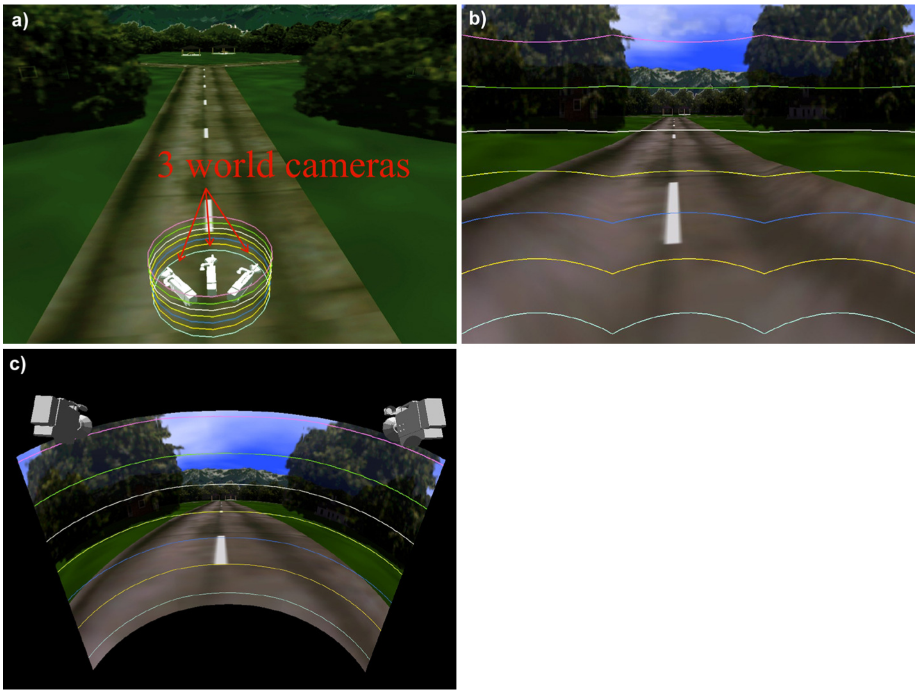

Figure 4. (a) In this example three world cameras are used to render the virtual scene. The colored circles around the cameras are introduced to show clearly the deformation due to the mapping. (b) Image which is generated by the three world cameras. This image has to be mapped from the back buffer into the texture memory. Pay attention to the asymmetrical vertical FOV of these cameras as mentioned in section 1.2. (c) The texture is mapped onto a virtual model of the projection screen. In our case two projection cameras are used to capture the scene. The images of these two cameras are projected onto the real projection screen. There, the projection cameras need the same virtual positions and optical properties as the real video projectors related to the virtual/real screen.

1.3. Image warping

The rationale of this procedure is to render the desired image firstly onto a planar surface and subsequently map this image into the texture memory (cf. figure 4). This texture has to be deformed so that equal sized azimuth and elevation angles in the planar image correspond to equal sized distances in the resulting projected image. The uv-coordinates (grid points) of the planar texture must be calculated as follows:

$$u_{ij} = r \cdot \tan(\alpha_i) \qquad (1)$$

$$v_{ij} = \frac{r \cdot \tan(\varepsilon_j)}{\cos(\alpha_i)} \qquad (2)$$

with r = radius in eye height (1.62 m), α = angle in azimuth direction, ε = angle in elevation direction (see also figure 5); *i, j* indicate the grid points in horizontal and vertical direction. Note that the size of α_i and ε_j depends on the number of grid points in horizontal and vertical direction. In our implementation the grid point numbers were equal for the horizontal and vertical direction.

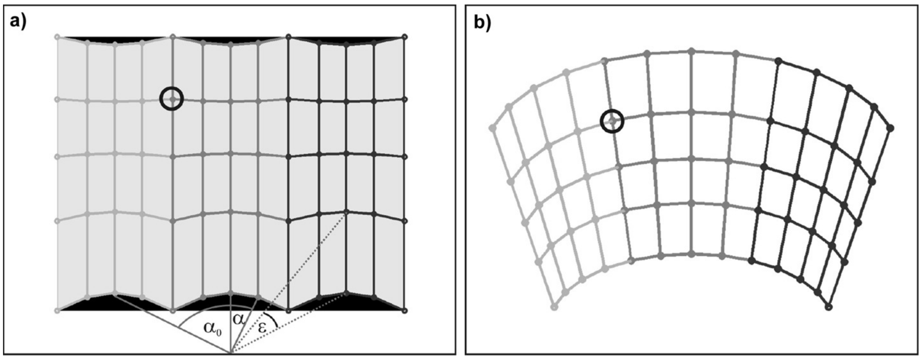

Figure 5. Texture mapping for a setup of three world cameras and 5x5 grid points per camera. (a) Grating of the original texture. The texture area is marked in grey. Note that the black area below and above the grating will not be used for the texture mapping. (b) Grating of the mapped texture. As an example, one corresponding grid point before and after the mapping is marked by a black circle.

The uv-coordinates must be transformed that $0 \le u \le 1$ and $0 \le v \le 1$. By using more than one cameras the following consideration has to be taken into account: with c = number of world cameras $\frac{m}{c} \le u \le \frac{m+1}{c}$ and $\frac{m}{c} \le v \le \frac{m+1}{c}$ with $m = [0 \ldots c-1]$ must be valid. This texture has to be mapped onto a virtual projection wall, which represents a simulated model of the real projection screen. This projection wall needs the same number of coordinates as the number of grid points of the texture. The 3D coordinates for the virtual wall used in our setup must be calculated as follows:

$$x_{ij} = \frac{r \cdot \cos(\nu) \cdot \cos(\varepsilon_j) \cdot \sin(\gamma_m + \alpha_i)}{\cos(\varepsilon_j) + \nu} \quad (3)$$

$$y_{ij} = \frac{r \cdot \cos(\nu) \cdot \cos(\varepsilon_j) \cdot \cos(\gamma_m + \alpha_i)}{\cos(\varepsilon_j) + \nu} \quad (4)$$

$$z_{ij} = h - r \cdot \sin(\nu) \cdot \cos(\nu) + r \cdot \cos(\nu) \cdot \tan(\varepsilon_j + \nu) \cdot \cos(\nu) \quad (5)$$

with ν = tilt of the projection screen (15°) and h = height of the observer's eyes (1.2 m), γ_m = heading of each $m = [0 \ldots c-1]$ world cameras with $\gamma_m = -\frac{\omega}{2} + \frac{\omega_c}{2} + m \cdot \omega_c$, ω = horizontal width of the projection screen = 150°, ω_c = FOV of one camera = $\frac{\omega}{c}$.

Each grid point of the texture must be assigned properly to a coordinate of the projection screen (cf. figure 5).

1.4. Quality criterion

We had to solve a trade-off between the computational speed of the application and the image quality. This quality is defined by the number of grid points and the number of world cameras. Thereby, a virtual reality application intended for psychological investigations has to run at least with a frame rate of 30 Hz.

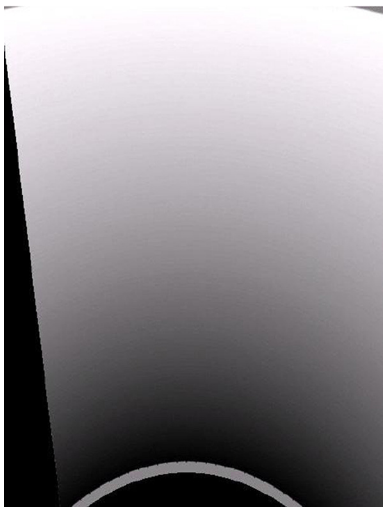

Figure 6. Stimulus image used for judging the image quality of the distortion algorithm. Since the image is symmetrical, just one half of the whole projection image was used to quantify the image quality.

To judge the quality of the mapping, we rendered one optimal image for which we used 50 world cameras and 30x30 grid points per camera. These cameras obtained a view from a cylindrical environment which was textured with a black/white gradient from the bottom to the top of the cylinder (cf. figure 6). Due to the symmetric image, just one half of the whole projection image was used to quantify the image quality. We compared different configurations (i.e. different amount of world cameras and number of grid points) with this optimal image by calculating the image differences D for each pixel:

$$D = \frac{\sum_{i=1}^{f}\sum_{j=1}^{h}\left(I^{*}_{ij} - I_{ij}\right)^{2}}{k} \qquad (6)$$

with f = number of pixels in vertical direction, h = number of pixels in horizontal direction, I^{*} = Image intensity of a pixel in the optimal image, I = image intensity of a pixel in a tested image, $k = h \cdot v$.

1.5. Psychophysical evaluation of the projection quality

To verify our results concerning the quality of the projection, we developed the following psychophysical procedure: two identical scenes (scene A and B) – one after the other – will be presented to a subject, that is, one trial. As environment we used a virtual world which consisted of 1600 cubes each with 6 polygons. The two scenes differ from each other in the quality of the texture mapping due to a different number of world cameras and grid points. The reference scene was rendered with a very high quality (i.e. 20x20 grid points and 20 world cameras). To improve the possibility of judging the image quality, a two-second lasting period of (world) camera rotation around the z axis was simulated for each scene. Afterwards, the subjects had to decide in which presented scene the quality was higher and to indicate that scene by pressing a mouse button. Each trial was presented 5 times. The sequence of scenes A and B was generated in random order and was balanced related to the amount of each possibility. Eight subjects participated in this experiment which comprises further parameters listed in table 1.

	Scene A	Scene B
number of grid points (per camera)	20	3 - 24
number of world cameras	20	2,3,4,5,6

Results:

2.1. Image loss

In consequence of the image warping procedure, some regions of the original texture could not be used for the mapping (cp. figure 5). We investigated this image loss as a function of the number of world cameras. The dependent variable was the percentage of the image which will be discarded. Figure 7 shows the amount of image loss influenced by the number of world cameras. There, the highest decrease in image loss occurs when using one or two cameras.

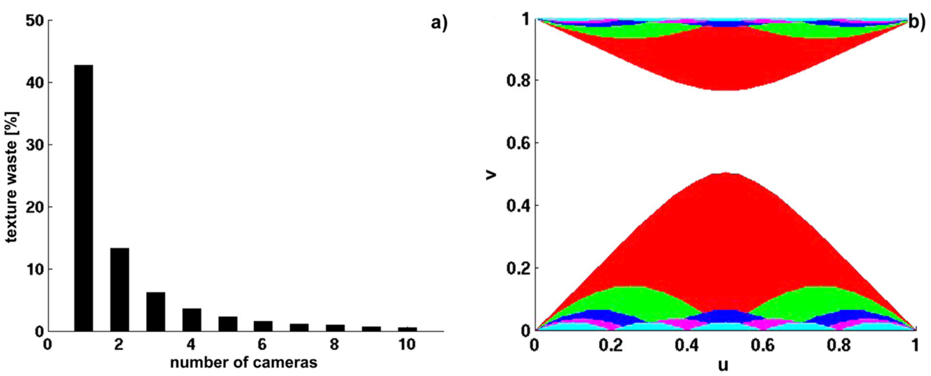

Figure 7. (a) Lost area of the original image (in % of the original texture) as a function of the number of world cameras. The texture consisted of 10x10 grid points per world camera. (b) Visualized lost area; red: 1 camera, green: 2 cameras, dark blue: 3 cameras, magenta: 4 cameras, light blue: 5 cameras.

2.2. Frame rate

Achieving a stable frame rate of at least 30 Hz is important for psychological experiments and in particular for eye movement measurements. Hence, we analyzed the dependency of the frame rate as a function of the number of world cameras and grid points per cameras. As stimulus for this evaluation we used the cube arrangement (cp. chapter 1.5). Figure 8 shows that the time for rendering one frame increases linearly with the number of cameras. In contrast, the number of grid points influenced the result only marginally.

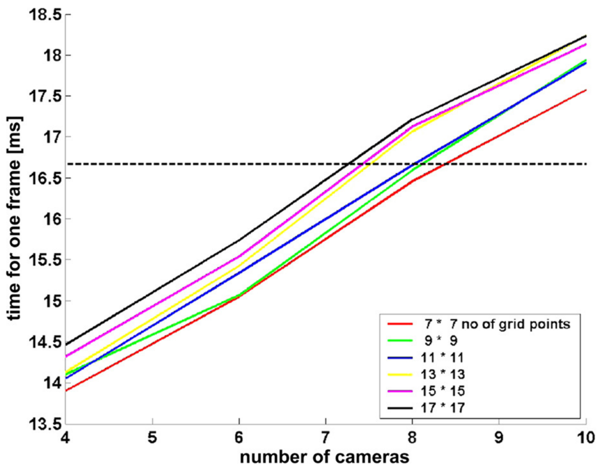

Figure 8. Frame rate as a function of the number of world cameras. Colors indicate for different number of grid points per camera, which are encoded in the legend. The desired frame rate (60 Hz) is marked by the dotted black line.

2.3. Image quality

As described in section 1.4., the quadratic image differences of an optimal image and images generated with a smaller number of world cameras and coordinates were analyzed. This image quality was particularly influenced only by the number of cameras. With more than 3 cameras the increase in image quality was only small. The same was true for more than 6x6 grid points per camera (see figure 9).

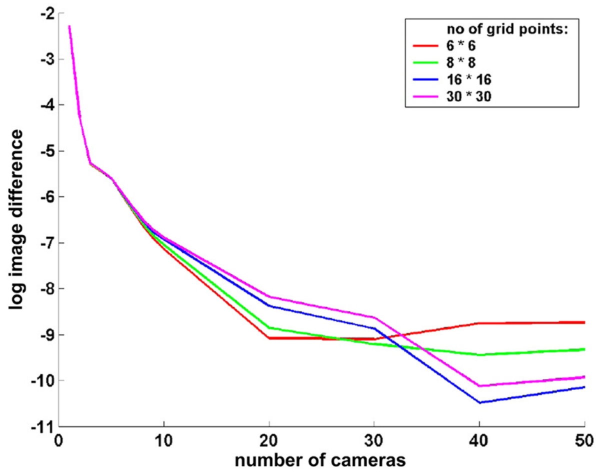

Figure 9. Logarithm of the image difference *D* of optimal and test image (defined inequation 6) as a function of the number of world cameras. Colors indicate for different number of grid points per camera, which are encoded in the legend.

2.4. Psychophysical evaluation of the quality

We performed an experiment, where eight subjects had to judge the difference concerning the image quality of two images rendered from two scenes differing in the number of world cameras and grid points. In this experiment the high quality reference scene was rendered with 20 cameras and 20x20 grid points per camera. In figure 10 the confusion probability, that is, the probability to make an error in indicating the image with the highest quality, as a function of the overall number of grid points (= $u \cdot v \cdot c$ with c = number of world cameras) is shown. Note that the reference scene was rendered with 20 cameras and 20x20 grid points, resulting in an overall grid point number of 8000.

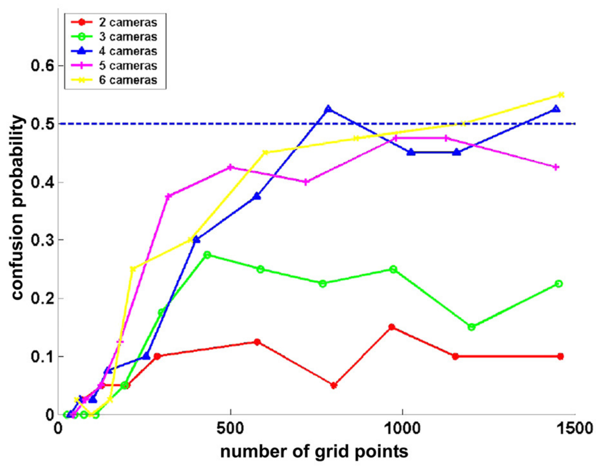

Figure 10. Result of the experiment concerning the psychophysical evaluation related to the quality of images generated with a different number of grid points and world cameras. There the reference scene was rendered with 20 cameras and 20x20 grid points per camera. Eight subjects participated in this experiment judging each deformation 5 times.

It turns out that a scene, rendered with more than around 1000 polygons could not be discriminated from the reference scene, as long as more than three cameras were used for rendering the scene.

Discussion:

In the present study we report on a VR projection setup designed for psychophysical investigations, which additionally offers an inexpensive solution with a large FOV in horizontal and vertical direction. The FOV in the vertical direction is asymmetrical, according to eye movement studies with pedestrians and car drivers (cf. Land, & Hayhoe, 2001; Patla, & Vickers, 2003) where most of the eye movements were directed in the lower part of the FOV.

We developed and implemented an algorithm solving the image warping problem which occurs if a planar image is projected onto a curved projection screen. The number of world cameras in the virtual environment generates a smooth, correct distortion with a minimal amount of image loss, by taking into account the amount of image loss, the time for rendering one frame and also the quality of the resulting image. Thereby, only the last factor was influenced by the number of grid points. From the psychophysical experiment it was concluded that an image distortion with less than three world cameras is not appropriate for a psychological application. Using a finer mesh of grid points could not compensate for the disadvantage of using a small number of cameras. The reason for this might be the image loss as shown in figure 7.

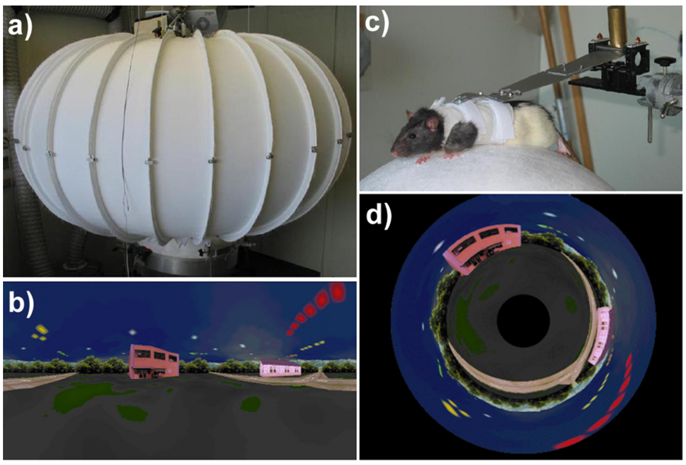

Figure 11. VR projection setup for rats running on top of an air-cushioned polystyrene sphere. (a) 360° projection screen. (b) Image generated by the world cameras with a 360° FOV in horizontal direction. (c) Rat fixed on top of the sphere is located inside of the screen. (d) Distorted image projected via one video projector onto the 360° projection screen.

The setup we present is used already in a number of psychophysical experiments. We could show that the FOV in both directions, horizontal and vertical, is large enough to induce head movements (Hardiess, Gillner, & Mallot, in press). This offers the possibility to investigate the coordination of head and eye movements also during driving or walking tasks. In an evaluation study we could show, that the eye movements recorded in this setup are comparable to eye movements performed by subjects in the real world (Schoch, Gillner, & Mallot, 2005).

There is the advantage of adapting and using the distortion procedure for any form of projection screen. An example of a toroidal 360° projection screen is shown in figure 11. This setup is designed to enable VR experiments with rats (Hölscher, Schnee, Dahmen, Setia, & Mallot, 2005). There, a very large FOV is required while image resolution may be low. Here, it was appropriate to run the setup with only one projector, where the image is projected at first onto a mirror. The final image which had to be projected onto the lamp like projection screen is a ring (cf. figure 11d). Our algorithm is appropriate even for this type of texture warping. The only part, which has to be adapted, is the computation of the uv-coordinates and the shape of the virtual screen. So far, our VR arrangement is applied successfully in spatial cognition experiments with humans and rats and expands advantageously the available projection solutions by an easy-to-assemble and inexpensive one.

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Chapter two: Head and eye movements and the role of memory limitations in a visual search paradigm

Aim of this subproject, main results and my own contribution

The interplay of head and eye movements in a visual search task with large stimulus fields has not been investigated so far. Hence, very little is known about the coordination of the eyes and the head to execute gaze related strategies in such a paradigm. By using a wide field projection device, realized in our virtual reality lab, I was able to perform a comparative visual search task with large stimulus separations up to 120°. My main interest lies in the visual performance of HFVD patients. As an essential part of the experimental toolbox (see below) I introduced precisely such a comparative search paradigm to measure their gaze performing strategies. To become familiar with the measurement and analysis of large gaze movements performed in a virtual environment in combination with investigating gaze related strategies, I initially developed and carried out this gaze function based experiment only with healthy subjects. Additionally, I altered the size of the stimulus in order to differ the need for head movements. The scientific question of this subproject concerned the adaptation of gaze movements under varying requirements with different cost levels and the additional role of working memory.

The results obtained from this investigation reveal a shift in the trade-off between gaze movements and visual short-term memory towards the domain of memory for increased gaze movement costs. Furthermore, two different search strategies relating to the spatial location of areas responsible for encoding and comparison processes could be identified between the participants.

Concerning this comparative visual search experiment I was solely responsible for designing and administering the paradigm and analyzing the data. I published these results together with Dr. S. Gillner and Prof. H. A. Mallot in the Journal of Vision (currently in press).

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Head and eye movements and the role of memory limitations in a visual search paradigm

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The image information guiding visual behavior is acquired and maintained in an interplay of gaze shifts and visual short-term memory (VSTM). If storage capacity of VSTM is exhausted, gaze shifts can be used to regain information not currently represented in memory. By varying the separation between relevant image regions, S. Inamdar and M. Pomplun (2003) demonstrated a trade-off between VSTM storage and gaze shifts, which were performed as pure eye movements, that is, without a head movement component. Here we extend this paradigm to larger gaze shifts involving both eye and head movements. We use a comparative visual search paradigm with two relevant image regions and region separation as independent variable. Image regions were defined by two cupboards displaying colored geometrical objects in roughly equal arrangements. Subjects were asked to find differences in the arrangement of the objects in the two cupboards. Cupboard separation was varied between 30° and 120°. Images were presented with two projectors on a 150° × 70° curved screen. Head and eye movements were simultaneously recorded with an ART head tracker and an ASL mobile eye tracker, respectively. In the large separation conditions, the number of gaze shifts between the two cupboards was reduced, while fixation duration increased. Furthermore, the head movement proportions negatively correlated with the number of gaze shifts and positively correlated with fixation duration. We conclude that the visual system uses increased VSTM involvement to avoid gaze movements and in particular movements of the head. Scan path analysis revealed two subject-specific strategies (encode left, compare right, and vice versa), which were consistently used in all separation conditions.

Keywords: working memory, VSTM, eye movements, head movements, gaze, comparative visual search

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Introduction

Visual processing of large-field scenes is performed in an interplay of gaze shifts (gaze = eye-in-head + head-in-space) and memorization of local visual stimuli in a visual short-term memory (VSTM). VSTM is considered a subdivision within the visual part of the working memory (Baddeley, 1978, 1992, 2003) and characterized by a limited storage capacity (Phillips, 1974). The upper limit of this storage capacity was identified as three to four objects, independently of the number of feature dimensions (e.g., color, shape, or orientation) probed for each object (e.g., Irwin & Andrews, 1996; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). In addition, the total information capacity of VSTM is also limited (Alvarez & Cavanagh, 2004; Xu, 2002). Alvarez and Cavanagh (2004) suggested that there is an upper limit on storage that is set in terms of the total amount of information and that there is a functional dependence between the complexity of the objects and the total number of objects that can be stored. Limits in the storage capacity of the VSTM could be impressively shown by research on change detection, revealing the phenomenon of change blindness (Simons, 2000; Simons & Levin, 1997). In these experiments, two almost identical images are presented in alternation with short blanks separating them in time. Subjects are strikingly insensitive even to large changes between both images. For the case of eye movements, Ballard, Hayhoe, and Pelz (1995) and Hayhoe, Bensinger, and Ballard (1998) investigated VSTM usage in a block-copying task. During copying, a presented pattern of colored blocks from a model area to the workspace, participants made only minimal use of VSTM. The authors phrased this as "just-in-time" processing strategy, where observers acquire the specific information they need just at the point at which it is required in the task. This makes sense because the information is easily accessible by the sensors—the eyes. This "just-in-time" processing strategy could also be observed in everyday activities (e.g., Hayhoe, Ballard, Triesch, & Shinoda, 2002; Land, Mennie, & Rusted, 1999). Ballard et al. and Hayhoe et al. showed that this strategy cannot be attributed to hard capacity limitations. When the distance between the model and the workspace area was increased (70°), forcing subjects to perform larger eye and head movements, the frequency of the "memoryless" pattern decreased gradually and eye movements occurred about half as frequently (Ballard et al., 1995). The trade-off between memory load and saccadic behavior thus seems to be controlled by the minimization of combined "costs." On the memory side, such costs could be associated with the amount of stored information, whereas on the eye and head movement side, costs may arise from duration, energy consumptions, or an increased need for correction saccades at larger saccade amplitudes. A general discussion of costs in terms of time requirements has been given by Gray, Sims, Fu, and Schoelles (2006). To investigate the trade-off between the usage of VSTM and the execution of eye movements, Inamdar and Pomplun (2003) used a comparative visual search paradigm developed by Pomplun et al. (2001). In their study, two identical columns of simple geometrical objects (each column containing 20 objects) had to be compared to detect the single difference (target). To vary the costs of eye movements, three distances between the columns were used (15°, 30°, and 45°). For the larger hemifield separations, fewer inter-hemifield saccades was found. Furthermore, the processing time, that is, the time spent within a hemifield before jumping to the other side, was prolonged for larger hemifield separation. To further increase the time needed for inter-hemifield saccades, the attended hemifield was masked when the saccade started and was unmasked only after a delay of 0, 500, and 1000 ms. Delayed unmasking enhanced the original effects, that is, it decreased the number of gaze shifts (i.e., inter-hemifield saccades) between the two hemifields and it increased the time for processing intervals. Inamdar and Pomplun argued that VSTM usage can be flexibly adapted to optimize task performance as long as the creation of internal representations does not take longer than roughly one second. These findings together with the experiments by Ballard et al. provide strong evidence for the VSTM versus eye movement trade-off in visual tasks. In natural, large-field environments, head movements interact with eye movements to carry out gaze shifts. Within the functional range of eye movements (up to ±22°; Stahl, 1999), head movements are unlikely, but their frequency increases as the gaze saccade amplitude grows (Freedman & Sparks, 2000; Hanes & McCollum, 2006; Land, 2004). Because head movements are more costly than movements of the eye, both in terms of time and energy consumption, the VSTM versus gaze shift trade-off should be shifted toward increased memory use for tasks involving large gaze saccades. Indeed, Ballard et al. presented initial evidence showing that subjects use more memorization in a block-copying task requiring large head movements when making gaze changes.

The goal of this present study is to examine the trade-off between gaze movements (involving both eye and head movements) and VSTM usage for large-field stimuli. For that purpose, we developed a comparative visual search task, similar to those used by Gajewski and Henderson (2005), Inamdar and Pomplun (2003), and Pomplun et al. (2001), and we increased the distance between the two stimulus regions up to 120°. As comparative visual search stimulus, we used two cupboards filled with geometrical objects distributed over four shelves. The task in this paradigm was to identify differences between the object configurations in the left and right cupboards. For large gaze saccades, we anticipate a strong shift of the trade-off toward VSTM usage due to larger eye and head movement costs. The trade-off will be described quantitatively by a simple model based on the total time required to solve the task, cf. Gray et al. (2006). Further points include the possible additional costs of head movements in the gaze shift versus VSTM trade-off and the identification of scanning strategies used by individual subjects.

Methods

Experimental setup

All experiments are performed using a virtual reality environment displayed on a large, curved projection screen shown in Figure 1. This screen provided a horizontal field of view of 150° and a vertical one of 70° to the subject. The geometrical shape of the projection screen was that of a conic shell with a vertical axis, an upper radius of 1.83 m, and a lower one of 1.29 m.

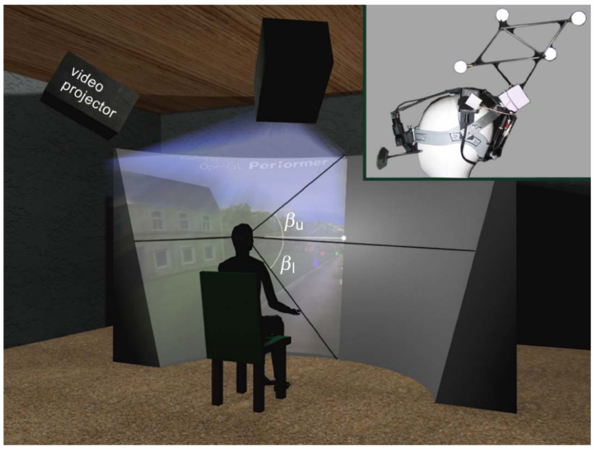


Figure 1. Schematic view of the experimental setup. Two video projectors illuminate the complete conical screen. The horizontal field of view at eye level is ±75°. The upper vertical elevation angle (β_u) is +25 and the lower one (β_l) −45°. Small picture: ASL501 eye tracker with fixed gauge object for head tracking, comprising four light reflecting balls.

Subjects were seated upright with the back tightly at the chair and with their head in the axis of the conical screen (eye level at 1.2 m with 1.62 m screen distance). Two video projectors (SANYO PLC-XU46 with 1024 × 768 pixel resolution) were used to illuminate the whole screen.

The setup was running on a 2.6-GHz PC under Linux RedHat 9.0 as operating system (graphic card: NVIDIA Quadro4 980XGL with dual video projector connection). The spatial resolution was 2048 × 768 pixels with a frame rate of 60 Hz. Experimental procedures and rendering of the virtual environment was programmed in the SGI OpenGL Performer™. Compensation for image distortion generated by the curved screen was programmed in C++. Soft edge blending was done in hardware using two partial occluders in front of the projector lenses.

Eye-in-head movements were recorded with a head mounted, infrared light-based eye tracker (bright pupil type, model 501 from Applied Science Laboratories, Bedford, USA) with approximately 2° accuracy and a real-time delay of 50 ms. To record head-in-space movements, an infrared light-based tracker system (ARTtrack/DTrack from A.R.T. GmbH, Weilheim, Germany) with 6° of freedom, 0.1° accuracy, and a real-time delay of 40 ms was used. This device tracks a rigid body (configuration of four light reflecting balls) fixed to the eye tracker (see Figure 1, small picture). Both trackers had a temporal resolution of 60 Hz.

Experimental task

Two cupboards equally filled with simple geometrical objects in four geometrical shapes (triangles, circles, diamonds, and squares) and in four different colors (green, blue, yellow, and black) were used as stimuli (see Figure 2). Each cupboard included 20 objects in four shelves. Each shelf included five objects in a row and one cupboard subtended 30° of the subjects' horizontal field of view. The diameter of an object was 3°, the horizontal separation between two objects was 5°, and the vertical one was 11°.

For the comparative visual search task, the object configurations in the two cupboards were either completely equal (zero target condition) or differed at one or two positions (one and two target conditions, respectively). Target objects differed only in shape whereas all other objects pairs had identical features (distractors). A maximum number of two targets was introduced to avoid premature trial completion. Because subjects did not know the number of targets, they should not terminate the comparative search after detecting the first target. Four different cupboard distance conditions were used in the experiment. The horizontal distance between the centers of both cupboards was 30°, 60°, 90°, or 120°. These larger cupboard distances should induce the need for head movements and therefore higher costs for more time consuming gaze shifts. A session consisted of 36 trials in random order (4 distance conditions × 3 target conditions × 3 repetitions for each target condition). Object configuration for both targets and distractors was randomized for each trial.

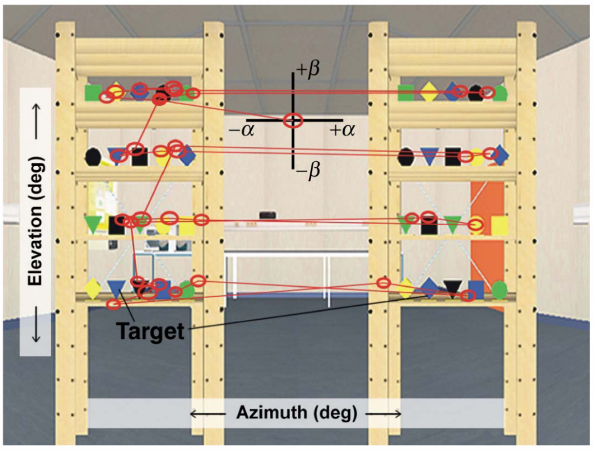


Figure 2. Screen shot of the comparative visual search task for a cupboard distance of 60° with superimposed gaze scan path example for one trial. Red circles indicate fixations and straight lines indicate gaze saccades. In this example, a one target condition is shown. Gaze position is expressed in angles (azimuth, α, and elevation, β) with respect to the point of origin.

In the beginning of the experiment, the eye tracker was calibrated by displaying a 9-point calibration pattern on the screen. For this procedure, head movements were prevented with a chin rest and all nine points had to be fixated. Also the head tracking target was calibrated with fixed head. Additionally, each experimental trial started with a 5-s fixation phase during which a fixation cross was displayed at eye level (1.2 m elevation) in the center of the screen (point of origin, cf. Figure 2). During this phase, the subject had to rotate the head to align the naso-occipital axis to the fixation cross followed by fixating the cross with the eyes. Thus, the subjects' gaze offset with respect to the calibrated systems was measured for each trial. After this fixation phase, the cross disappeared and the two cupboards became visible. The subjects were free to move their head and eyes to find the number of targets (i.e., zero, one, or two) as quickly and reliably as possible. The subject terminated the trial by pressing a button and reported verbally the number of targets. The next trial started with the fixation phase to the fixation cross after pressing the button. Participants were free to take breaks in between trials if desired.

Twenty-five subjects participated in this study (age: 23–34 years). Subjects were students at the University of Tübingen with normal or corrected to normal (only contact lenses were allowed) vision and were naive to the purpose of the experiment. They received monetary reimbursement for their participation. Because of the wide spread stimulus size, satisfactory eye tracking was obtained only for 12 of 25 subjects. Eye tracking loss was indicated by the tracker

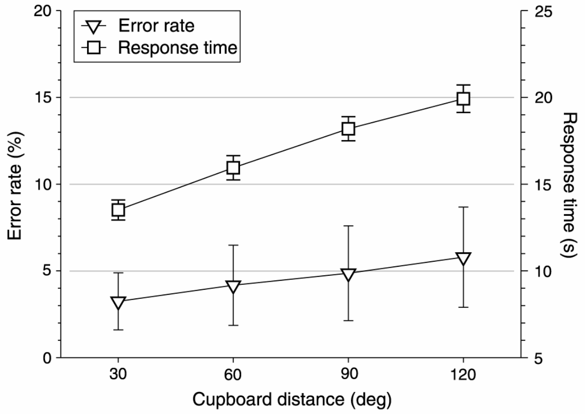


Figure 3. Averaged error rate and response time for each of the four cupboard distance conditions over all subjects and all trials. Error bars indicate standard error of the mean.

by a zero value for the pupil diameter. This was resulting from eye blink or a loss of the Purkinje reflex or of the pupil. Subjects were excluded if percentage of eye tracking loss exceeded 15% of all time. Only data from the 12 subjects were analyzed for the recent study.

Data analysis

To analyze the recorded data, the MATLAB® software (The MathWorks Company, Natick, USA) was used. Based on head and eye tracking data, the gaze vector was calculated in angles with an azimuth and an elevation component (α and β, respectively) relative to the point of origin (see Figure 2). Thus, the gaze vector includes both the head-in-space and the eye-in-head vectors. Gaze fixations were defined in the following way: For each time step t_o, we consider a gliding window of length 120 ms centered at t_o. Let v_{min} and v_{max} denote minimal and maximal gaze velocities obtained within the window. The instant t_o is classified as belonging to a fixation, if $v_{max} - v_{min} < 100$ deg/s. This procedure is iterated through all time steps. Adjacent instants in time satisfying the condition are combined to fixational events.

Results

Stimulus-related search performance

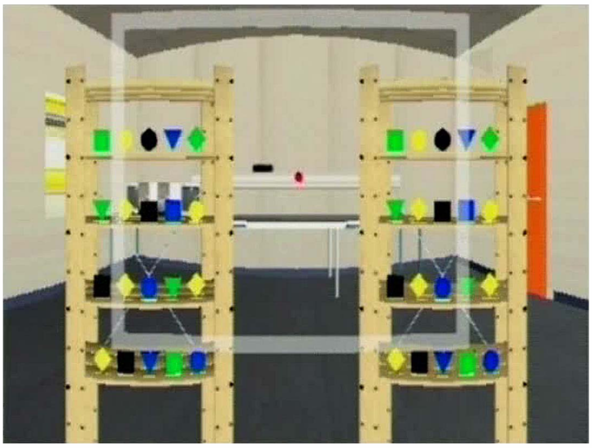
As error rate, we defined the proportion of subjects' incorrect responses in terms of the number of targets. Similar to Inamdar and Pomplun (2003), we found relatively low error rates of less than 7% for all cupboard distance conditions (Figure 3), indicating for subjects' accurate task performance. The error rates did not vary significantly between the four cupboard distance conditions, $F(3,33) = 1.416$, $MSE = 9.84$, $p = .256$.

Furthermore, we analyzed the response time, that is, the time needed to detect the number of targets and finishing one trial. We found a significant increase with increasing cupboard distance, $F(3,33) = 33.186$, $MSE = 4.754$, $p < .001$, $\text{eta}_p^2 = .751$ (Figure 3). The response time increased linearly by about 2 s for each 30° step of cupboard distance.

Stimulus-related eye and head movements

The subjects' initial gaze fixation was directed to the point of origin (i.e., $\alpha = 0$ and $\beta = 0°$). This was ensured by the calibration cross fixation phase before starting an experimental trial. After both cupboards became visible, all investigated subjects shifted their gaze to the upper left part of the left cupboard (cf. Figure 2 and Movie 1). This was followed by oscillating gaze changes between the left and right hemifield including shelf level shifts down to the lowest part of the cupboards. This general search pattern could be observed for all participants.

The smooth oscillatory shape of horizontal head movements is clearly visible in Figure 4. Maximum head movement velocities, averaged over all participants, of about 165 deg/s have been observed for the largest cupboard distance condition (120°), whereas the averaged velocity for 60° distance was only 48 deg/s. These



Movie 1. Example movie from the 60° cupboard distance condition (zero target condition). The red point indicates the gaze position and the grey frame the head movement of the subject. Eye movements can directly be extracted by subtraction of head from the gaze coordinates. The horizontal extent of the head frame is ±25°. Note that the eye movements always remain within this frame.

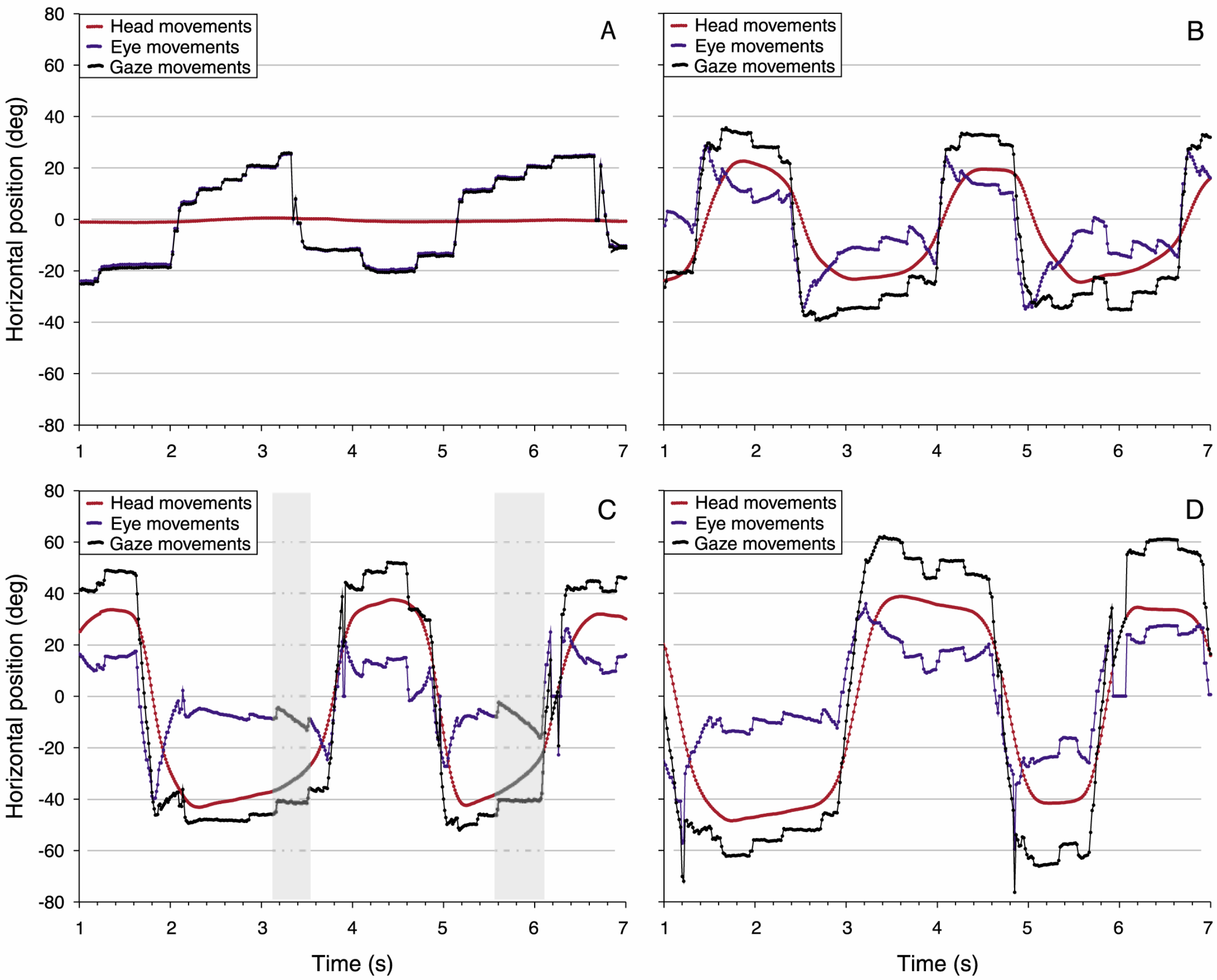


Figure 4. Example traces of the horizontal eye, head, and gaze movements for one subject. The plots display data for the different cupboard distance conditions (A: 30, B: 60, C: 90, and D: 120°). The steplike shapes of the gaze traces result from the consecutive sequence of fixations and saccades onto and between the objects. (C) Grey areas mark examples for compensatory eye movements maintaining gaze fixations. Note that under moving head conditions, target fixation amounts to compensatory movements of the eyes relative to the head under control of the vestibular–ocular reflex.

maximum velocities are reached during the head's left/right and right/left shifts, respectively. To enable a stable fixation during head movements, subjects performed compensatory eye movements in the direction opposite to the head movement under the control of the vestibular–ocular reflex (cf. Figure 4C).

Figure 5 shows the head and eye components of all recorded gaze saccades pooled over all subjects. Due to the cupboard design we used, gaze saccades were mainly performed in horizontal directions (cf. Figures 2 and 9). Under these circumstances, head and eye movements occur in parallel. Thus, eye saccade amplitudes can directly be obtained by subtracting head from gaze amplitudes. For 30° gaze saccades, eye movement amplitudes dominated the gaze and reached about 27.3°. For larger gaze amplitudes, the proportion of the head component increased up to 71° for gaze saccade amplitudes of 130°. This corresponds to approximately ±35.5° for the head's movement range and ±29.5° for the eye's movement range. This result (±29.5°) is well below the anatomical limit of the ocular motor range estimated to be ±53° (Guitton & Volle, 1987). The relation between gaze amplitude and head's proportion was quadratic with a correlation coefficient r = .879 (see Figure 5). The clustered distribution of the data points in this figure reflects the four cupboard distance conditions.

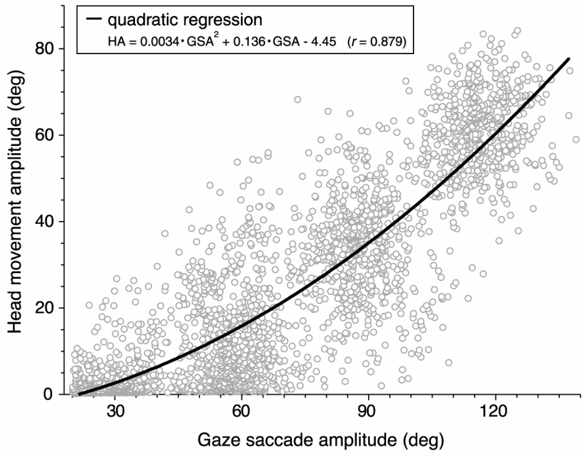


Figure 5. Relation between saccadic amplitude of gaze performed during the experiment and the proportion of head movement pooled over all subjects and gaze saccade directions. Regression indicates a quadratic relation with r = .879.

Stimulus-related gaze behavior

The most important objective of the experiment was to analyze the trade-off between gaze movements and VSTM for large gaze shifts. As compared to the results of Inamdar and Pomplun (2003) for eye saccades, we expected increased preferences for memory use resulting from high head movement costs. In the experiment, this should show up by a reduced number of inter-hemifield gaze saccades and longer fixation durations.

Figure 6A2 shows the number of inter-hemifield gaze shifts per trial, averaged over all subjects and depending on the cupboard distance. This number of inter-hemifield saccades per trial was significantly reduced for larger hemifield distances, $F(3,33) = 75.341$, $MSE = 3.714$, $p < .001$, $\text{eta}_p^2 = .873$. Subjects performed approximately 10 gaze shifts for the largest cupboard distance condition. This value is roughly half compared to the 30° condition.

The decrease of inter-hemifield gaze shifts was approximately the same for all 12 participants (cf. Figure 6A1). The fixation duration for each level of distance averaged over all subjects is shown in Figure 6B2. We found a significant increase for the fixation duration with increasing hemifield distance, $F(3,33) = 9.331$, $MSE = 137.01$, $p < .01$, $\text{eta}_p^2 = .459$. On average, subjects fixated about 25 ms longer for the most "expensive" condition in this experiment compared to the relatively "inexpensive" 30° cupboard distance condition. Figure 6B1 shows the fixation duration averaged over all trials per distance condition separately for each subject. All subjects performed longer lasting fixations related to the increased distance between both cupboards. Both the fixation duration and the number of inter-hemifield saccades over all subjects tend to saturate for large hemifield separations.

The fixation number per trial, averaged over all subjects (Figure 6C2), did not vary with the cupboard distance and was 39.8 fixations per trial, $F(3,33) = 0.974$, $MSE = 11.606$, $p = .417$. The same holds for the individual subjects, but with variation across subjects in large (Figure 6C1). Subjects performed the search task with a minimal fixation number of about 25 and a maximal number of about 65. Still, each subject showed a constant number of fixations over all distance conditions.

For large distances between the two cupboards, the time needed for a gaze shift was increased. Related to this increased time costs, the number of inter-hemifield saccades was decreased. This relation is shown in Figure 7. Per trial, subjects needed on average 4.97 s for all inter-hemifield gaze shifts in the 120° distance condition. For a single gaze shift, this amounts to a duration of about 0.5 s. For the 30° distance condition, the cumulative duration for all gaze shifts within one trial was only 2.15 s. Subjects performed on average 17.5 gaze shifts between the hemifields. This leads to 0.12 s duration for a single inter-hemifield gaze saccade.

To investigate the role of head proportions, the maximum head amplitude occurring in each trial within the two largest separation conditions (i.e., 90° and 120°) was considered. For each subject, two correlations were analyzed, (i) maximal head amplitude versus fixation duration and (ii) versus number of gaze shifts. The t tests performed over the correlation coefficients of all 12 subjects revealed significant differences from zero correlation, for details see Figure 8. Correlations of maximum head amplitude with the number of inter-hemifield saccades were negative for 10 of 12 subjects in both separation conditions (Figure 8, left). Correlations of maximum head amplitude with the fixation duration were positive for 11 of 12 subjects in both separation conditions (Figure 8, right). These data indicate that for a fixed hemifield separation, larger head proportions correlate with smaller number of inter-hemifield saccades and longer fixation duration.

Stimulus-induced search strategies

It turned out that the number of fixations (on average, 40 per trial over all subjects and conditions) was not evenly distributed over both stimulus hemifields. For example, in the gaze scan path shown in Figure 2, most fixations are located in the left cupboard. We analyzed the number of fixations with respect to the left and the right hemifield. The results indicate strong differences between the subjects (Figure 9). Eight participants showed more frequent fixations into the left and three participants more frequent fixations into the right hemifield. In the sequel, the first group is called "left hemifield subjects" and the second one is called "right hemifield subjects." Only one

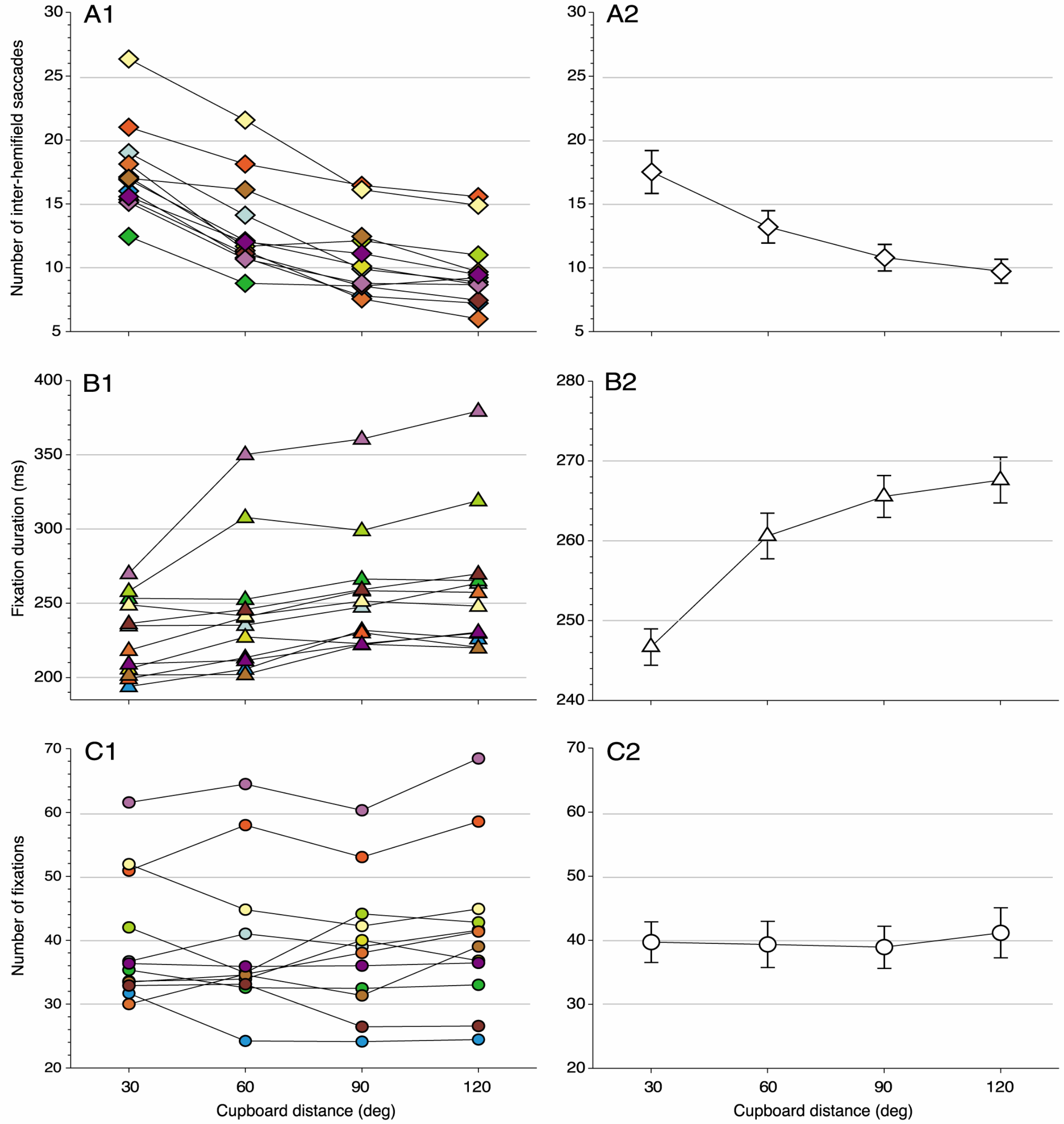


Figure 6. Number of inter-hemifield saccades (A1), fixation durations (B1), and number of fixations (C1) for each individual subject averaged over all trials for all four distance conditions. The plots A2, B2, and C2 display the same dependent variables but are averaged over all subjects. Note the different scales for fixation duration between B1 and B2. Error bars indicate standard error of the mean.

subject performed about 50% in either hemifield over all cupboard distances. The dependence of the proportion of fixations in the left hemifield on subjects was significant, $F(11,384) = 52.52$, $MSE = 46.8$, $p < .001$, $\text{eta}_p^2 = .6$. The post hoc analysis produced a significant difference between the right hemifield subject group and the left hemifield subject group ($p < .01$).

Interestingly, for the left hemifield subjects, the duration of individual fixations in the left hemifield was longer than fixation durations in the right hemifield. Conversely,

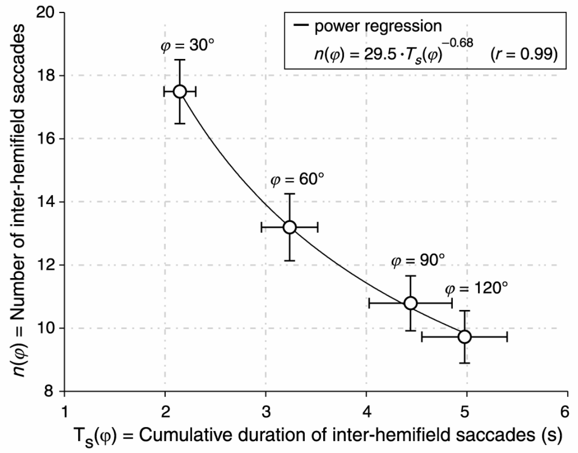


Figure 7. Trade-off between the sum of all inter-hemifield saccade durations ($T_s(\varphi)$) and the number of inter-hemifield saccades ($n(\varphi)$) for each trial averaged over all subjects for each cupboard distance (φ). Regression indicates a power function relation with $r = .99$. Error bars indicate standard error of the mean.

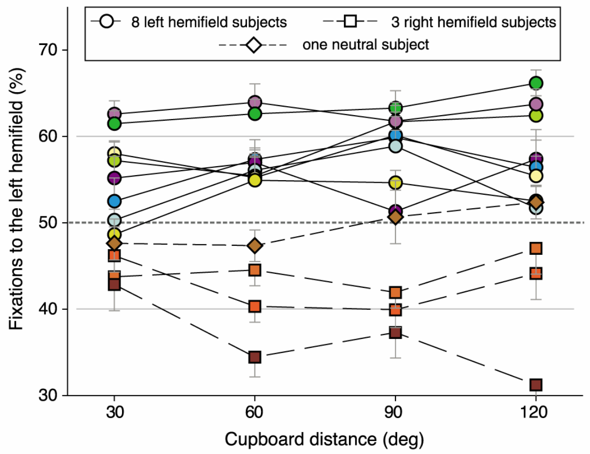


Figure 9. Hemifield distribution of all fixations for each subject. Subjects with more than 50% fixations over all distance conditions into the left cupboard are called left hemifield subjects and these with less than 50% right hemifield subjects. Only one subject showed no preference for the left or the right side. Error bars indicate standard error of the mean.

right hemifield subjects' fixations to the right hemifield lasted longer than their fixations to the left. This phenomenon is illustrated in Figure 10. There the previously shown fixation duration averaged over all 12 subjects (cf. Figure 6B2) was split up for the left and the right hemifield subjects' fixation duration to the left and to the right hemifields. Two sample *t* tests revealed significant differences between the fixation duration in the left and in the right hemifield for all cupboard distance conditions except for the one case marked in the Figure 10. The main effect for increased fixation duration with increased cupboard distance level was still visible in all four distance conditions. In addition, the left hemifield subjects' fixation durations were always longer than those performed by the right hemifield subjects.

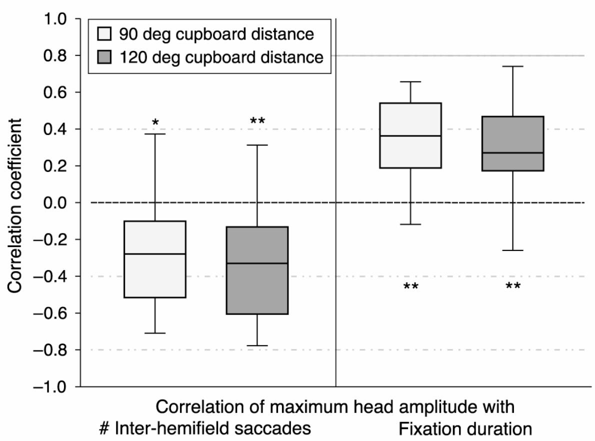


Figure 8. Box-whisker plots (median with 10th and 90th percentiles) of the correlation coefficients of the maximum head movement amplitude with the number of inter-hemifield saccades (left side) and the fixation duration (right side) in the 90° and the 120° cupboard distance conditions. Correlations were calculated over trials and separately per subject. Significant differences from zero correlation are given for each box-plot (*$p < .05$; **$p < .01$).

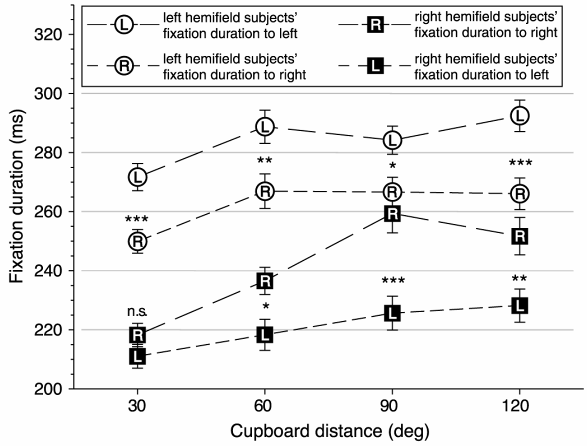


Figure 10. Fixation duration for the left and the right hemifield subjects divided for the two hemifields for all four cupboard distance conditions. Significant differences are calculated for the left and the right hemifield subjects between their fixation durations to the left and to the right hemifield for each cupboard distance (*$p < .05$; **$p < .01$; ***$p < .001$). Error bars indicate standard error of the mean.

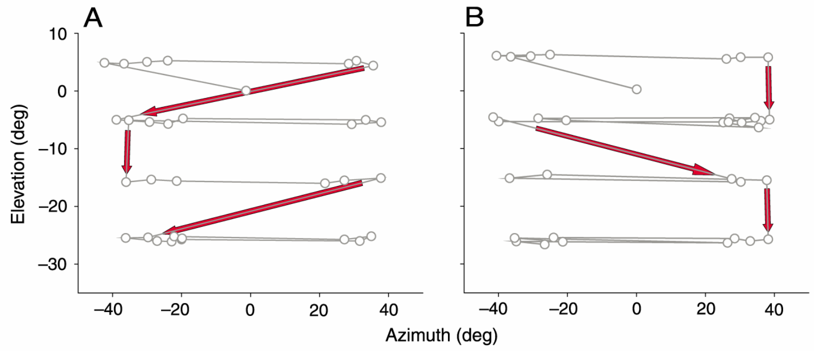


Figure 11. Two example gaze scan paths for the 60° distance condition representing the possible shelf level shifts depending on the search strategy. (A) Red arrows indicating for "left side shelf level shifts" within or into the left side. (B) Red arrows indicating for "right side shelf level shifts" within or into the right side.

As an additional parameter characterizing the search strategy, we analyzed the level shifts between shelves in the gaze scan path. Because the search task is carried out in a sequential manner, information encoded from one cupboard shelf has to be compared to information on the same shelf level of the opposing hemifield (cupboard). Therefore, shelf level shifts should occur only after one comparison has been completed and novel information is to be encoded. We divided the occurring shelf level shifts into two groups according to their goal, that is, level shifts within or into the left hemifield (cf. Figure 11A) and level shifts within or into the right hemifield (cf. Figure 11B).

For the left hemifield subjects, as classified on the basis of fixation frequency and duration, we found a preference for shelf level shifts within or into the left hemifield. These subjects showed a strong preference to begin a new shelf encoding stage on the left side performing about 80% of the shelf level shifts within or into the left hemifield. Vice versa, subjects from the right hemifield subjects group showed a preference for shelf level shifts within or into the right hemifield. They performed about 60% of all shelf level shifts within or into the right hemifield (Figure 12). Statistical analyses showed a significant difference between the left and the right hemifield subjects' search strategies related to the shelf level shifts for all cupboard distance conditions (see Figure 12).

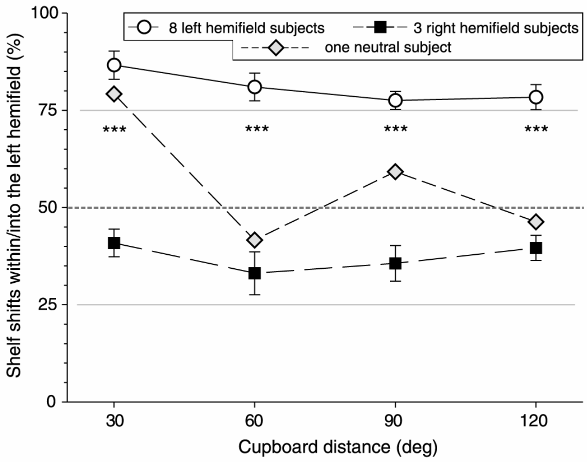


Figure 12. Percentage of shelf level shifts within or into the left hemifield also separated left and right hemifield subjects. Significant differences (***p < .001) have been found between left and right subjects within each distance condition. Error bars indicate standard error of the mean.

Discussion

Head movement proportion on gaze amplitude

In normal scene perception, humans naturally use head and eye movement together to direct their gaze (Hayhoe, 2000; Hayhoe & Ballard, 2005; Hayhoe et al., 2002; Land et al., 1999). To understand the role of head movements and their interaction with eye movements in relation to visual working memory use, we performed a comparative visual search paradigm similar to Inamdar and Pomplun (2003). Our results confirm the findings by Inamdar and Pomplun on eye saccades ranging from 15° to 45°, and these by Ballard et al. (1995) on combined eye and head movements ranging up to 70°. Furthermore, we extend these results toward larger gaze shifts with more pronounced trade-off effects resulting from stronger head movement involvement. To increase the costs for gaze movements, we increased the inter-hemifield distance between two stimuli up to 120°. To perform large gaze amplitudes corresponding to this stimulus size, head movements are required because the full-scale ocular motor range is limited to ±53° (Guitton & Volle, 1987). Furthermore, Stahl (1999) identified the customary ocular motor range with about ±22°, that is, well below the full-scale ocular motor range. Head movements are performed, Stahl argued, to maintain the eyes within the customary range. Also Becker (1989) reported that when the head is free to move, head movements become a regular feature of gaze saccadic shifts at approximately 20°. Our data support this finding. For the largest cupboard distances, we used 90° and 120°; the averaged eye amplitude was about ±29°. For these large gaze amplitudes, the head was used to maintain the eyes within a range, as described by Stahl. For smaller gaze amplitudes (below 60°), the head's proportion on gaze saccades showed more variance. With these small distances, the eyes could reach both stimulus hemifields without leaving the customary ocular motor range and no head movements were necessary. This finding differs from other studies (Kowler et al., 1992; Pelz, Hayhoe, & Loeber, 2001) where head movements were a regular feature even for small gaze shifts. In experiments by Pelz et al. (2001), head movements ranged between 1° and 10° for gaze changes of 15°. These different findings about head amplitudes suggest that this property of gaze shifts is not reliable and the authors concluded that the head movement magnitude is probably a function of the experimental constraints (Pelz et al., 2001). The large intersubject variability of head proportion on gaze saccades observed in our study was also reported by Fuller (1992), Pelz et al., and Stahl (1999, 2001). Moreover, even the same subject can alter the movement strategy to better address the demands of a specific task (Oommen, Smith, & Stahl, 2004). Unfortunately, the reason of this variability in head movement tendencies is still unknown.

Trade-off between VSTM and gaze movement behavior

The findings in experiments on scene comparison of Gajewski and Henderson (2005) suggested a strong general bias toward minimal use of VSTM. The authors showed that for complex visual tasks, often only one object is encoded at a time and maintained in visual memory. If subjects make such minimal use of memory also in our experiment, the following optimal scan path can be predicted: Starting from the upper left object, which is usually fixated at the beginning of each trial, fixation should shift to the corresponding position on the right cupboard. If the object at this place is identical, memory could be cleared and the next object right to the last fixated one should be memorized and compared with the corresponding object and so on. In our results, we found similar scan paths, but only for the smallest cupboard distance condition. In this condition, subjects produced on average 4.4 gaze shifts between the two hemifields within one shelf level, 2.2 in each direction. With the five objects per shelf level which have to be compared, a single cycle corresponds to approximately two memorized objects. This hints toward a memoryless search strategy. Also the relatively short fixation duration in the 30° condition, which we take as an indication of processing time, supports the lower memory load (Velichkovsky, 1995). For the largest distance condition (i.e., 120°), we found an approximately halved value for inter-hemifield gaze saccades. Because long lasting fixations are generally taken to indicate extraordinary memory load, the increased number of memorized items together with the much higher processing time hints toward an increased usage of VSTM. The higher the costs for gaze movements, the more memory load will be necessary. The overall fixation durations measured in this study (about 250–270 ms) corresponds well to those reported in other studies (Gajewski, Pearson, Mack, Bartlett, & Henderson, 2005; Henderson, Weeks, & Hollingworth, 1999; Rayner, 1998), which found fixation durations as low as 275 and 247 ms for a visual search task.

In the study by Inamdar and Pomplun (2003), without head movements the maximum inter-hemifield distance between the two columns of objects was 45°. The reported number of gaze shifts of about 14.3 matches very well with our findings for comparable distances (see Figure 13). With delayed unmasking of the attended hemifield, Inamdar and Pomplun tried to shift the trade-off between VSTM and eye movements as far as possible toward memory use. Masking time intervals up to 1 s were used. By increasing the time requirements, the authors could show that the employment of VSTM can be flexibly adapted to optimize task performance as long as the creation of internal representations does not take more than about 1 s. The data for the fixation duration (Figures 6B1 and 6B2) and the number of

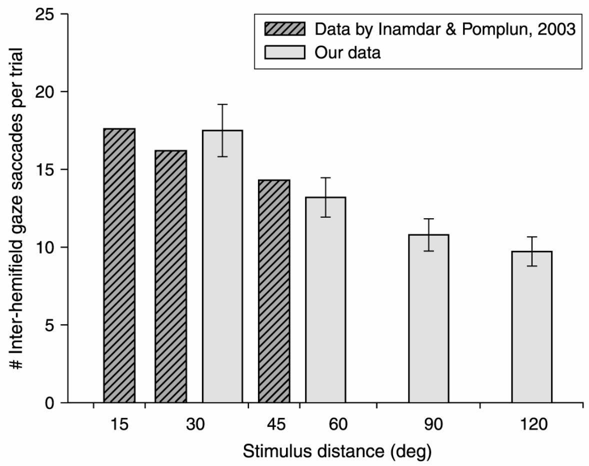


Figure 13. Combined presentation of decreasing inter-hemifield gaze saccades with increased stimulus distance for our data and these from Inamdar and Pomplun (2003). Error bars indicate standard error of the mean.

gaze shifts (Figures 6A1 and 6A2) indicate a tendency to approach asymptotically a limit for 120° inter-hemifield distance. For increased hemifield separations, we expect no further change of these variables. Thus, the upper limit of working memory load for the comparative visual search task seems to have been obtained.

The question whether head movements impose additional costs on gaze shifts has been addressed by a correlation analysis of head proportions with the number of gaze shifts and with fixation duration within the 90° and 120° hemifield separation conditions. When pooling over all subjects, the correlations did not reach significance. However, correlation coefficients per subject consistently showed positive signs for fixation duration and negative signs for number of gaze shifts. Across subjects, these effects did reach significance as shown in Figure 8. If gaze saccades with a given amplitude are carried out using a larger head proportion, the costs therefore seem to be increased. These data suggest that costs depend on both gaze shift amplitude and head proportion.

The comparative visual search task requires dealing with a fixed amount of information which does not depend on the hemifield separation. By eye movements, this amount of information is broken up into a number of chunks each of which is processed in a cycle of (i) encoding, maybe including intra-hemifield gaze shifts, (ii) inter-hemifield gaze shift, (iii) comparison, maybe including intra-hemifield gaze shifts, and (iv) inter-hemifield gaze shift back to the encoding side. The total cost can thus be divided into a cost of processing (encoding and comparing; steps i and iii) and a cost for shifting gaze between hemifields (steps ii and iv). The number of cycles, n, needed to solve the task equals half the number of inter-hemifield gaze-shifts. The amount of information processed during each cycle equals $I = 1/n$, where the total information is arbitrarily set to unity. We now assume that the number of cycles, n, is adjusted to minimize the total cost of processing. One possible measure of costs is the time needed to solve the task as suggested, for example, by Gray and Fu (2004) and Gray et al. (2006). This measure is consistent with the instruction given to our subjects, that is, to solve the task as quickly and reliably as possible. Because the error rate was generally low, it seems that time is indeed the most important factor. With respect to the processing cycle, we need to distinguish two time variables. First, the processing time per cycle, $T_p(I)$, equals the time needed for the encoding and comparison steps; it is assumed to depend on the size $I = 1/n$ of the information chunk, but not on hemifield separation. We choose a power law for $T_p(I)$, that is, $T_p(I) = b \cdot I^\alpha$ with constants b, α. Second, shift duration per cycle, $T_s(\varphi)$, is assumed to depend on hemifield separation φ, but not on chunk size I. Note that the dependence of T_s on φ is taken simply as an empirical fact as reported in Figure 7. It may result from the varying relative contributions of eye and head movements, both in terms of mechanical properties and in terms of neural planning effort for the compound movement. With the above notations, we can compute the total time needed to carry out the comparison in n steps:

$$T_{\text{tot}} = n \cdot [T_p(n^{-1}) + T_s(\varphi)] = b \cdot n^{(1-\alpha)} + n \cdot T_s(\varphi). \quad (1)$$

The latter equality results from the assumed power law for T_p. The idea of the model is that the trade-off results from minimizing T_{tot} with respect to n. Taking the derivative with respect to n and setting the result to zero yields

$$(\alpha - 1) \cdot b \cdot n^{-\alpha} = T_s(\varphi), \quad (2)$$

and further

$$n = c \cdot [T_s(\varphi)]^{-(1/\alpha)}, \quad (3)$$

that is, the relation of the number of cycles to the total time required for gaze shifting follows a power law. Here, c is a constant depending on b and α. Figure 7 shows the relation of n and T_s from our empirical data together with the theoretical curve given by Equation 3. If T_s is measured in seconds, the fitting parameters are $c = 29.5$ and $\alpha = 1.47$.

Why should T_p depends on the size of the encoded information chunk? One possible explanation for this is that the encoding of additional information may become more error prone as the amount of information already encoded increases. In this situation, additional fixations within one hemifield might be necessary, resulting in a longer processing time T_p. Indeed, the total number of fixations was found to be constant across all separation conditions (see Figure 6C), indicating that the number of intra-hemifield saccades increases as the number of inter-hemifield gaze shifts decreases. We therefore suggest that working memory involvement increases with hemifield separation and that encoding time increases in a nonlinear way with the amount of encoded information.

Subject-specific search strategies

An analysis of the number of fixations divided for the left and right hemifields indicated that subjects use one of two search strategies. On the basis of the percentage of fixations made into the left hemifield, we defined three subject groups. For all four cupboard distance conditions, the left hemifield group (eight subjects) performed more than 50% of all fixations into the left side. The second group, termed right hemifield subjects (three members), made more fixations in the right hemifield. In these two groups, we found no obvious correlation between the cupboard distance and the asymmetry of fixation numbers. Only one subject showed no preference for either side. All tested subjects are right-handed, so this attribute could not explain these fixation asymmetries.

The existence of such a strategy was furthermore supported by the findings on different fixation durations for left and right hemifield subjects for the right and the left sides. We found that the left hemifield subjects not only performed more fixations into the left hemifield; also, their fixation duration to this side was significantly longer. The same effect was true in the other way around for the right hemifield subjects. One could argue for two functional task stages processed by the subjects solving our comparative visual search paradigm. One stage is defined by more and longer fixations related to the preferred hemifield and could be interpreted as "encoding" stage. During the second stage, subjects performed fewer and shorter fixations to the other side. We called this stage the "comparison" stage.

The scheme in Figure 14 summarizes the search strategy process found in our experiment. Within a shelf level (shelf level: both corresponding cupboard shelves together), subjects started the visual search with the encoding stage and performed inter-hemifield gaze shifts in alternation between the comparison and the encoding stage. The encoding stage was identified by increased and the comparison stage by decreased fixation frequency and duration. After processing a shelf level completely, the following between shelf level gaze shift was started with the encoding stage. Left hemifield subjects were left encoders with their first encoding stage for a new shelf level mainly in the left hemifield, and correspondingly right hemifield subjects were right encoders.

Pomplun et al. (2001), using two fields with randomly distributed items, also distinguished two phases of comparative search, based on eye movement characteristics. In a "search and comparison" phase, subjects identified suspicious regions for further inspection. In a "detection and verification" phase, detailed scanning was performed to identify deviating items. In our structured layout, items

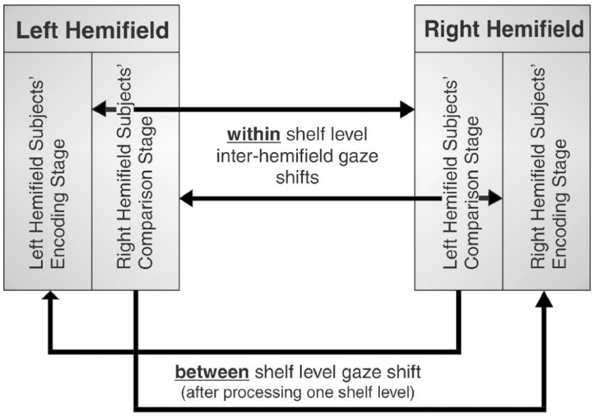


Figure 14. Scheme of the search strategy with the encoding and the comparisons stage alternation within and between shelf level gaze shifts.

are grouped on shelf levels that are searched one by one. Therefore, we do not find a "search and comparison" phase in the sense of Pomplun et al. We suggest that our distinction between encoding and comparison stages corresponds to a subdivision of Pomplun et al.'s "detection and verification" phase. Because Pomplun et al. do not analyze their "detection and verification" phase further, a deeper comparison of the search strategies and subject-specific effects is not possible.

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Chapter three: Assessment of vision-related quality of life in patients with homonymous visual field defects

Aim of this subproject, main results and my own contribution

HVFDs have a major impact on the quality of life of patients with impaired vision. However, such extensive restrictions in the size of the useful visual field can affect the patients' quality of life in various ways. While a variety of methods for quantifying visual field loss exist, there is not enough information about the degree of functional impairment in everyday life and about how homonymous visual field loss relates to patient-reported functioning. Furthermore, reports that specifically describe the vision-related quality of life of the patients by using vision-targeted, standardized instruments are missing. Hence, the aims of this study were to describe the vision-targeted, health-related quality of life in HVFD patients after cerebro-vascular lesion, and to determine the relationship between patients' self-reported difficulties and the characteristics of HVFDs in the binocular visual field. These characteristics were quantitatively ascertained by the method of semi-automated kinetic perimetry. Concerning their gaze performance, individuals selected out of this collective of patients were afterwards investigated in the tasks of the experimental tool box (see below).

The patients' general quality of life score assessed with the NEI-VFQ-25 questionnaire was significantly lower than the reference value for healthy subjects, and this was also the case for general vision, near activities, vision specific mental health, driving, color, and peripheral vision. The score for general health was also significantly lower in patients than in reference subjects. However, only a weak correlation of the composite score with the area of sparing within the affected hemifield was observed. The lack of a strong correlation suggests that an assessment of the visual field (using perimetry) may not accurately reflect patients' perceived difficulty in visual tasks. Additional consideration of visual exploration via eye and head movements may improve the correlation between visual function and its perception.

Together with E. Papageorgiou and B. Schoefisch I was involved in acquiring and analyzing the data, as well as in preparing and finishing the material for publication. I published our findings with E. Papageorgiou, Prof. F. Schaeffel, Prof. H. Wiethoelter, Prof. H-O. Karnath, Prof. H. A. Mallot, Dr. B. Schoenfisch and Prof. U. Schiefer as a full paper in a scientific journal.

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CLINICAL INVESTIGATION

Assessment of vision-related quality of life in patients with homonymous visual field defects

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Abstract
Background and purpose Homonymous visual field defects (HVFDs) are among the most common disorders that occur in the elderly after vascular brain damage and can have a major impact on quality of life (QOL). Aims of this study were to describe the vision-targeted, health-related QOL in patients with HVFDs after cerebrovascular lesion, and to determine the relationship between patients' self-reported difficulties and the characteristics of HVFDs in the binocular visual field.
Methods The German version of the 25-item National Eye Institute Visual Functioning Questionnaire (NEI-VFQ-25) was used. NEI-VFQ-25 scores for patients were compared to reference values of healthy German subjects from Franke (Z Med Psychol 7:178–184, 1999). Extent and location of absolute HVFDs were assessed by binocular semi-automated kinetic perimetry (SKP) within the 90° visual field. Correlations of the NEI-VFQ-25 scores of patients with the area of sparing within the affected hemifield (A-SPAR) were estimated by Spearman's r_s.
Results The mean NEI-VFQ-25 composite score for 33 patients (time span after brain injury at least 6 months) was 77.1, which was significantly lower ($p<0.0001$) than the reference value for 360 healthy subjects (composite score= 90.6), and this was also the case for general vision, near activities, vision specific mental health, driving, colour, and peripheral vision. The score for general health was also significantly lower in patients than in reference subjects ($p<0.0001$). A weak correlation of the composite score with A-SPAR ($r_s=0.38$) was observed.
Conclusions Our findings indicate that detectable decrements in vision-targeted, health-related QOL are observed in patients with homonymous visual field loss. A relationship of the perceived visual functioning with objective parameters is by definition difficult; however, understanding what components of visual function affect certain visual tasks, would help in developing more efficient, clinical assessment strategies. The results reveal a tendency for increasing QOL with advancing size of the area of sparing within the affected hemifield (A-SPAR). The lack of a strong correlation between NEI-VFQ-25 subscales and A-SPAR suggests that an assessment of the visual field may not accurately reflect patients' perceived difficulty in visual tasks. Additional consideration of visual exploration via eye and head movements may improve the correlation between visual function and its perception.

This paper was presented at the 2006 annual meeting of the German Ophthalmological Society (DOG) in Berlin, Germany on September 21, 2006.

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Keywords Homonymous hemianopia · Homonymous visual field defect · Vascular brain damage · Questionnaire · Exploration · Visual exploration · Quality of life (QOL)

Introduction

In developed countries stroke is the third most common cause of death after heart disease and cancer. As stroke mortality rates decline, individuals are increasingly likely to live with their residual impairments [15]. Homonymous visual field defects (HVFDs) are among the most common disorders that occur in the elderly after vascular brain damage and can pose a considerable impact for survivors' subsequent well-being. Approximately 30% of all patients with stroke and 70% of those with stroke involving the posterior cerebral artery suffer from HVFDs [30]. In Germany there is an incidence of approximately 550,000 brain-injured patients per year, 135,000 of them suffer from visual disturbances, mostly HVFDs.

There have been several studies focussing on stroke-related disabilities mainly assessed with generic questionnaires. Such generic instruments describe health-related quality of life (QOL) in terms of various dimensions including physical, functional, psychological, and social health as well as utility measurements [15]. Specific QOL measures have also been used in order to identify vision-related QOL in patients with binocular visual field defects due to various ophthalmological diseases [6, 14, 16, 17, 25, 31, 39]. However, to our knowledge, reports that specifically describe the vision-related QOL of patients with HVFDs after vascular brain damage by using vision-targeted, standardized instruments are missing. Specific functional impairments related to HVFDs have been repeatedly described in the literature. Patients complain mainly of difficulties with reading and scanning scenes fast enough to make sense of things as a whole. Consequently, they fail to notice relevant obstacles or avoid obstacles on their affected side and may collide with approaching people or cars. This has far reaching repercussions on their vocational and private lives [49]. While a variety of methods for quantifying visual field loss exist, there is not enough information about the degree of functional impairment in everyday life and about how homonymous visual field loss relates to patient-reported functioning.

Since previous research suggests that patients with HVFDs face a considerable degree of disability in everyday life, aims of this study were to describe the vision-targeted, health-related QOL, assessed with the 25-item National Eye Institute Visual Functioning Questionnaire (NEI-VFQ-25) in patients with HVFDs after cerebrovascular lesion, and to determine the relationship between the NEI-VFQ-25 scores and the characteristics of HVFDs in the binocular visual field, assessed with semi-automated kinetic perimetry (SKP).

Material and methods

Forty-five patients with HVFDs were recruited from the Department of Neuro-Ophthalmology at the University of Tuebingen (Germany), the University Neurology Clinic of Tuebingen, as well as the Neurology Clinic of Buerger Hospital in Stuttgart and the Bad Urach Rehabilitation Centre. All patients had a homonymous visual field defect, varying from a complete homonymous hemianopsia to homonymous paracentral scotomas, due to a unilateral vascular brain lesion, which was documented by neuroradiological imaging (magnetic resonance imaging or computerized tomography). In the majority of patients the lesion was located in the area supplied by the posterior cerebral artery. Inclusion criteria were a normal function of the anterior visual pathways, as evaluated by ophthalmologic examination (including ophthalmoscopy and slit-lamp exam), and a best corrected monocular (near and distant) visual acuity of at least 16/20. Exclusion criteria were severe unilateral visual hemi-neglect identified by pathological findings in horizontal line bisection, copying of figures [18], and by means of the "Bells test" [13], as well as evidence of cognitive decline, aphasia, apraxia, visual agnosia or physical impairment.

Since many of the patients with HVFDs show impaired reading performance, reading ability was tested with a German text used in the stroke unit of the University Neurology Clinic of Tuebingen. The text was a short story with a simple vocabulary and was easy to read. It was printed on an A4 page in landscape format and was read with best corrected visual acuity and the age-related addition for presbyopia. Reading distance was 30 cm. The total number of letters was 1614, which was equivalent to 276 words. Reading ability of patients was expressed as reading speed in letters/minute.

Furthermore, hemianopic patients may have difficulties in assessing the presence or absence and the severity of their visual handicap; therefore, anosognosia for hemianopsia was examined using a German translation of the anosognosia scale suggested by Bisiach et al. [4, 19]. The scale is based on direct observation of the patient's behaviour during the clinical examination, filled in by the examiner, with a grading scale as follows: grade 0 (no anosognosia)—the disorder is spontaneously reported or mentioned by the patient following a general question about their complaints; grade 1 — the disorder is reported only following a specific question about the strength of the patient's limbs; grade 2 — the disorder is acknowledged only after demonstrations through routine techniques of neurological examination; and grade 3 — no acknowledgement of the disorder can be obtained.

Finally, in order to check for cerebral achromatopsia, the colour naming test of the "Aachener Aphasie Test" was applied. However, colour naming is not an adequate tool for cerebral dyschromatopsia, because residual colour perception may allow an approximate categorization of colours despite the inability to make fine judgements about hue and saturation. Therefore the desaturated panel D-15 test was additionally used [37, 47]. The test requires that the subject sorts 15 coloured chips into an orderly progression on the basis of hue. Patients were instructed to sort the hues in the conventional direction, i.e. from left to right, and test scores were calculated as described by Lanthony [22].

The validated German version of the NEI-VFQ-25 in the self-administered format was used in the study population [1, 9]. The NEI-VFQ-25 is a validated, reliable instrument that assesses the dimensions of self-reported, vision-targeted health status that are most important for persons who have chronic eye diseases (http://www.rand.org) [10–12, 26, 27]. The questionnaire focuses on the influence of visual disability and visual symptoms on generic health domains, such as emotional well-being and social functioning, in addition to task-oriented domains related to daily visual functioning. It consists of a base set of 25 vision-targeted questions representing 11 vision-related constructs, plus an additional, single-item, general health rating question. The NEI-VFQ-25 generates the following vision-targeted subscales: global vision rating, difficulty with near vision activities, difficulty with distance vision activities, limitations in social functioning due to vision, role limitations due to vision, dependency on others due to vision, mental health symptoms due to vision, driving difficulties, limitations with peripheral and colour vision, ocular pain as well as a single, general health rating item. Subscales are scored on a 0- to 100-point scale in which 100 indicates the best possible score on the measure and 0 indicates the worst. The composite NEI-VFQ-25 score is the mean score of all the items except for the general health item.

Size and location of absolute HVFDs were assessed by binocular SKP within the 90° visual field (stimulus III4e, background luminance 10 cd/m^2, angular velocity 3°/s) with the OCTOPUS 101 perimeter (HAAG-STREIT Inc., Koeniz, Switzerland). From the visual field data we calculated the area of sparing within the affected hemifield (A-SPAR in degrees^2), the area of visual field loss (A-HVFD) in the binocular visual field, and the distance of the visual field border from the visual field centre along the horizontal axis (in degrees) for stimulus III/4e (Fig. 1). We used the binocular visual field because it provides more realistic information about the visual field a patient uses for performing daily activities. The degree of sparing along the horizontal axis was assessed because it plays a crucial role, in particular, for reading. Furthermore, only the stimulus III/4e was used because this is a functionally relevant target that is typically used to define legal blindness and also the visual field extent in driving license forms in Germany.

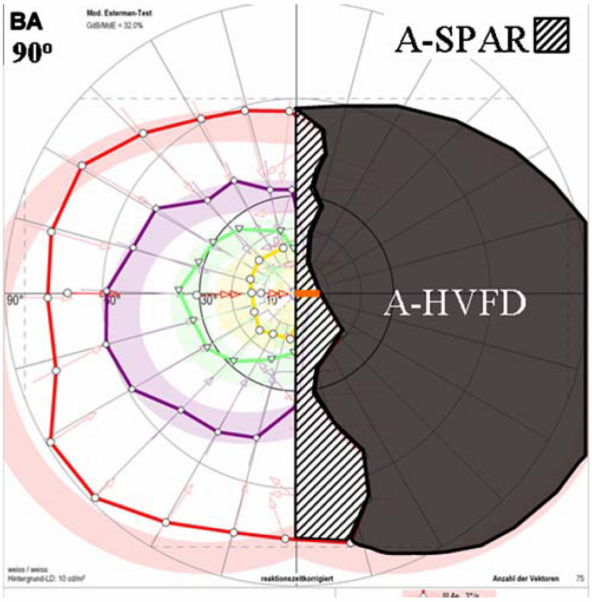

Fig. 1 Binocular visual field of a patient with a homonymous hemianopia to the right. Graphical representation of the area of sparing within the affected hemifield (A-SPAR, *hatched region*), the area of the visual field loss in the binocular visual field (A-HVFD, *black region*, obtained with stimulus III4e, angular velocity 3°/s) and the distance of the visual field border from the visual field centre along the horizontal axis or macular sparing (*orange line*, in degrees)

The research study was performed according to the Declaration of Helsinki and was approved by the Institutional Review Board of the University of Tuebingen, Germany. Following verbal and written explanation of the experimental protocol each subject gave written consent, with the option of withdrawing from the study at any time. None of the patients denied participation in the study and there were no missing data. The study was conducted between September 2005 and August 2006.

Statistical analysis

The patients' NEI-VFQ-25 subscale scores and the composite score were calculated according to the guidelines of the NEI-VFQ-25 manual. NEI-VFQ-25 scores were compared to reference values of a stratified sample of 360 healthy German subjects from Franke [10].

Since the reference values from Franke [10] were obtained from a large population (N=360), we choose one sample tests to compare values from our study group. For each subscale of the NEI-VFQ-25 a one sample Wilcoxon rank test was performed. For multiple testing adjustments we used the Bonferroni correction. Differences in reading speed between two groups of patients were tested with the two-sample Wilcoxon rank test. The distributions of individual NEI-VFQ-25 subscale scores are shown by boxplots using medians, quartiles, and minimal and maximal values. In order to detect relations of the binocular visual field impairment with the questionnaire scores, correlations of the NEI-VFQ-25 subscale scores with A-SPAR were estimated by Spearman's r_s. We used JMP 5.0.1 (SAS Institute Inc., Cary, NC, USA) for most of the graphics and the correlation coefficient calculations. The boxplots are produced by R 2.2.1 (R foundation for statistical computing, Vienna, Austria) and the package "exactRankTests" of R was used in order to obtain exact values in the presence of ties [34].

Results

Of the 45 recruited patients, 12 were excluded due to the presence of bilateral HVFDs and/or pathological findings of the anterior visual pathways; 33 patients with HVFDs without visual neglect (24 male and 9 female), with a mean age of 51.4 years (SD±15.8; range 21–74) were deemed eligible for participation in the study. Mean time since lesion onset was 2.7 years (range 6 months to 16 years) and exceeded 1 year in the vast majority of patients (27 out of 33 patients). There were 16 patients with right-sided HVFDs and 17 patients with left-sided HVFDs. The distribution of the area of sparing within the affected hemifield (A-SPAR in degrees^2) is shown in Fig. 2.

Patients were divided in three groups: 0–2°, >2–5°, >5° according to the distance of the visual field border from the visual field centre along the horizontal axis (macular sparing, obtained with stimulus III4e, angular velocity 3°/s, Fig. 3). Mean reading speed was slower in right-sided HVFDs (510 letters/min, equivalent to 85 words/min) than in left-sided HVFDs (669 letters/min, equivalent to 112 words/min); however, the difference is not significant (p=0.080). For comparison, the abstract of this paper contains about 350 words. In right HVFDs, reading speed was much lower if macular sparing was 5 degrees or less (Fig. 3).

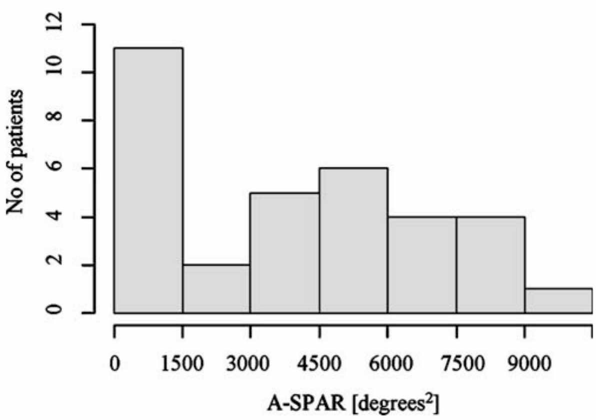

Fig. 2 Distribution of the area of sparing within the affected hemifield (A-SPAR, obtained with stimulus III4e, angular velocity 3°/s)

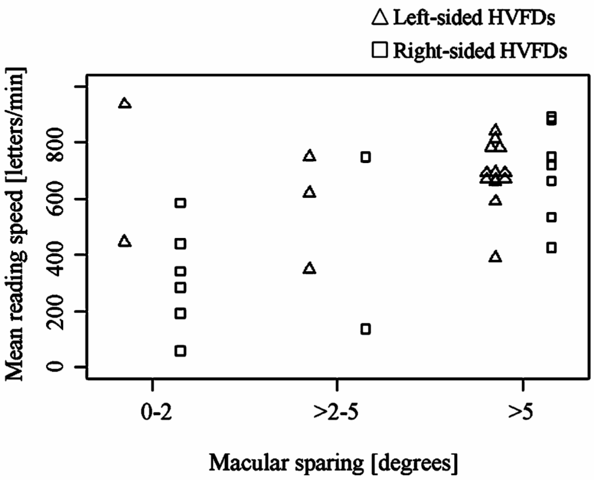

Fig. 3 Scatter plot of mean reading speed (letters/min) in patients with left- and right-sided HVFDs by the degree of macular sparing (distance of the visual field border from the visual field centre along the horizontal axis in degrees, obtained with stimulus III4e, angular velocity 3°/s)

Regarding the presence of anosognosia for hemianopsia in regard to visual field loss, 30 (91%) of the 33 brain-damaged patients mentioned their visual field defect spontaneously following a general question about their symptoms. Only 3 (9%) of the patients had a denial grade of 1, that is, they reported their visual field impairment only following a specific question about their visual complaints.

All patients showed an adequate performance in the colour naming test of the "Aachener Aphasie Test". In 7 (21%) of 33 patients the error score was slightly pathological according to the age-related normal values established by Lanthony [22].

When compared with the reference group, patients with HVFDs had significantly poorer scores on 7 of 12 NEI-VFQ subscales (Table 1): general health, general vision, near activities, mental health, driving, colour vision, and peripheral vision. Furthermore, the composite score was significantly lower in patients (Table 1, Fig. 4).

Female patients had a higher composite score (82.5) in comparison to male patients (75.1), but this difference was not statistically significant (p=0.27). When comparing each subscale of the NEI-VFQ-25 separately, female patients always had slightly higher scores compared to male patients, except for the item regarding self-assessment of driving performance, where the mean value was similar (female 32.4, male 32.6). There was no significant difference between female and male patients when the area of sparing within the affected hemifield (A-SPAR in degrees^2) was considered (p=0.49). There was no influence of time since

Table 1 NEI-VFQ-25 subscale scores for the patient and the reference group and p values for one sample Wilcoxon rank test

NEI-VFQ-25 subscales	NEI-VFQ-25 scores		One sample Wilcoxon rank test
	Patients N=33	Reference group N=360 resp. 302[a]	
General health	44.7[b]	69.4	<0.0001
General vision	65.5[b]	82.6	<0.0001
Ocular pain	92.0	89.2	0.052
Near activities	78.0[b]	93.3	<0.0001
Distance activities	84.8	94.7	0.057
Social functioning	89.0	96.6	0.369
Mental health	77.8[b]	90.2	0.001
Role difficulties	73.9	91.6	0.024
Dependency	89.9	96.6	0.368
Driving	32.6[b]	92.4	<0.0001
Colour vision	94.7[b]	97.0	0.002
Peripheral vision	69.7[b]	95.6	<0.0001
Composite score	77.1[b]	90.6	<0.0001

Data are presented as mean values
[a] Reference values from Franke [10] (N=360 resp., N=302 for driving)

injury on either A-SPAR (r_s=−0.21) or on the composite score (r_s=−0.12). Similarly, our data showed no evidence for an effect of age on NEI-VFQ-25 responses (r_s=0.17).

Table 2 shows the correlation coefficients r_s between the area of sparing within the affected hemifield (A-SPAR in degrees^2) for each of the NEI-VFQ-25 subscales.

A moderate correlation was only detected for the subscale social functioning (r_s=0.51). Weak correlations were detected for the subscales near activities (r_s=0.25), distance activities (r_s=0.31), dependency due to vision (r_s=0.25), peripheral vision (r_s=0.26), and for the composite score (r_s=0.38) (Fig. 5). Similarly, there was a weak correlation between reading speed (letters/min) and A-SPAR values (r_s=0.29). The correlation with the NEI-VFQ-25 driving score was moderate (r_s=0.44). However, more than half of the patients (19 out of 33) did not drive a car due to the existing visual field defect, therefore the NEI-VFQ-25 score for the driving item was zero in this subgroup. If we consider the remaining 14 patients, then the correlation with A-SPAR decreased (r_s=0.25, Fig. 6). A similar problem occurred in

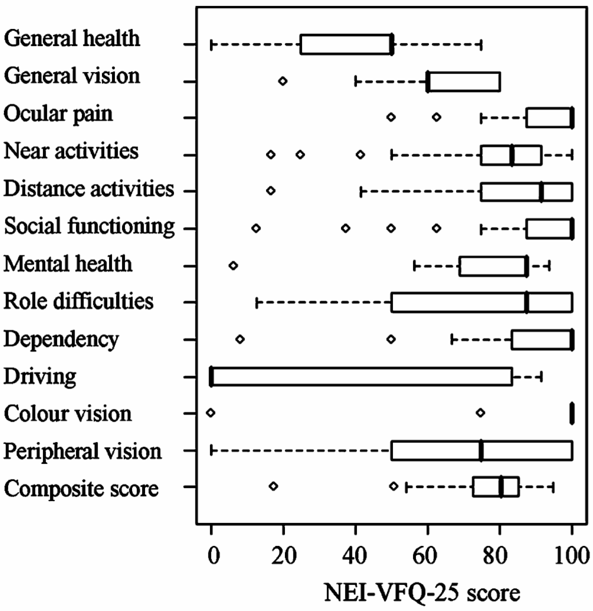

Fig. 4 Boxplots of subscale scores of the NEI-VFQ-25 for 33 patients suffering from homonymous visual field defects (HVFDs)

Table 2 Spearman's correlation coefficients r_s between NEI-VFQ-25 scores and A-SPAR values in patients with HVFDs (N=33). Additionally, the correlation coefficient r_s between reading speed (letters/min) and A-SPAR values is shown (r_s=0.29)

Rating items	Correlation coefficient r_s
General health	−0.04
General vision	0.13
Ocular pain	−0.12
Near activities	0.25
Distance activities	0.31
Social functioning	0.51
Mental health	0.15
Role difficulties	0.11
Dependency	0.25
Driving	0.44
Colour vision	0.02
Peripheral vision	0.26
Composite score	0.38
Reading speed	0.29

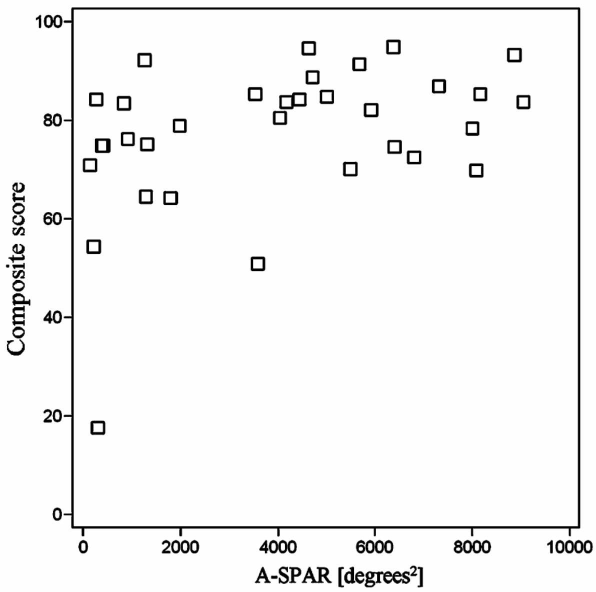

Fig. 5 Scatterplot of the area of sparing within the affected hemifield (A-SPAR, obtained with stimulus III4e, angular velocity 3°/s) with the NEI-VFQ-25 composite score for 33 patients. A weak trend for increasing QOL by advancing A-SPAR is depicted (r_s=0.38)

the social functioning and dependency subscales, where identical values (score=100%) occurred in 21 and 14 out of 33 patients, respectively. Due to the presence of ties in these subscales the correlation coefficients are of limited value.

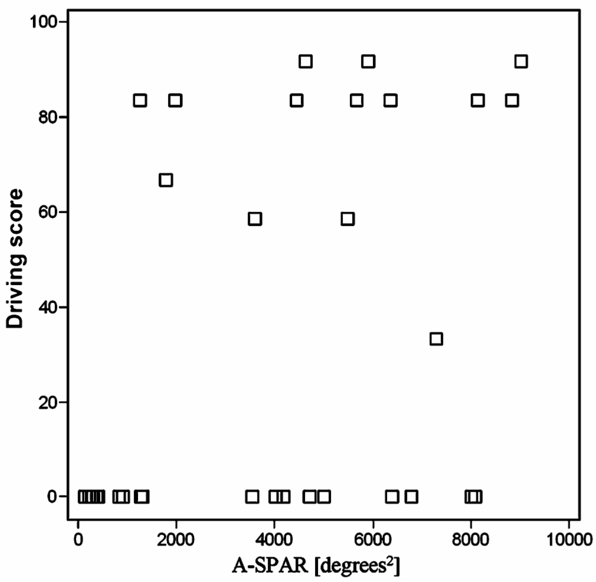

Fig. 6 Scatterplot of the area of sparing within the affected hemifield (A-SPAR, obtained with stimulus III4e, angular velocity 3°/s) with the NEI-VFQ-25 driving score (r_s=0.44) for 33 patients. If the patients who are not driving (N=19, score=0) are excluded, r_s decreases to 0.25

Discussion

Our findings suggest that patients with HVFDs due to cerebrovascular disease experience a reduction in vision-targeted QOL as indicated by 6 of 11 NEI-VFQ-25 subscales: general vision, near vision, vision-specific mental health, driving, colour vision, and peripheral vision. Furthermore, the composite score as well as the general health score were significantly lower in patients than in reference subjects. Homonymous visual field loss is apparently correlated with a general deterioration in perceived visual function. Especially regarding near vision, NEI-VFQ-25 includes three items that assess reading ability, difficulties in near activities (e.g. cooking or using hand tools), and finding objects on crowded shelves (http://www.rand.org). It is likely that the decrease in the subscale "near vision" is due to an impairment of reading performance. Reading ability is commonly affected in homonymous visual field loss and patients with HVFDs have reading difficulties that reflect the laterality of the visual field defect and depend on the degree of macular sparing (Fig. 1). Fluent reading demands at least 2° of visual angle to the left and right of the central fixation point and 1° above and below [2, 42, 43]. Reading disorders of patients with HVFDs result from the loss of parafoveal field regions which form a "perceptual window" for reading, subserving letter identification [49]. In western societies this reading window extends 3–4 characters to the left of fixation and 7–11 characters to the right of it; due to the asymmetry of this perceptual window right-sided HVFDs cut a larger part of the reading window and therefore impair reading more than left-sided HVFDs (approximately 5° vs. 2°), and reading speed improves with increasing distance to the visual field centre [21, 42, 49]. Left HVFDs cause difficulties with eye movements required to find the beginning of a new line, resulting in omissions of the first word or syllables of the line. Right HVFDs cause more severe reading difficulties, with loss of the anticipatory parafoveal scanning process, increased number of saccades, and significant reduction of reading speed, which result in a characteristic reading disorder termed "hemianopic dyslexia", which in some patients is nearly equivalent to spelling [2, 23, 24, 42, 43, 49]. Our results are consistent with other studies, suggesting that patients with right-sided HVFDs are more handicapped than those with left-sided HVFDs and reading speed improves with increasing degree of macular sparing (Fig. 3) [42, 49]. The weak correlation of reading speed and of the near vision item with A-SPAR also indicates this tendency (Table 2). However, when the patients are divided into further subgroups based on the degree of macular sparing, the number of patients remaining in each group is limited. Therefore, these results can only be descriptive and can show some trends (Fig. 3). Impaired reading ability clearly causes a significant decline in QOL, because a considerable amount of the information acquired at educational, professional, and social levels is transferred by written documents.

Driving with HVFDs is one of the critical issues in traffic ophthalmology. Up to 90% of the information input regarding driving is visual [40]. Consequently, impairments in the binocular visual field will lead to deficits in nonvisual activities (cognition and motor control) [21]. Due to the unilateral peripheral affection of the visual field, patients with HVFDs show similar problems in daily activities demanding the use of peripheral vision (e.g. for detecting vehicles or persons to avoid collisions or falls [21]). Many of these patients do not feel safe enough to drive a car. Others do not meet the minimum standards for a driving license, since traffic safety regulations in the European Union require a horizontal extent of the binocular visual field of 120 degrees [41]. According to the recommendations of the German Ophthalmological Society for patients with HVFDs, the central 20 degrees of the binocular visual field, as well as 10 degrees above and below the horizontal meridian at 30 degrees eccentricity, should be unaffected [36]. Since driving represents the primary mode of travel in most western societies and is commonly linked to personal independence, one could imagine the socio-economic aspects as well as the individual impact on personal autonomy.

In poststroke patients, besides physical functioning, neuropsychological sequelae such as depression and cognitive impairment contribute to a reduced QOL and can be associated with a handicap that affects the ability to work and diminished social activity [7, 15, 32, 33]. These limitations — potentially combined with an impaired reading ability — could give a possible explanation for the decline in perceived mental and general health, as observed in the patient group. Our results indicate clearly that homonymous visual field loss can create a remarkable amount of subjective inconvenience in everyday life, since vision is one of the major input channels to memory, and the most important medium in the workplace in our visually and PC-dominated world.

However, in most of the scales we failed to demonstrate strong correlations with the extent of the binocular visual field assessed by kinetic perimetry. We calculated the area of sparing within the affected hemifield (A-SPAR) and demonstrated its relation with the questionnaire scores because the central 30 degrees of the visual field are thought to play an outstanding role in performing activities of daily living (ADL) [36]. When calculating the correlation coefficients of the questionnaire scores with the area of the visual field loss in the binocular visual field (A-HVFD, Fig. 1), we obtained analogous inverse correlations, which indicated a tendency for poorer NEI-VFQ-25 scores with increasing visual field defects. This result was expected, since the values A-SPAR and A-HVFD are complementary indices of the affected hemifield (Fig. 1); therefore, only the results for correlations with A-SPAR were demonstrated.

The findings suggest that an objective assessment of the visual field alone may not accurately reflect the actual or perceived ability of the patient to function. Over the past several years increased awareness of the effect of ophthalmic disease upon QOL has led many investigators to evaluate vision-related QOL for various ophthalmic conditions, such as glaucoma and retinitis pigmentosa, and their relation to binocular visual field loss [25, 29, 31, 38, 44]. A study by Gutierrez et al. showed that a steady decline characterized the relation between visual field loss and health related QOL in glaucoma assessed by the NEI-VFQ-25 [14]. Other studies also indicated a good association between some types of perceived visual disability and the severity of binocular visual field loss in glaucoma and in retinitis pigmentosa [25, 29, 31, 35, 38, 44]. However, the correlation with measures of the binocular visual field was in some cases moderate or modest and was only detected for some of the examined subscales [31]. It was also observed that some glaucoma patients with visual field loss did not have any limitations in visual function [25]. Moreover, some investigators reported a poor correlation of subjective QOL values with the Esterman score in glaucoma patients and suggested that clinical tests and QOL assessments only partially characterize the effect of glaucoma damage and thus provide complementary information [17]. Although these studies are not directly comparable to ours because of substantial differences in the etiology and pattern of binocular visual field loss, they provide evidence that subjective visual limitations are not always related to the total amount of visual field loss. Reports on vision-related QOL of patients with HVFDs are, to our knowledge, currently missing; however, the need to design clinical tests of vision that better correlate with patient perception is growing. Additional features which could be considered when performing ADL are exploratory eye movements and head turns. Particularly in driving, no strong correlation between perceived disability and A-SPAR could be detected. This leads to the hypothesis that there is great interindividual variability and that the extent of the HVFD per se is not a good predictor of the perceived disability in driving. Especially in patients with homonymous visual field defects, visual exploration through saccadic eye movements and head turns plays a substantial role because it enables the shift of circumscribed (binocular) visual field defects from relevant to less important areas of the visual environment [36]. Intact exploration ability thus can at least partially compensate for an existing visual field defect [8, 28, 45, 48]. These exploratory viewing strategies represent a substantial characteristic of our visual behaviour and should therefore be assessed in any attempt to describe vision-related QOL. A future challenge for investigators is the design of innovative clinical tests in order to quantify visual exploration and its impact on QOL.

According to the anosognosia scale of Bisiach et al., 9% of the patients should be classed as having "mild anosognosia" [4]; however, analysis of the verbal responses showed that all three patients rated grade I complained spontaneously about other neurological deficits such as speed arrest, loss of concentration, and tiredness, which were real and are indeed common in poststroke patients. When the examiner asked about their visual complaints, all three patients immediately acknowledged the homonymous visual field loss. Thus our results are consistent with those of a former study by Baier et al., suggesting that patients in denial grade I did not appear to have a problem in accepting their hemianopsia, but simply perceived other symptoms as being more prominent, when asked a general question about their complaints [3]. Thus these patients were not considered as suffering from general anosognosia.

In patients with bilateral occipitotemporal injury, colour vision may be moderately affected in the entire visual field, or in rare cases may even be completely lost (cerebral achromatopsia). After unilateral occipitotemporal brain injury colour vision may be lost in the contralateral hemifield or the upper quadrant (cerebral hemiachromatopsia or hemidyschromatopsia). Foveal colour vision may also be affected [47, 49]. The performance of 7 out of 33 patients in the desaturated panel D-15 test was, compared to normative data, only slightly pathological, and indicated a mild form of cerebral dyschromatopsia with foveal involvement. The NEI-VFQ-25 score for colour vision however was significantly lower indicating that the desaturated panel D-15 test may not be sensitive enough to detect less severe cerebral disturbances of colour vision. A more detailed hue discrimination test may be necessary [47]. On the other hand, colour vision in the NEI-VFQ-25 is assessed by only one item:"Because of your eyesight, how much difficulty do you have picking out and matching your own clothes?" One could question the relevance of this item, since it addresses colour discrimination only in an indirect way and assesses at most a global impairment. Moreover, it has been reported that not all patients with moderately impaired colour vision after unilateral posterior brain injury are aware of their deficit and therefore will not mention it [49]. An alternative test is the questionnaire for the subjective assessment of cerebral visual disorders, developed and validated in the German language by Kerkhoff et al. [20]. Disturbances of colour vision are assessed here with a more specific question: "Do you perceive colours as saturated and clear as earlier? Yes or no? If not, are they now brighter, desaturated or strange?"

It was not expected that time since brain injury would influence A-SPAR or the NEI-VFQ-25 responses because the time span after lesion onset was at least 6 months. Recent quantitative studies of visual field recovery suggest that spontaneous improvement of homonymous hemianopsia is seen in at least 50% of patients within 1 month of injury and in most cases the improvement occurs within the first 3 months after injury [30, 46]. After this period spontaneous field recovery is very rare. Therefore an improvement in the visual field, which could have an impact on QOL, would be rather unlikely.

This study has several limitations. First, we considered a rather small sample size with a wide range of visual field impairment, which reduces the generalizability of the results. The time span between brain injury and data collection was at least 6 months, so our results are valid for patients with HVFDs existing longer than 6 months. Furthermore, our patient group is not representative of the general poststroke population, because we only included nonhospitalized subjects with HVFDs, who could be examined perimetrically in the outpatient care unit and thus had only minor motor or cognitive deficiencies. This fact could provide evidence that our patient sample has probably reported a higher QOL in comparison with the general poststroke population with HVFDs. Further research should concentrate on larger population samples, because individuals may respond to questions in an overly positive or overly negative manner, depending on idiosyncratic personality styles, motivations, or incentives [38].

In general, a relationship of the perceived visual functioning with objective parameters is by definition difficult [5]; however, understanding what components of visual function affect certain tasks, would help in developing more efficient, clinical assessment strategies [38]. Different tasks may emphasize different aspects of visual function, therefore we aimed at observing trends about the activities with which patients have perceived difficulty and about which tests of visual function best relate to these activities. The development of the clinical tests that best predict self-reported functioning would be important to better define practical, and perhaps more efficient, clinical assessment strategies for the evaluation of patients with HVFDs [38].

In conclusion, our results indicate that there is a trend for decreasing QOL with advancing HVFDs. However perceived difficulty is not strongly related to the extent of the binocular visual field. Conventional clinical measures such as visual field assessments do not seem to fully capture the influence of visual disability on daily functioning and on abilities to perform ADL that are valued by patients. From a functional point of view, additional assessment of visual exploration by means of eye and head movements should be helpful in evaluating global, vision targeted QOL in order to improve the correlation between visual function and its perception.

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Chapter four: Functional compensation in hemianopic patients under the influence of differing task demands

Aim of this subproject, main results and my own contribution

The main goal of this work was to gain a deeper and more fundamental understanding about eye and head movement, specifically, gaze functions due to compensatory strategies in patients with homonymous visual field defects (HVFDs). Therefore, in cooperation with Prof. U. Schiefer from the Centre for Ophthalmology in Tübingen, I developed a new experimental toolbox. The idea of this toolbox was the creation of a sequence of tasks, differing in their cognitive demands, that would allow various levels of gaze movement adaptations to the patients. Contrary to most of the existing paradigms, our goal was to introduce more realistic tasks. The first task was a “simple” visual sampling (DC) task; the second one was a more demanding comparative visual search (CVS) task (cp. chapter two); and the third a dynamic traffic-related paradigm, mainly integrating higher visual functions (top-down processing). Our aim was to stimulate as much of the visual field as possible in all tasks. In this chapter, the results due to the compensatory strategies of HVFD patients in first two tasks are presented.

With the data for adaptive gaze behavior in patients with HVFDs two subgroups of patients differing in their capability to solve different visual scanning tasks were identified. The subgroup of adequate patients seems to compensate well for their visual field loss in the cognitively unchallenging sampling task as well as in the more demanding visual search task in a spontaneous manner. But compared to their oculomotor functions in the DC task, which did not differ from these of healthy subjects, the adequate patients’ gaze behavior showed increased compensational adaptations in the CVS task. On the other hand, for the subgroup of inadequate patients the compensational correlates were increased in a more massive manner to overcome their HVFDs. But regardless of their increased adaptations, these patients failed in performing the two scanning tasks as accurately as controls or adequate patients. The results related to the gaze parameters are interpreted in terms of task specific demands related to the patients’ different abilities of effective compensation.

I was mainly involved in the development and implementation of these toolbox experiments. Together with E. Papageorgiou I performed all experimental investigations. Furthermore, I had analyzed, prepared, and described the data for a publication.

The results of these investigations are prepared for submission (together with E. Papageorgiou, Prof. U. Schiefer and Prof. H. A. Mallot) in the journal of Neuropsychologia.

Manuscript

Title: Functional compensation of visual field deficits in hemianopic patients under the influence of differing task demands

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Title, shortened: Task dependent scanning behavior in hemianopics.

Abstract:

To investigate the adaptive strategies due to functional gaze compensation in patients with homonymous visual field defects (HVFDs) in comparison with healthy controls, two tasks with different cognitive demand were applied. The dot counting (DC) paradigm as a relatively simple visual sampling task was chosen to restrict visual scanning to a process without additional visual processing such as object recognition. As a more cognitively demanding visual scanning task, a comparative visual search paradigm (CVS) was introduced. Based on the patients' task performance (i.e. measurements of error rate and response time) two subgroups of HVFD patients could be separated (i.e. "adequately" performing $HVFD_A$ patients and "inadequately" performing $HVFD_I$ patients). Regarding the gaze related parameters in the DC task we obtained results in perfect concordance with previous studies: the subgroup of $HVFD_A$ patients showed similar visual performance compared to healthy controls and $HVFD_I$ patients performed with increased oculomotor adaptation. For the more complex CVS task we identified a strikingly different pattern of compensatory strategies. All gaze parameters identified as important for functional compensation by other studies were significantly adapted in the case of $HVFD_A$ patients. These results are interpreted in terms of task specific demands related to the patients' different abilities of effective compensation. In the cognitively simple DC task no further oculomotor adaptations are necessary for $HVFD_A$ patients in order to complete this sampling paradigm in the range of controls. However, the inadequate patients needed adaptations and showed increased compensatory visual scanning. To overcome their visual limitations this adapted compensation became also prominent for the adequately performing patients in the more complex comparative search task.

Introduction:

Orienting movements of the human's head and eyes serve to bring the image of the intended object of regard onto the retinal area with the highest resolution, that is, the fovea. The peripheral retinal areas with comparatively coarse visual resolution allow us to gain a view over the visual surrounding apart from the fovea. Information transmitted by these peripheral areas is involved in making decisions about which information in the perceptual database (Boothe, 2002) are most likely for being updated. This process of guiding attention is important for calculating subsequently orienting gaze movements (gaze = eye-in-head + head-in-space) to the most informative area of the subject's exogenous surrounding. Additionally, endogenous expectations and intentions may influence the oculomotor behavior of the observer.

Patients with homonymous visual field defects (HVFDs) are impaired by a restricted visual field due to "blind" areas (scotomas) caused by unilateral post-chiasmal brain damage (Zihl, 1994). Common causes are cerebrovascular accident, traumatic brain injury, and tumors (e.g. Kerkhoff, 1999; Zihl, 2000). With this restriction, the visual system of these patients theoretically lacks up to one hemifield (in case of complete homonymous hemianopia - HH) for acquiring information. As a consequence, these patients have difficulties in reading (e.g. Zihl, 1995a; McDonald, Shillcock, Wise, & Leff, 2006), may bump into obstacles on the affected side (Zihl, 2000), and have generally problems to comprehend a scene as a whole at a glance. However, some hemianopic patients are able to compensate the visual limitation, at least to a certain extent, by performing additional, adaptive eye and head movements. And the mentioned deficits are related to the degree of this functional compensation. To compensate for HVFDs, patients need an appropriate ocular motor strategy for efficient use of the remaining areas of the visual system. Ishiai, Furukawa & Tsukagoshi (1987) described one obvious adaptation used by hemianopic patients. Whereas normal controls look mainly at the centre during viewing to simple patterns, hemianopic patients concentrate on their blind hemifield. This deviation of the fixation point towards the hemianopic side brings more of the visual scene into the seeing hemifield and could hint for a compensatory strategy (Gassel, & Williams, 1963). Meienberg, Zangemeister, Rosenberg, Hoyt, & Stark (1981) identified different compensatory strategies in HH patients when faced with simple visual targets which are presented in a predictable or unpredictable fashion. Overall compensatory effects identified in many studies showed that patients spend more (search) time in the stimulus half corresponding to their visual loss, perform generally more saccades but with decreased amplitudes when directed into the area of the visual loss, and differed therefore in their scanpath pattern as compared to healthy subjects (e.g. Zangemeister, Meienberg, Stark, & Hoyt, 1982; Zihl, 1995b; Zangemeister & Oechsner, 1996; Kerkhoff, 1999; Zihl, 1999; Pambakian, Wooding, Patel, Morland, Kennard, & Mannan, 2000; Zihl, 2000; Tant, Cornelissen, Kooijman, & Brouwer, 2002). With the introduction of the dot counting paradigm (see below), Zihl (1995b) was able to divide the investigated hemianopic patients into two subgroups, depending on whether their search time exceeded the highest value found in the group of normal subjects (this group was named “pathologic hemianopics”) or not (this group was named “normal hemianopics”). For the “normal hemianopics” the author identified similar effective search pattern compared to the healthy subjects. The scanpaths of the “pathologic” group were significantly longer and showed a higher number of fixations not only in the affected, but also in the “intact”, hemifields.

In the majority of studies concerning the oculomotor compensational behavior, the stimuli were presented on computer screens and therefore limited in size related to the subjects’ field of view. There, the dot counting task introduced by Zihl (1995b, 1999, 2000) was used as the most prominent paradigm to objectively and quantitatively assess oculomotor compensational behavior. In this counting task subjects had to sample a certain amount of dots (e.g. 20). This simple stimulus display was chosen to restrict the visual scanning to the process of visual sampling without the primary involvement of other complex higher-order visual functions (Zihl, 1999).

The goal of the present study was to investigate the task performance and the gaze related strategies of HVFD patients in two experiments with different cognitive demand. As first experiment the dot counting task was applied as visual sampling paradigm but with increased stimulus size compared to the original setup (cp. Zihl, 1995b). Secondly, a comparative visual search task (Pomplun, Sichelschmidt, Wagner, Clermont, Rickheit & Ritter, 2001; Hardiess, Gillner & Mallot, in press) as more cognitively challenging paradigm was introduced. There two almost identical stimulus hemifields (cupboards filled with geometrical objects) have to be explored in order to find the amount of differences between them. To enable a most natural field of view combined with eye and possibly head movements, a large field projection setup for displaying the stimuli was used. Similar to Zihl (1995b, 1999) we anticipated to identify two patient subgroups in both experiments related to their task performance. The task performance together with the gaze strategies of both patient subgroups was analyzed and discussed in comparison with the results of healthy controls to possibly identify functional compensation pattern on the side of the HVFD patients.

Methods:

a) Experimental setup

To enable standardized and completely programmable experimental environments, all experiments are performed using virtual reality (VR) technology programmed in C++. The computed VR stimuli were presented on a large, curved projection screen shown in figure 1. The geometrical shape of this projection screen was that of a conic shell with a vertical axis, an upper radius of 1.83 m and a lower one of 1.29 m. Subjects were seated upright with the back tightly at the chair and with their head in the axis of the conical screen (eye level was adjusted at 1.2 m with 1.62 m screen distance).The screen provided a horizontal field of view of 150° and a vertical one of 70° to the subject. Furthermore the vertical field of view was asymmetrically, spanning 45° to the ground and 25° upwards. To illuminate the whole projection screen, two video projectors each with 1024 by 768 pixel resolution and a fixed 60 Hz frame rate were used. The light in the experimental lab was dimmed nearly to complete darkness to avoid disturbing cues from the surrounding.

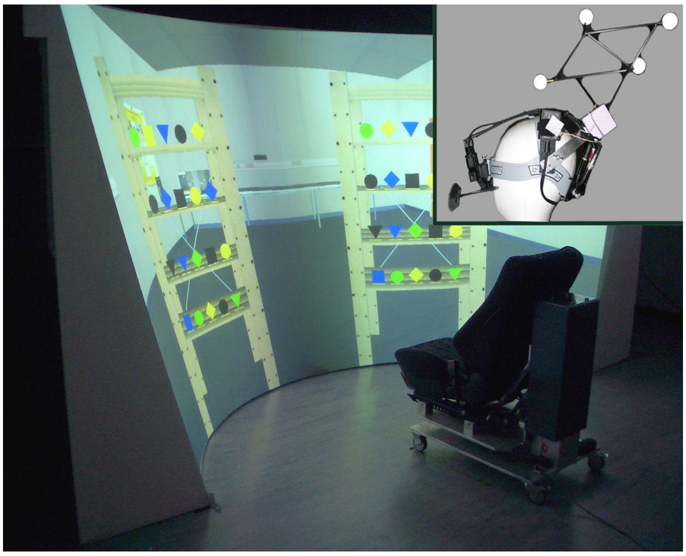

Figure 1. Image of the curved projection screen and the displayed comparative visual search paradigm (cupboard task). Subjects sit comfortably in a high adjustable seat while performing the experiments. Small picture: ASL501 eye tracker with fixed rigid body enabling head tracking.

The setup to provide the experiments was running on a 2.6 GHz PC under Linux RedHat 9.0 as operating system (graphic card: NVIDIA® Quadro4® 980XGL with dual video projector connection). The spatial resolution of the generated images was 2048 by 768 pixels with a fixed frame rate of 60 Hz. The SGI® OpenGL Performer™ was used to render the virtual environments as well as to handle the programs for the experimental tasks.

Eye-in-head movement recordings were realized with an infrared light based, head mounted and lightweight eye tracker (bright pupil type, model 501 from Applied Science Laboratories, Bedford, USA). This tracker records movements by the pupil-corneal-reflection method and enables an accuracy better than approximately two degrees (depends on the eccentricity of the eye position) with a real time delay of 50 ms. To record head-in-space movements, an infrared light based tracker system (ART-track/DTrack from A.R.T. GmbH, Weilheim, Germany) with 6 degrees of freedom, 0.1° accuracy, and a real time delay of 40 ms was used. A configuration of four light reflecting balls fixed to the eye tracker device and thus to the head (see figure 1) provided the tracking target for this head tracking system. Both trackers had a fixed temporal sampling frequency of 60 Hz. The online position recordings from eyes and head were transmitted via socked connection to an experimental PC for storage.

b) Experimental tasks

Dot counting task - Visual sampling

To enable a visual sampling paradigm, the dot counting (DC) task introduced by Zihl (1995b) was implemented. To perform this task, subjects had to scan consecutively three different dot patterns. Each pattern included 20 bright dots randomly scattered over the projection screen. After an enlargement of the stimulus dimension used by Zihl (1995b, 1999; i.e. 40° by 32°), the dots in our study were presented within a field of view of 60° horizontally and 40° vertically. The dots were arranged with a minimal spatial separation of 7° and the diameter of a single dot was 54 min of arc.

Subjects were instructed to scan the pattern and to count silently the number of dots as quickly and reliably as possible and to terminate each trial by pressing a button on a joystick. Afterwards they should report verbally the number of dots to the experimenter. No instruction was given how to proceed with scanning. The next trial started with the fixation phase to the fixation cross (see below) after pressing the button.

Cupboard task - Comparative visual search

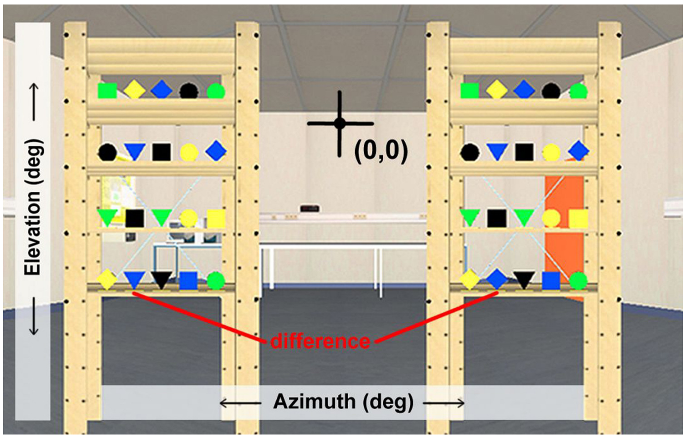

Figure 2. Screenshot of the cupboard experiment as comparative visual search task. In this example trial a one target condition is shown. Gaze position is expressed in angles (azimuth, α and elevation, β) with respect to the point of origin.

In the comparative visual search (CVS) paradigm (cp. Pomplun et al., 2001; Hardiess et al., in press), two cupboards equally filled with simple geometrical objects in four geometrical shapes (triangles, circles, diamonds, and squares) and four different colors (green, blue, yellow, and black) were used as stimuli (see figure 2). Each cupboard included 20 objects in four shelves. Each shelf included five objects in a row and one cupboard subtended 30° of the subjects' horizontal field of view. The diameter of an object was 3°, the horizontal separation between two objects was 5° and the vertical one was 11°. The horizontal separation between the centers of both cupboards was 60° (± 30° distance related to the subject's straight ahead direction).

With regard to the CVS the object configurations in the two cupboards were either completely equal (zero target condition) or differed at one or two positions (one and two target conditions, respectively). Target objects differed in shape only whereas all other object pairs had identical features (functioning as distractors). A maximum number of two targets was introduced, to avoid premature trial completion. Since subjects did not know the number of targets, they could not terminate the comparative search after detecting the first target. A complete cupboard task session consisted of 21 trials in random order (3 target conditions x 7 repetitions for each target condition). Object configuration for both targets and distractors was randomized for each trial. The subjects were free to move their head and eyes to find the number of targets (i.e. zero, one or two) as quickly and reliably as possible and no instruction was given how to proceed with scanning. Subjects had to terminate each trial by pressing a button and reported the number of targets verbally to the experimenter. The next trial started with the fixation phase to the fixation cross (see below) after pressing the button. Participants were free to take breaks in between trials if desired.

c) Procedure

In the beginning of the experimental investigation, the subject was seated in the chair and the eye level was adjusted to 1.2 m. Afterwards the eye tracker was calibrated by displaying a 9-point calibration pattern on the projection screen. For this procedure, head movements were prevented with a chin rest and all nine points had to be fixated. Also the tracking target for head movement recordings was calibrated with fixed head. After completion of the calibration procedure, subjects started to perform the DC paradigm. During this sampling task the head remained at the chin rest to avoid head movements. Immediately after finishing this first experiment, subjects had to proceed with the CVS task. For this task the head was freed and unrestricted movements became possible.

Additionally, in both paradigms, each single experimental trial started with a five second lasting fixation phase during which a fixation cross was displayed at eye level (1.2 m elevation) in the center of the projection screen (point of origin, cf. figure 2). During this phase participants had to rotate the head (only in case of the CVS task) to align the naso-occipital axis to the fixation cross followed by fixating the cross with the eyes. With this procedure the subjects' gaze offset with respect to the calibrated systems was measured before each trial. After this fixation phase the cross disappeared automatically and the dots (in case of the DC task) or the two cupboards (in case of the CVS task) became visible.

d) Subjects

Twelve homonymous visual field defect (HVFD) patients without visual neglect (age: 45.2 ± 16.1 mean ± sd, range: 22 - 71 years) and twelve normal sighted control subjects (age: 44.4 ± 15.8 mean ± sd, range: 20 - 66 years) participated in this study. Patients were recruited from the Department of Neuroophthalmology at the University of Tübingen (Germany), the University Neurology Clinic of Tübingen, as well as the Neurology Clinic of Burger Hospital in Stuttgart and the Bad Urach Rehabilitation Centre. All patients had normal function of the anterior visual pathways, as evaluated by orthoptic and ophthalmologic tests (fundus and slit-lamp examinations). Best corrected monocular visual acuity was at least 16/20 (near and far).

Table 1. Clinical and demographic data of all 12 HVFD subjects

Pat. ID	Sex	Age [yr]	Δt [yr]	Aetiology	Site / Extent of lesion	Side of brain lesion	Type of HVFD	A-HVFD [degrees^2]	A-SPAR [degrees^2]	D [degrees]	RT [ms]
ECG	male	33	1	Brain surgery	parieto-occipital	Right	Left cHH; mac. sparing	9559	414	3.2	1062
ANE	male	40	4.9	Ischemia	occipital	Right	Left cHH; mac. sparing	9258.9	923.7	2.3	299
AIH	female	46	16	Ischemia	parietal	Left	Right cHH; mac. sparing	9881	391	2.1	442
ULH	male	64	0.7	Ischemia	occipital	Right	Left upper iQA	2837	6790.6	7.8	348
FRH	male	65	0.5	Ischemia	occipital	Left	Right iHH; mac. sparing	7720.4	1986.6	15.4	518
URF	male	71	1	Ischemia	occipital	Left	Right iHH; mac. sparing	4739.4	4632	19	305
ARG	female	36	11.2	Ischemia	occipital	Left	Right cHH; mac. sparing	9003.3	1335	7	344
ARJ	male	31	1.6	Hemorrhage (Aneurysm)	parietal	Left	Right cHH; mac. sparing	10342.5	149.4	0	357
AYC	female	33	1.1	Ischemia	occipital	Left	Right cHH; mac. sparing	9370.8	845.5	4.5	260
TRH	female	40	2.7	Ischemia	occipital	Left	Right upper iQA	567.8	8853.2	4.7	311
TTC	female	22	3.9	Ischemia	parieto-occipital	Left	Right upper cQA	5867	4710.7	1.7	267
CKF	male	61	3.6	Ischemia	occipital	Right	Left upper iQA	2748.1	5496.4	8	387
Mean		45.2	4.02					6824.6	3044.0	6.3	408.3
± SD		16.1	4.80					3358.6	2935.7	5.7	218.6

Δt - time since brain lesion and neuro-ophthalmological examination; Type of HVFD - characterization of homonymous visual field defect (HH: homonymous hemianopia, QA: quadrantanopia, c: complete, i: incomplete); A-HVFD - area of the visual field loss in the binocular visual field for stimulus III/4e; A-SPAR - area of the spared visual field in the affected hemifield for stimulus III/4e; D - minimum linear distance between the central fixation point and the defect border; RT - perimetric reaction time

Patients with severe unilateral visual hemi-neglect were excluded from the study by testing horizontal line bisection (Stone, Halligan, Wilson, Greenwood & Marshall, 1991), copying of figures (Johannsen & Karnath, 2004), reading ability and by means of the "Bells test" (Gauthier, Dehaut & Joannette, 1989). Furthermore they showed no evidence of cognitive decline, aphasia, apraxia, visual agnosia or physical impairment. Clinical and demographic data of subjects are summarized in table 1. After the visual field evaluation (see below) subjects were interviewed about their everyday life difficulties using the standardized 25-item National Eye Institute (NEI) Visual Function Questionnaire (VFQ-25, version 2000; see Mangione, Lee, Pitts, Gutierrez, Berry & Hays, 1998; Mangione, Lee, Gutierrez, Spritzer, Berry & Hays, 2001). The NEI-VFQ-25 focuses on the influence of visual disability and visual symptoms on generic health and task-oriented domains related to daily visual functioning. The questionnaire includes twelve vision-targeted subscales (i.e. eleven subscales due to vision: global rating, difficulty with near activities, difficulty with distance activities, limitations in social functioning, role of limitations, dependency on others, mental health symptoms, driving difficulties, limitations with peripheral and color vision, ocular pain; and one general health rating item). Subscales are scored on a 0- to 100-point scale in which 100 indicates the best possible score on the measure and 0 indicates the worst. The composite NEI-VFQ-25 score is the mean score of all the items except for the general health item.

Normal-sighted control subjects were recruited from the Department of Neuroophthalmology at the University of Tübingen and were in many cases patients' relatives. They had normal or corrected to normal vision, normal-appearing fundus, normal visual fields, normal orthoptic status, and no physical or cognitive impairment.

The research study was performed according to the Declaration of Helsinki and was approved by the independent ethics committee of the University of Tübingen (Germany). Following verbal and written explanation of the experimental protocol each subject gave their written consent, with the option of withdrawing from the study at any time.

e) Visual field evaluation

Assessment of the patients' visual field was enabled by monocular supraliminal automated static perimetry within 30°-area, binocular supraliminal automated static perimetry within 90°-area as well as binocular semi-automated 90° kinetic perimetry obtained with the OCTOPUS 101-perimeter (Fa. HAAG-STREIT, Koeniz, Switzerland). Visual fields of control subjects were assessed with binocular supraliminal automated static perimetry within 90°-area and binocular semi-automated 90° kinetic perimetry.

f) Data analysis and statistics

The MATLAB® software (MathWorks Company, Natick, USA) was used to analyze the recorded experimental data. Based on head and eye tracking data, the gaze vector was calculated in angles with an azimuth and an elevation component (α and β, respectively) with respect to the point of origin (see figure 2). Thus, the gaze vector includes both the head-in-space and the eye-in-head vectors.

Object fixations were defined as sections of the gaze trajectory where gaze velocity did not exceed 100 °/s for at least 120 ms. A gliding window procedure was used to distinguish such gaze fixations (stable gaze position related to the processed stimulus region) from gaze saccades (cf. Hardiess et al., in press).

For statistical analysis parametric statistics were applied for the majority of the data. The data for some variables without standard distribution had to be transformed via the log10(x) operation to reach normally distributed values. For all other variables non-parametric statistics were applied.

To compare the patient's ability to solve the two experimental tasks, a rank order was introduced. This order was based on the two task performance parameters error rate and response time. To compute this rank order, first error rate and response time were ordered and assigned a rank number independently. In a second step, to get the final task performance rank order, both rank numbers (i.e. for error rate and response time) were multiplied and the results of all 12 patients were consecutively ordered from 1 (i.e. best task performance) to 12 (i.e. worst task performance). To compare the patients task performance with their statements related to the quality of life questionnaire (VFQ-25; cp. Papageorgiou, Hardiess, Schaeffel, Wiethölter, Karnath, Mallot, Schönfisch & Schiefer, 2007) the calculated final scores of the VFQ-25 were also ranked from 1 (i.e. best quality of life) to 12 (i.e. worst quality of life).

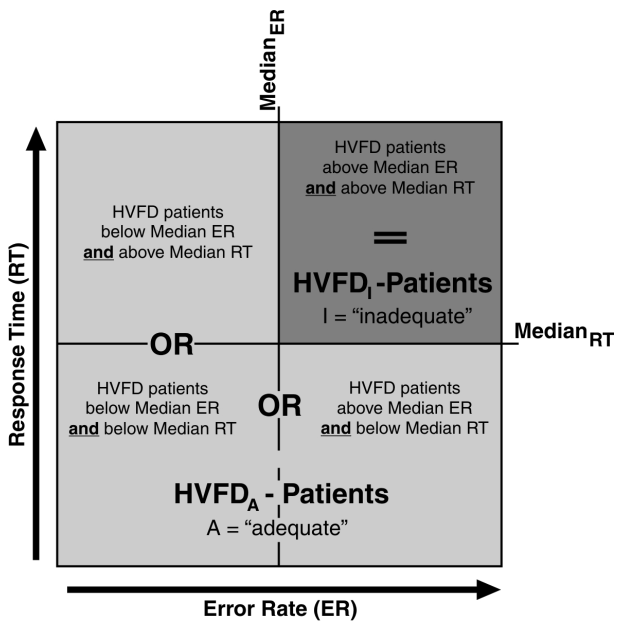

Figure 3: Scheme for illustrating the median splitting method. The both task performance variables error rate and response time span a two dimensional co-ordinate system. Independently for each task the data of all 12 HFVD patients were added to this system. The medians of the patients data related to error rate and response time divide the sample into four quadrants. All patients whose data points are located into the quadrant labeled as above median ER and RT fall into the patients group called $HVFD_I$. All other patients are grouped to $HVFG_A$.

A distinction between adequate and inadequate patients was made with the median splitting method. Independently for each task both performance parameters (i.e. error rate and response time) were used to span a two dimensional co-ordinate system (see figure 3). All 12 data points from the patients' experimental performance were mapped into this system. The medians of both parameters divided the co-ordinate system in four quadrants. For this study, each patient whose data point was within the quadrant defined by above median of error rate and above median of response time was denoted in the following as inadequate and all remaining patients as adequate (i.e. $HVFD_I$ and $HVFD_A$, respectively). With the median splitting method an intrinsic (coming from the experimental data) criterion to divide these patients into two subgroups was applied and not the comparison with the healthy subjects' performance. Only after separating the patients into two subgroups the task performance comparisons between each of these groups and the control subjects were calculated.

Results:

a) Evaluation of the subjects' task performances

To enable a comparison between the homonymous visual field defect patients' (HVFD) task performance in the visual sampling (DC, i.e. dot counting) and in the cupboard (CVS, i.e. comparative visual search) task all 12 patients were ranked independently for each task (cp. section 'data analysis and statistics' in the methods chapter). This rank order assigned the rank 1 to 12 to the patients and was based on the two task performance measurements error rate and response time. The task performance comparison enabled by the ranking method (see figure 4) reveals a significant correlation of the patients' rank orders between both tasks (Rho-S = 0.63, $p < 0.05$).

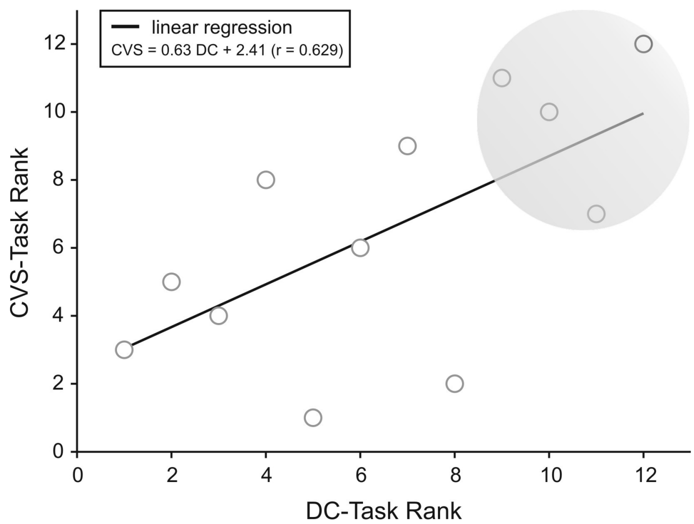

Figure 4. Patients' task performance correlation based on the ranking method between the DC and the CVS task. Regression indicates a linear relation with a correlation coefficient r = 0.63. The four patients with the highest ranks in both tasks marked with the grey circle are indicated as inadequate patients ($HVFD_I$).

Furthermore the patients' rank order related to their answers in the quality of life questionnaire (VFQ-25) was compared with their task performance rank order for both tasks (see figure 5). Both correlations indicate a weak but not significant causal relationship (Rho-S = 0.48 for the DC task and Rho-S = 0.29 for the CVS task comparison).

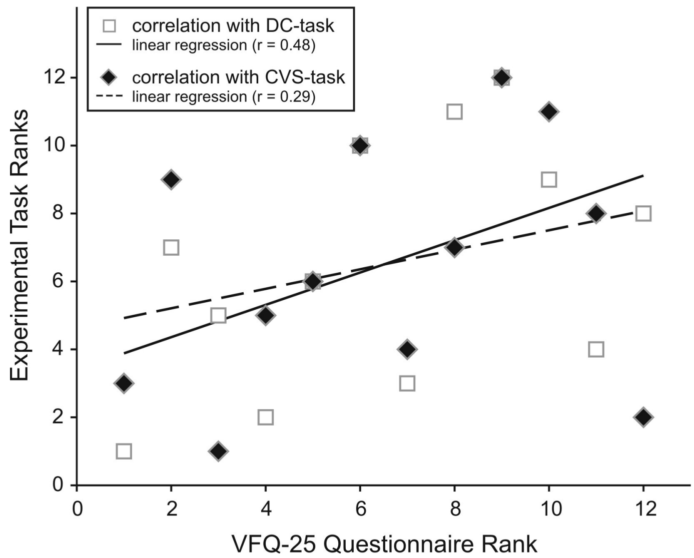

Figure 5. Correlations between the patients' ranks due to the VFQ-25 Questionnaire and their performance ranks in both experimental tasks (DC and CVS). Regressions indicate for weak relations with correlation coefficients r = 0.48 (correlation with DC-task) and r = 0.29 (correlation with CVS-task).

The median splitting method (cp. section 'data analysis and statistics' in the methods chapter) was used to divide all 12 HVFD patients into an adequate and an inadequate subgroup ($HVFD_A$ and $HVFD_I$, respectively) based on their task performance (i.e. error rate and response time). This method produced independently for both tasks a distinction between the same four inadequately performing vs. the same eight adequately performing patients. The four $HVFD_I$ patients appear also clearly separated in the rank order comparison (cf. figure 4).

The subgroup of $HVFD_A$ patients performed the DC task in the same manner as the control subjects with respect to both, the measured performance values error rate and response time (see figure 6 A and C). In contrast, statistical analysis confirmed that $HVFD_I$ patients performed significantly worse than controls related to error rate ($p < 0.05$, two-sided Mann-Whitney-U test; cf. figure 6 A) and to response time ($F(2, 60) = 6.32$, MSE = 11.63, $p < 0.01$, $eta_p^2 = 0.17$; post-hoc comparison between controls and $HVFD_I$ subjects, $p < 0.01$; cf. figure 6 C). Also the comparison between two patient subgroups and the controls in the CVS task confirmed that $HVFD_I$ patients reported wrong answers more often than controls ($p < 0.01$, two-sided Fisher's exact test) whereas the error rate of the $HVFD_A$ patients was comparable to the controls (see figure 6 B). The analysis of variance between the three subject groups related to the response time revealed a significantly increased search time for both patients subgroups ($F(2, 501) = 59.84$, MSE = 22.34, $p < 0.001$, $eta_p^2 = 0.19$; see figure 6 D).

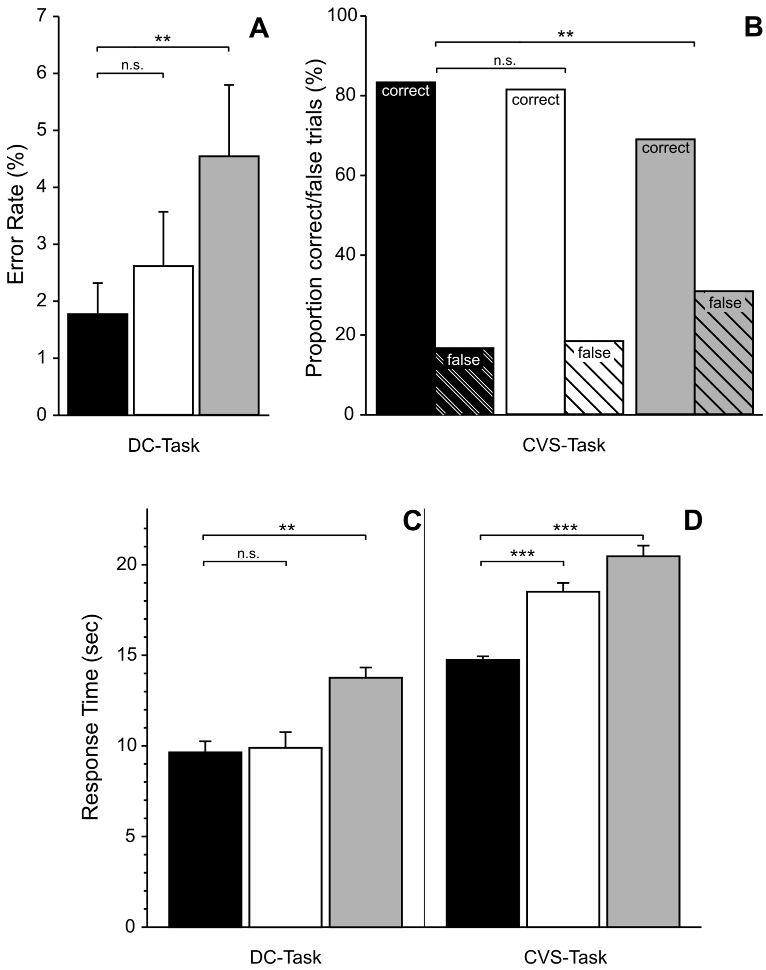

Figure 6. Task performance comparison (A and B: Error Rate; C and D: Response Time) between normal subjects (black bars) and the $HVFD_A$ (white bars) respectively the $HVFD_I$ (grey bars) patient group. Post-hoc analysis was calculated to identify significance between the control subjects and each of the patients' group (Bonferroni: * p<0.05, ** p<0.01, and *** p<0.001). Error bars indicate standard error of the mean.

The difference between the $HVFD_A$ and the $HVFD_I$ patients becomes also evident in their scanpath patterns. Figure 7 shows recordings of individual scanning patterns in a normal subject, in a $HVFD_A$, and in a $HVFD_I$ patient for both tasks. For the DC task no differences regarding the scanpaths between the normal and the adequately performing patient are noted (see figure 7 A and B). Both participants showed a systematic scanning behavior. They did not fixate exactly every dot to solve the task, some fixations are several degrees away from the closest one. In contrast to the behavior of these two subjects, the $HVFD_I$ patient (cf. figure 7 C) performed the scanning with a highly increased number of saccades and fixations. No systematic oculomotor scanning behavior could be accomplished and the patient exhibited a very detailed and time-consuming pattern of visual scanning. The scanpath pattern for this patient in the CVS task differed in the same manner compared to the normal subject and the $HVFD_A$ patient (see figure 7 F). There are numerous fixations not landing accurately to the cupboard objects and the search strategy appears to be spatially disorganized. On the other hand, the $HVFD_A$ patient showed a scanning pattern which was very similar to that of the unimpaired normal subject (cf. figure 7 D and E).

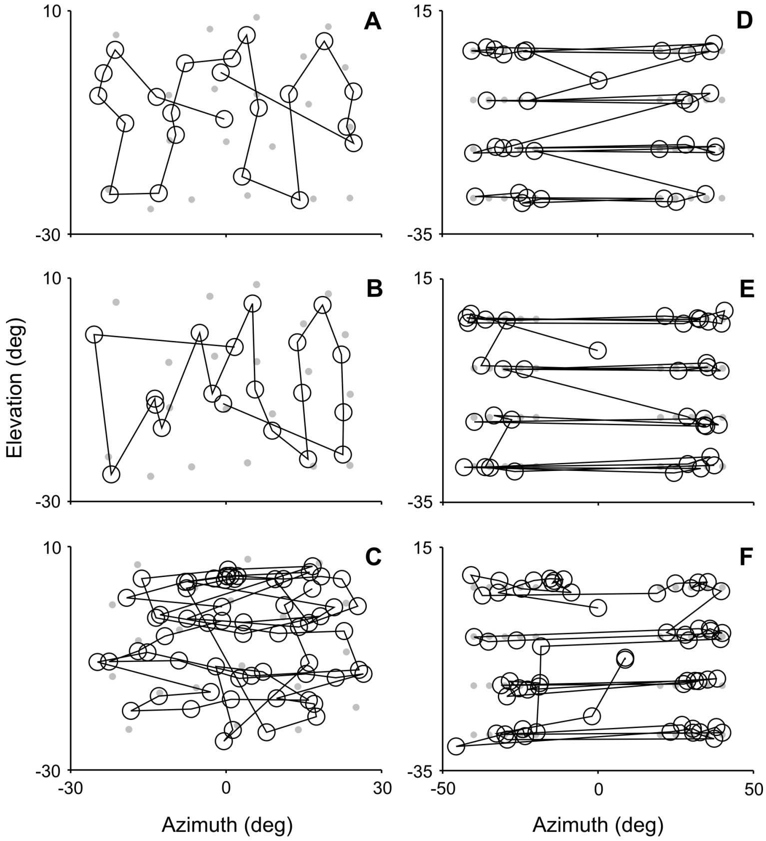

Figure 7. Scanning pattern (scanpaths) examples for both tasks of a normal subject (A and D), of a $HVFD_A$ patient (B and E) and of a $HVFD_I$ patient (C and F). Grey filled circles mark the dot position for the DC task and the objects' position for the CVS task. The open black circles indicate for the averaged gaze positions during fixations and the black lines illustrate the rapid gaze changes between fixations (saccades).

b) Subjects' gaze parameter in the DC task

To identify the strategies used for the visual field loss compensation in both patient subgroups, several relevant oculomotor parameters were calculated and compared with the data of the control group (all parameters are plotted together in figure 8). For a better overview, all statistical results related to the analyzed oculomotor parameters are summarized in table 2.

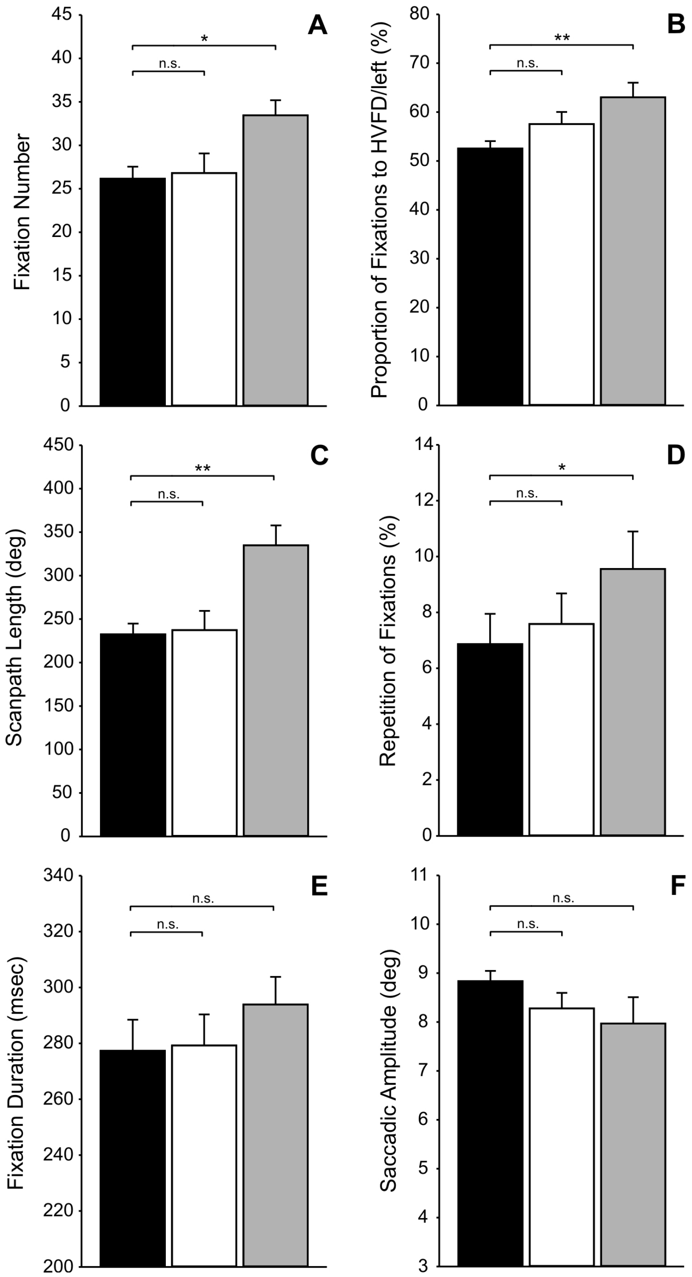

Figure 8. Oculomotor performance of all subjects showed in the dot counting task. Comparisons were analyzed between the normal subjects (black bars) and the both patient groups (white bars: $HVFD_A$ patients, grey bars: $HVFD_I$ patients) related to different oculomotor parameters (A: number of fixations; B: proportion of fixations to the patients' impaired side or the control subjects' left side; C: length of the scanpath; D: percentages of repetition of fixations; E: duration of fixations; F: amplitude of saccades). Post-hoc analysis was calculated to identify significances between the controls and each of the patients' group (Bonferroni: * p<0.05, ** p<0.01, and *** p<0.001). Error bars indicate standard error of the mean.

Table 2. Summary of the statistical results for all gaze performance parameters analyzed in the dot counting task

Parameter	Statistical data	Significance
Fixation Number [1)]	$F(2,60) = 4.18$, MSE = 0.014, $eta_p^2 = 0.12$	$p < 0.05$
Prop. of Fixations to HVFD	$F(2,60) = 5.07$, MSE = 94.725, $eta_p^2 = 0.14$	$p < 0.01$
Scanpath Length [1)]	$F(2,60) = 7.32$, MSE = 0.017, $eta_p^2 = 0.2$	$p < 0.01$
Repetition of Fixation	Median test: $\chi^2 = 6.07$	$p < 0.05$
Fixation Duration	Median test: $\chi^2 = 2.98$	$p = 0.23$
Saccadic Amplitude	$F(2,60) = 1.97$, MSE = 1.938	$p = 0.15$

[1)] this parameter was $\log_{10}(x)$ transformed to reach normally distributed values

$HVFD_I$ patients performed significantly more fixations and therefore longer scan-paths whereas their saccadic amplitudes remained in the same range compared to normal subjects (see figure 8 A, C, and F). For these three gaze parameters no significant differences between the adequate patients and the normal subjects could be obtained. However, when the saccadic amplitudes were compared to those of the normal subjects a clear tendency for shorter (hypometric) saccades could be found in both patient subgroups. Further compensatory parameters could be investigated on the $HVFD_I$ patients' part. They showed a significantly elevated number of fixations to their impaired visual field and significantly more refixations (calculated as the number of fixations made within 1° of each other). Regarding these two parameters, $HVFD_A$ patients performed as adequately as the normal subjects (cf. figure 8 B and D). Concerning the time used for acquiring information during each fixation, the inadequate patients showed longer fixation durations compared to the healthy subjects, however, this difference reached no significance (figure 8 E).

c) Subjects' gaze parameter in the CVS task

Similar to the analysis of the dot counting task the same most relevant gaze behavior parameters were investigated for the cupboard task. But instead of analyzing the repetition of fixations, the amount of gaze shifts between the two cupboards was obtained (all parameters are plotted together in figure 9). The statistical results for all gaze parameters are summarized in table 3.

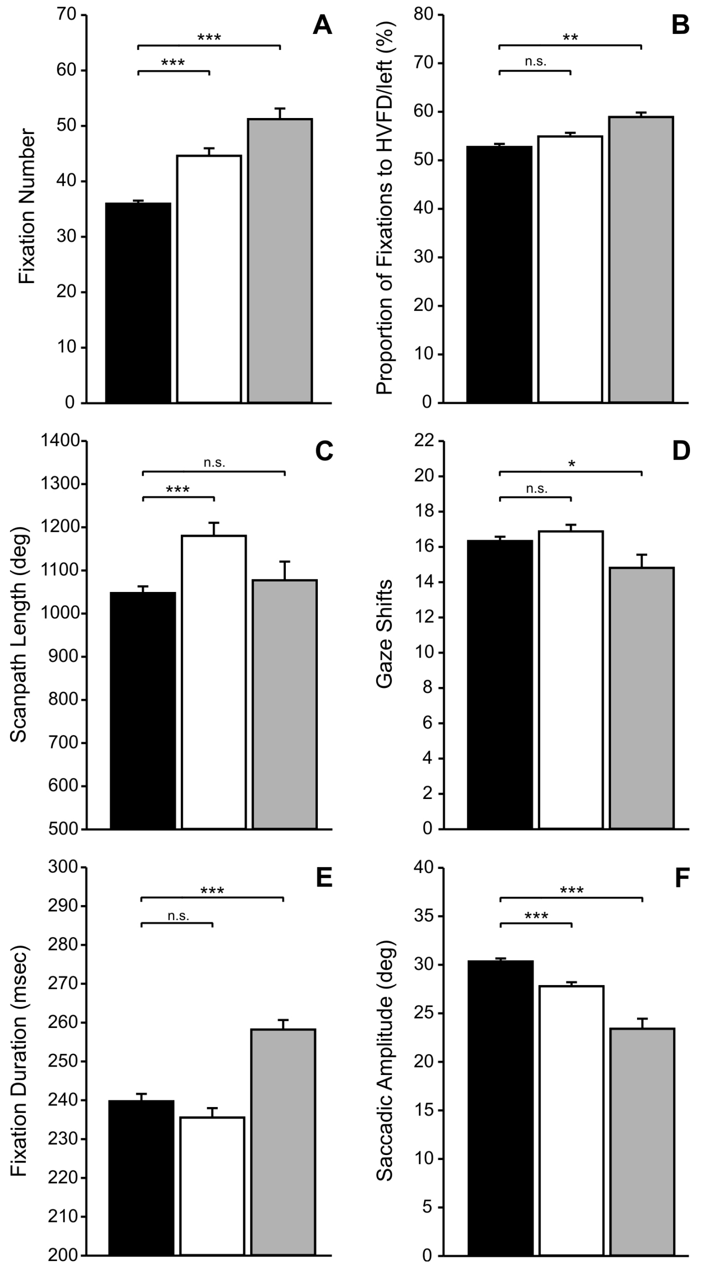

Figure 9. Gaze performance of all subjects showed in the cupboard task. Comparisons were analyzed between the normal subjects (black bars) and the both patient groups (white bars: $HVFD_A$ patients, grey bars: $HVFD_I$ patients) related to different gaze parameters (A: number of fixations; B: proportion of fixations to the patients' impaired side or the control subjects' left side; C: length of the scanpath; D: number of gaze shifts between the two cupboards; E: duration of fixations; F: amplitude of saccades). Post-hoc analysis was calculated to identify significances between the controls and each of the patients' group (Bonferroni: * p<0.05, ** p<0.01, and *** p<0.001). Error bars indicate standard error of the mean.

Table 3. Summary of the statistical results for all gaze performance parameters analyzed in the cupboard task

Parameter	Statistical data	Significance
Fixation Number	$F(2,462) = 44.2$, $MSE = 177.43$, $eta_p^2 = 0.16$	$p < 0.001$
Prop. of Fixations to HVFD	$F(2,462) = 12.93$, $MSE = 85.04$, $eta_p^2 = 0.053$	$p < 0.001$
Scanpath Length	$F(2,462) = 8.49$, $MSE = 99446$, $eta_p^2 = 0.035$	$p < 0.001$
Gaze Shifts	$F(2,462) = 5.02$, $MSE = 21.7$, $eta_p^2 = 0.021$	$p < 0.01$
Fixation Duration [1)]	$F(2,462) = 17.89$, $MSE = 0.0026$, $eta_p^2 = 0.072$	$p < 0.001$
Saccadic Amplitude	$F(2,462) = 43.22$, $MSE = 32.43$, $eta_p^2 = 0.16$	$p < 0.001$

[1)] this parameter was $log_{10}(x)$ transformed to reach normally distributed values

In this more cognitive demanding visual search task the $HVFD_I$ and also the $HVFD_A$ patients showed a significantly increased number of fixations compared to the normal subjects (see figure 9 A). However, the scanpath length for the $HVFD_I$ patients was not extended compared of that of the normal subjects contrary to this of the $HVFD_A$ patients (cf. figure 9 C). This equal length of the $HVFD_I$ patients' scanpath together with an increased number of fixations may be due to the findings of a significantly decreased number of gaze shifts compared to the healthy subjects (see figure 9 D). Here, gaze shifts are defined as gaze saccades from one stimulus area (cupboard) to the other one. Similar to the DC task only the $HVFD_I$ patients showed a significantly increased proportion of fixations to the blind field compared to the normal ones and performed also significantly longer fixations (see figure 9 B and E). Significantly more hypometric saccades could also be measured in both patient subgroups compared to the healthy subjects' saccadic amplitudes (cf. figure 9 F).

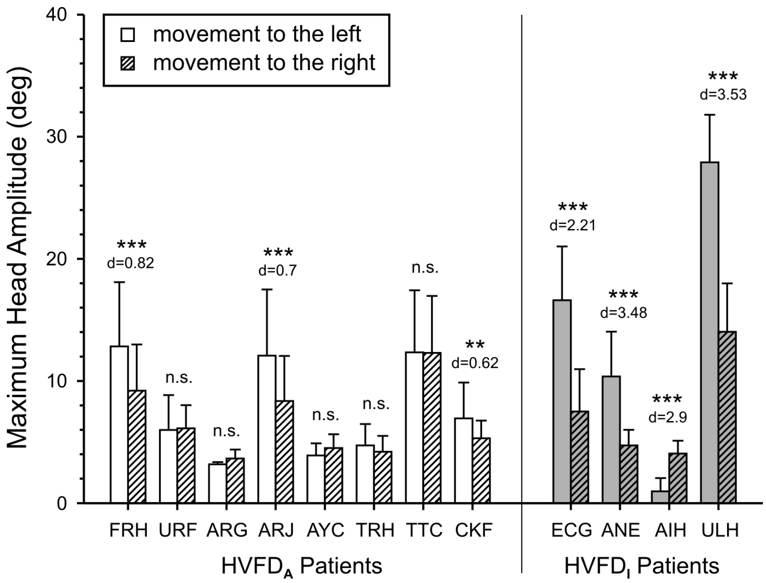

Figure 10. Comparison of the averaged maximum amplitudes for horizontal head movements to the left (unstriped bars) and to the right side (striped bars) between the $HVFD_A$ (white bars) and $HVFD_I$ patients (grey bars) in the CVS task. Error bars indicate standard error of the mean. Statistical results for unpaired group comparisons are shown (unpaired t-tests: * $p<0.05$, ** $p<0.01$, and *** $p<0.001$). The effect size of these statistics is marked as d.

In the free-head comparative search task all subjects performed maximum head movements in a range of $\pm 3°$ and $\pm 20°$. The averaged maximum amplitudes were larger for the $HVFD_I$ patients (14.13 ± 8.0 mean $\pm$ sd) while in the $HVFD_A$ patients they were within a range (8.89 ± 4.78 mean $\pm$ sd) similar to those of the normal subjects (9.12 ± 5.0 mean $\pm$ sd). Interestingly, all $HVFD_I$ patients showed significant differences for maximum head amplitudes to the left compared with those to the right (see figure 10). All three $HVFD_I$ patients with left sided HVFDs (ECG, ANE, and ULH) used larger head movements to the left, while the only $HVFD_I$ patient with a right sided HVFD (AIH) performed larger amplitudes to the right. This effect of different maximum head amplitudes between movements to the left and to the right could not be obtained for the majority of the $HVFD_A$ patients (see figure 10). Only three patients from this subgroup (FRH, ARJ, and CKF) showed significances in different amplitudes but the effect sizes (between 0.62 and 0.82) were relatively low related to those of the inadequate patient subgroup (between 2.21 and 3.53).

Discussion:

a) Differences in task performance between the HVFD patients

Following the concept of Zihl (1995b, 1999) we divided the collective of HVFD patients into two subgroups (i.e. $HVFD_A$ and $HVFD_I$ patients; A = adequate task performance, I = inadequate task performance). But instead of relating the patients' task performance to that of the healthy controls (cp. Zihl, 1995b) or using their behavior in everyday life evaluated with questionnaires (cp. Zihl, 1999), we split up the patients based on their achieved intrinsic task performance (i.e. error rate and response time). Interestingly, the majority of HVFD patients could reach adequate performance (i.e. $HVFD_A$ patients) and only four subjects became members of the $HVFD_I$ patient subgroup. Also Zihl (1995b, 1999) could identify a high number of adequately performing patients. In his investigations, about one half showed search times in the range of healthy subjects or was labeled as "unimpaired" because of their almost normal behavior in everyday life. Unfortunately in the majority of studies about hemianopics' oculomotor performance all patients were handled as similar and pooled together into one population. In accordance with the findings of Zihl, we can show that there could be immense differences between HVFD patients and hence support the given importance of separating them depending on task or everyday life performance.

To evaluate the patients' subjective impression of performing in everyday life situations we used standardized questionnaires (i.e. VFQ-25). Correlations between the patients' VFQ-25 ranks and their task performance ranks reveal small but not significant relations. Here, we found a higher correlation between the quality of life rating and the performance in the simpler DC task. Generally, patients who are better in handling everyday life situations tend to perform more accurate in visual scanning tasks (cp. Zihl, 1999).

The comparison of both patient subgroups with the task performance of the unimpaired healthy subjects suggests for equal abilities to reach the goal for the subgroup of $HVFD_A$ patients, at least in the case of the dot counting (DC) task. This subgroup also performed equally to the controls related to the error rates in the cupboard (CVS) task. The increased time cost of this subgroup was based on their compensatory gaze behavior during the comparative search, that is, a highly elevated number of fixations (cp. section 'gaze strategies developed by the HVFD patients' in this chapter). On the other hand the subgroup of $HVFD_I$ patients performed in both paradigms significantly worse than controls. The values of the error rates and search times measured in the healthy subjects and the $HVFD_A$ patients in the present study are similar to those investigated by other authors (cp. Zihl, 1995b, 1999; Tant et al., 2002). However we obtained for the subgroup of $HVFD_I$ patients shorter search times and less errors than these authors. But this could be due to our small sample of only four inadequate volunteers.

The strong correlation between the two rank orders, calculated over all patients and for both tasks independently, hints for a stable performance quality for each patient. Independent of the cognitive demand of the task (visual sampling vs. visual search) a patient who was good/bad in the DC task performed as well as good/bad in the more difficult CVS task. This stable quality could be reasoned on the one hand by compensatory, differently effective strategies which are developed during everyday life tasks and are helpful in different situations. On the other hand clinical and demographic characteristics could influence the ability to compensate adequately for the visual loss. However, none of these parameters (listed in table 1) was correlated with the rank orders of the patients (data not shown). We found only a week but not significant correlation based on the perimetric reaction time. These findings are supported by other studies. Zihl (1999, 2000) concluded that the presence, time since and severity of the HVFDs could not sufficiently explain the observed scanning deficit. Also Pambakian et al. (2000) analyzed a task concerning viewing of naturalistic pictures and found that neither the location nor the size of the visual loss can be correlated with any of the analyzed oculomotor parameters. Additionally, in an ongoing own study implemented to investigate the HVFD patients' performance in a car driving intersection task none of the clinical or demographic parameters could explain the patients' task performance related to avoid a crash in this paradigm (Papageorgiou et al., submitted).

b) Lateralization effect

Interestingly, there is a tendency for a lateralization effect related to the task performance between both HVFD patient subgroups. All except for one volunteer in the worse performing $HVFD_I$ subgroup show lesions into the right brain hemisphere. This hemisphere is affected in only one of the $HVFD_A$ patients. Also some other studies indicate that patients with right-hemispheric lesions perform worse on performance measures and driving tasks (Mazer et al., 1998; Korner-Bitensky et al., 2000; Meerwaldt & Van Harskamp, 1982). In a similar dot counting paradigm Tant et al. (2002) identified that patients with left-HH had increased error rates and search times. But they found this side effect also in healthy subjects with simulated HH. Together with other results Tant et al. (2002) concluded that HH scanning behavior is largely visually elicited, namely by the HVFD and brain-related functions serve in a subtle interplay to complete real HH scanning. But there is an ongoing debate about the functional influence of brain damage on the oculomotor scanning behavior with the knowledge that right-sided posterior brain injury is known to affect visual spatial abilities (e.g. Zihl & Hebel, 1997).

c) Gaze strategies developed by the HVFD patients

Our results derived from the DC task are in perfect concordance with the findings of previous studies based on hemianopics' oculomotor behavior (Zihl, 1995b, 1999, 2000; Tant et al., 2002). We identified one subgroup of patients (i.e. $HVFD_A$ patients) which showed no significant differences at all in any of the investigated gaze parameters when compared to healthy subjects. This similar gaze performance was achieved with the enlarged stimulus size of 60° by 40° used in our study. Furthermore, patients of a second subgroup (i.e. $HVFD_I$ patients) showed significantly increased values for their gaze parameters including fixation number, proportion of fixations to the side of HVFD, scanpath length, and repetition of fixations when compared with the controls.

A completely different result was obtained for the cognitively more demanding comparative visual search paradigm. Here the subgroup of adequately performing patients showed significant differences in their gaze performance compared with the controls. The number of fixations and the scanpath length were elevated, while the mean amplitude of saccades was decreased. These adaptations in the gaze strategy were required to overcome the increased challenge of the CVS task. So these patients were able to perform also in this paradigm in the range of healthy subjects at least in the case of error rate. The costs for these increased adaptations are reflected in longer search times. Furthermore, the search time for the $HVFD_I$ patients was additionally elongated because they needed much more fixational events related to the $HVFD_A$ patients in order to solve the task. Also their saccadic amplitudes were shortened in the highest manner.

In previous studies concerning the role of head movement proportion in patients with HFVDs, some authors identified smaller head movement amplitudes during combined head-eye saccades (Zangemeister et al., 1982, 1986; Schoepf et al., 1992, 1993). They argued that head movement programming, which entails more complex movement than eye movement programming alone, takes more time for HVFD patients. Subsequently, the role of head movements is a minor one due to a malfunctioning coordination of the eye and head. In contrast we found in the head unrestricted CVS task, that head amplitudes of $HVFD_A$ patients were within the same range like healthy controls (i.e. about $\pm$9.0°). Furthermore, the subgroup of $HVFD_I$ patients achieved head movements within a larger range (i.e. about $\pm$14.0°). Interestingly the extent of the latter subgroup's movements to the direction of their impaired hemifield was proportionally larger compared to the $HVFD_A$ patients. In contrast to the above mentioned studies a large stimulus area was used for the CVS task in the present study (i.e. up to $\pm 45°$). So we conclude that HVFD patients may use head movements in order to archive additional compensation in a task specific manner.

Conclusion:

In the way of analyzing the adaptive gaze behavior in patients with HVFDs we identified two subgroups of patients differing in their capability to solve two different visual scanning tasks. The subgroup of $HVFD_A$ patients seems to compensate adequately for their visual field loss in the cognitively unchallenging sampling task as well as in the more demanding visual search task in a spontaneous manner. But compared to their oculomotor functions in the DC task, which did not differ from these of healthy subjects, the $HVFD_A$ patients' gaze behavior showed increased compensational adaptations in the CVS task. For the subgroup of inadequate patients the compensational correlates were increased in a more massive manner to overcome their HVFDs. But regardless of their increased adaptations, these patients failed in performing the two scanning tasks as accurately as controls or adequate patients. The results related to the gaze parameters are interpreted in terms of task specific demands related to the patients' different abilities of effective compensation. In the cognitively simple DC task no further oculomotor adaptations of $HVFD_A$ patients are necessary to accomplish this sampling paradigm within the range of controls. However, the inadequate patients need adaptations and showed increased compensatory visual scanning. And to overcome their visual limitation this adapted compensation became also prominent for the adequate performing patients in the more complex comparative search task.

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Chapter five: Driving performance in patients with homonymous visual field defects and healthy subjects in a standardized virtual reality environment

Aim of this subproject, main results and my own contribution

Vision is inarguably a fundamental component of safe motor vehicle operation, since it accounts for up to 90% of driving related-inputs. The visual field, and especially its central parts, plays a crucial role. This observation has led to the hypothesis that visual field impairments may reduce driving performance. However, it is unequivocally difficult to assess the degree of functional impairment due to visual field loss in activities of daily living, such as driving As a result, the recommendations for minimum standards of the driver's visual field are still under discussion in many countries, and as a result, there is widespread variability of visual requirements for safe driving, particularly with regard to the extent of the visual field. It is clear that establishing standards for visual field in individuals with regard to their fitness to drive is a rather difficult task, mainly because the association between visual loss and driving performance is still controversial. The aim of this study was to use the intersection task to assess whether visual field-related parameters per se are able to predict driving performance of patients with homonymous visual field defects (HVFDs) and healthy controls in a standardized virtual reality environment.

For this study the driving performance was characterized by the frequency of accidents. Binocular kinetic perimetry was used in order to calculate the area of sparing within the affected hemifield, the minimum linear distance between the central fixation point, and other visual field related values. In a multiple regression model formulated for all subjects 78% of the total variability in the frequency of accidents was explained. But the clinical and demographic characteristics could only explain about 6% of this variability. Thus, the extent of the visual field loss is weakly related to driving performance. This finding suggests that the visual field related parameters should not be taken as the sole indicator of driving fitness.

Concerning this part of my work I was mainly involved in the development and implementation of the virtual and dynamic intersection task. Together with E. Papageorgiou I performed all experimental investigations, data extraction and analysis.

The results of this project are submitted for publication (together with E. Papageorgiou, Dr. R. Vonthein, Prof. H. Ackermann, Prof. H. Wiethoelter, Dr. B. Schoenfisch, Prof. H. A. Mallot, and Prof. U. Schiefer) in the Journal of Neurology, Neurosurgery & Psychiatry.

Manuscript

Title: Driving performance of patients with homonymous visual field defects and healthy subjects in a standardized virtual reality environment

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Abstract:

Purpose: Aim of this study was to assess whether visual field-related parameters per se are able to predict driving performance of patients with homonymous visual field defects (HVFDs) and healthy controls in a standardized virtual reality environment.

Methods: Thirty-two patients with HVFDs due to cerebro-vascular lesions and 32 healthy control subjects underwent testing on a driving simulator under two levels of traffic density. Driving performance was characterized by the frequency of accidents. We used binocular kinetic perimetry in order to calculated the area of sparing within the affected hemifield (A-SPAR), the minimum linear distance between the central fixation point and the defect border for stimulus III 4e (D), and the perimetric reaction time (RT).

Results: A model including traffic density, age, A-SPAR and RT explained 78% of the total variability ($R_{adj}^2 = 0.78$) in the frequency of accidents. All factors were significant. The effect of traffic density explained 63.4 % of the total variability. Age, A-SPAR and RT explained 2.7%, 2.0% and 0.9% respectively.

Conclusion: The extent of the visual field loss is weakly related to driving performance. This finding suggests that – at least for this group of patients – the visual field-related parameters should not be taken as the sole indicator of driving fitness. Some patients with HVFDs demonstrated sufficient compensatory driving behavior during the simulated test ride. Driving performance declined slightly with age; these changes were exacerbated in the presence of cerebro-vascular disease.

Introduction:

Driving represents the primary mode of travel in most western societies and is commonly linked to personal independence and autonomy. [1] Vision is inarguably a fundamental component of safe motor vehicle operation, which accounts for up to 90 % of driving related-inputs. [1] Hereby, the visual field, and especially its central 30 degrees, plays an outstanding role. [2,3] This has led to the hypothesis that visual field impairment reduces driving performance. However, it is unequivocally difficult to assess the degree of functional impairment due to visual field loss under everyday living conditions, e.g. under driving scenarios. As a result, the recommendations for minimum standards of the driver's visual field are still under discussion in many countries and there is widespread variability of visual requirements for safe driving, especially regarding the extent of the visual field.

Numerous driving simulator studies and studies involving on-road testing of subjects with impaired visual fields have tried to assess the relationship between visual field loss and driving performance. Some authors have demonstrated an impaired driving simulator performance of patients with visual field defects [4-8], which was in some cases correlated with visual field measures. [9-11] In contrast, other studies did not report higher crash rates for patients with visual field impairments. [12-15] Furthermore, some authors have tried to develop new tests to measure the visual field component of fitness to drive. [16] Noteworthy is the useful field of view (UFOV) test, which assesses the visual area in which useful information can be acquired in a single glance without eye and head movements and seems to be a better predictor of accidents than any single measure of visual function. [17] Finally, some authors have tried to assess driving fitness by performing a variety of neuropsychological tests, whose predictive value however proved to be questionable. [18]

It is so far clear that establishing standards for visual field in individuals with regard to their fitness to drive is a rather difficult task, mainly because the association between visual loss and driving performance is still controversial. [16]

Aims of this study were (i) to assess the performance of patients with homonymous visual field defects (HVFDs) after vascular brain damage in a driving simulator, and to compare it with that of normal-sighted control subjects, (ii) to investigate potential correlations between the frequency of accidents under virtual reality (VR) -conditions with visual field measures, (iii) to assess the impact of age and side of cerebral lesion on the performance in a driving simulator.

Material and Methods:

a) Subjects

Forty-one patients were recruited from the Department of Neuro-Ophthalmology at the University of Tübingen (Germany), the University Neurology Clinic of Tübingen, as well as the Neurology Clinic of Buerger Hospital in Stuttgart and the Bad Urach Rehabilitation Centre. Two patients with severe unilateral visual hemi-neglect identified by pathological findings in horizontal line bisection, copying of figures and by means of the “Bells test” [19] were excluded. None of the enrolled patients showed any evidence of cognitive decline, aphasia, apraxia, visual agnosia or physical impairment. Seven further patients were excluded due to bilateral homonymous defects. Thirty-two eligible patients with HVFDs (21 male and 11 female), with a mean age of 46.6 years (SD 15.68 years, age range: 18-74 years) without visual neglect, and 32 normal-sighted control persons (18 male and 14 female), with a similar age distribution (mean age 45.3 years, SD 15.29 years, age range: 20-70 years) were finally enrolled in the study. All patients had a homonymous visual field defect, varying from a complete homonymous hemianopia to homonymous paracentral scotomas, due to a unilateral vascular brain lesion predominantly of the posterior cerebral artery, which was documented by neuroradiological (magnetic resonance imaging or computerized tomography) and clinical findings (Appendix 1). There were 16 patients with right-hemispheric and 16 patients with left-hemispheric lesions, which were in the majority of cases located in the occipital lobe. Time since lesion was at least six months, and in the vast majority of patients (27 out of 32 patients) it was longer than one year. Median time after lesion onset was 1.6 years (range: 6 months to 16 years). All patients had normal function and morphology of the anterior visual pathways, as evaluated by ophthalmological tests (fundus and slit-lamp examinations, ocular alignment, ocular motility). Best corrected monocular (near and distant) visual acuity was at least 16/20. Twenty-nine out of 32 patients had a valid driver’s license. Nine of them reported that they were still driving, although they had been told that they no longer met the vision requirements necessary for driving.

Normal-sighted control subjects were recruited from the Tuebingen region of Germany and comprised volunteers from friends and relatives of the authors, the staff and the patients in the Department of Neuro-ophthalmology at the University of Tuebingen. They had a corrected visual acuity of 20/20 or better, normal-appearing anterior segments and fundus, normal visual fields, normal orthoptic status and no physical or cognitive impairment.

The research study was approved by the Institutional Review Board of the University of Tübingen (Germany) and was performed according to the Declaration of Helsinki between August 2005 and June 2007. Following verbal and written explanation of the experimental protocol each subject gave their written consent, with the option of withdrawing from the study at any time.

b) Experimental task

Visual fields of patients were assessed with monocular threshold-related, slightly supraliminal automated static perimetry (sAS) within the central 30° visual field, binocular slightly supraliminal automated static perimetry (sAS) within the 90° visual field as well as binocular semi-automated 90° kinetic perimetry (SKP), each obtained with the OCTOPUS 101 Perimeter (Fa. HAAG-STREIT, Koeniz, Switzerland). Visual fields of control subjects were assessed with binocular slightly supraliminal automated static perimetry (sAS) within the 90° and binocular semi-automated 90° kinetic perimetry (SKP).

All participants underwent testing on an interactive driving simulator, which was developed in the Lab of Cognitive Neuroscience (Department of Zoology, University of Tübingen). The VR environment was displayed on a large, cone-shaped projection screen. This screen provided a horizontal field of view of 150° and a vertical one of 70°. Subjects were seated upright with the back tightly on the chair and with their head in the axis of the conical screen (eye level was set at 1.2 m altitude and distance to the screen at 1.62 m). The visual environment and the experimental procedures were programmed in the SGI OpenGL Performer™. Eye-in-head movement recordings were done with a head-mounted, infrared light-based eye tracker with approximately two degrees accuracy (model 501, Applied Science Laboratories, Bedford, USA). To record head-in-space movements an infrared light-based tracker system (ARTtrack/DTrack from A.R.T. GmbH, Weilheim, Germany) with six degrees of freedom and 0.1° accuracy was used. Both trackers had a temporal resolution of 60 Hz. The spatial resolution of the projected images was 2048 x 768 pixels.

The subject was instructed to drive straightforward along a road (Fig. 1A and 1B) and finally to cross an intersection without causing a crash. The driving distance to the virtual intersection was 172.5 m. Subjects started each trial in a tunnel. After leaving the tunnel they could adjust their driving speed by means of a joystick between 18 and 61.2 km/h for the next 150 m (Fig. 1A). During this period it was not possible to stop the car. After 150 m subjects overran a white line, just 22.5 m before the intersection (Fig. 1B). After this line they were driven across the intersection with the last adjusted speed and no further visual input, in order to maintain identical conditions for each trial. A potential accident was then calculated by the experimental program. All cars of the cross road traffic had a constant speed of 50 km/h and we introduced two traffic density levels: 50% and 75% crash probability, respectively. The density levels and correspondingly the distances between the cross road traffic cars were ascertained with a simulation program. The traffic density 50% corresponded to a chance level of 50% for having an accident and the density level 75% to a chance level of 75% respectively. Subjects performed 30 trials - 15 trials for each density level in randomized order – and were free to perform head and eye movements. During each trial we recorded the time, the velocity profile, the potential crash event and the eye and head movements. Prior to the start of the experiment all subjects underwent a brief training session in order to understand the experimental demands.

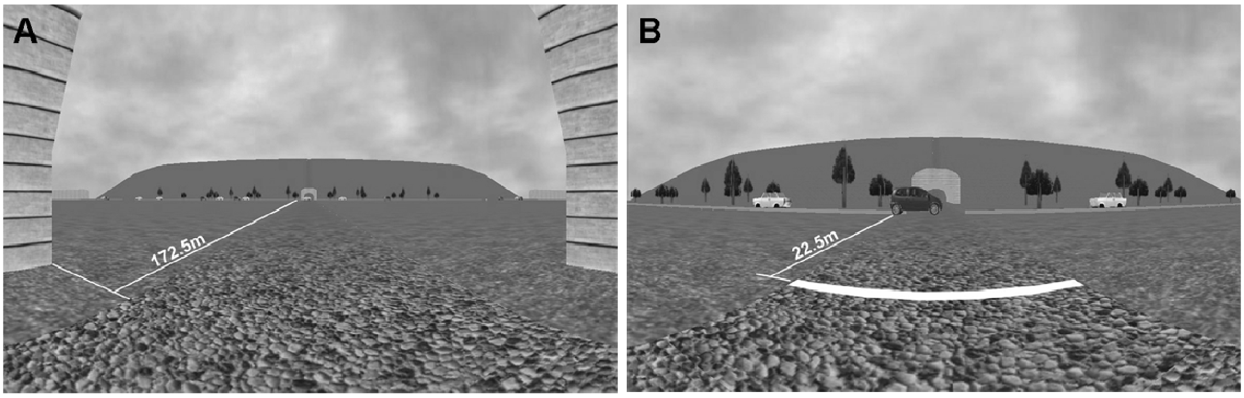


Fig. 1A: Start position of the virtual vehicle in the tunnel. The distance to the intersection is also depicted.
Fig. 1B: End position of the virtual drive at the white line 22.5 m before the intersection.

c) Statistical methods

From the binocular visual field we calculated the area of sparing within the affected hemifield (A-SPAR in degrees^2) and the minimum linear distance (D) between the central fixation point and the defect border (in degrees of visual angle) for the stimulus III 4e (stimulus size 30', stimulus luminance 320 cd/m^2, Fig. 2). We used the binocular visual field, because it is assumed to provide more realistic information about the visual field a patient uses for performing daily activities. Area of sparing (A-SPAR) and the degree of sparing (D) to the defect border were assessed, because the intact visual field – especially its central 30 degrees – is thought to play an outstanding role in performing activities of daily living. [3] Driving performance was quantitatively assessed as the number of virtual accidents in the simulator. For statistical analysis we calculated for every subject the mean proportion of accidents over all trials.

Data were analyzed using the programs JMP© 5.0.1 (SAS Institute Inc., Cary, NC, USA) and R 2.2.1 (R foundation for statistical computing, Vienna, Austria). [20] In order to identify factors important for the proportion of accidents, a multiple regression model for all subjects including individual as a random factor was formulated.

Being a proportion, the response variable (mean proportion of accidents) was transformed to normal distribution by taking the arcsine-root. Major factors were identified by forward and backward stepwise selection (p-to-enter=0.1, p-to-leave=0.1) of the factors traffic density, age, A-SPAR, perimetric reaction time (RT) and minimum linear distance between central fixation point and defect border (D). Residuals' normality and homoscedasticity were assessed by quantile-quantile plots (QQ plot) and residuals by predicted plots, respectively. To identify outliers with high leverage Cook`s distance was calculated and the distribution of random parameters estimates was inspected by histograms. Quality of fits was recorded as adjusted coefficient of determination (R_{adj}^2). Because of the obvious confounding of A-SPAR and D with the status of the subject (patient or control), and as we were interested rather in the visual field, the status was not considered explicitly in the model. Data on time since lesion and side of lesion are available for patients only. Therefore a similar model that included exclusively patients was investigated by adding these factors.

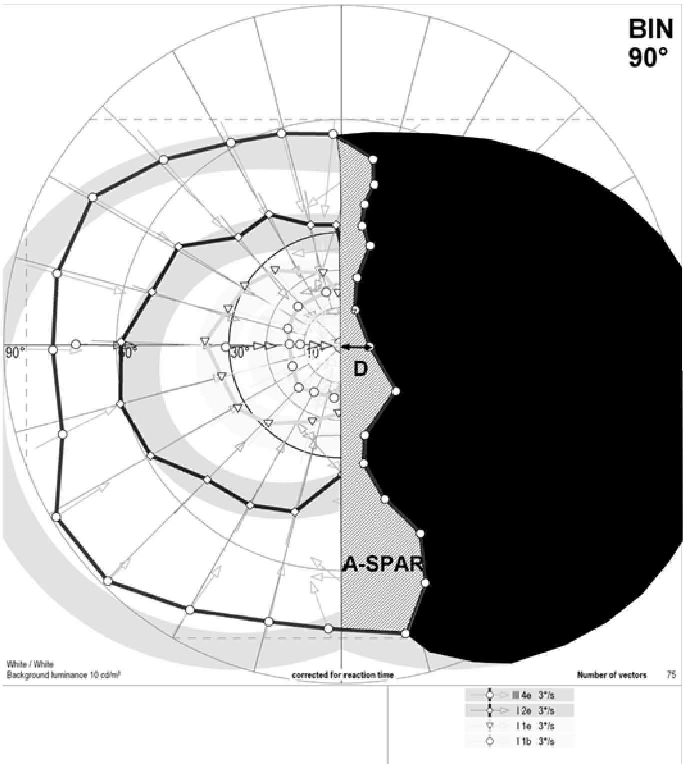


Fig. 2: Binocular visual field of a patient with a homonymous hemianopia to the right: Graphic representation of the area of sparing within the affected hemifield (A-SPAR as *hatched region*, obtained with stimulus III4e, angular velocity 3°/s) and the minimum linear distance (D) between the central fixation point and the defect border.

Results:

Frequency of traffic accidents was best explained by traffic density, age of individuals, the area of sparing within the affected hemifield (A-SPAR) and reaction time (RT). This model explained 78% of the total variability ($R_{adj}^2 = 0.78$). Adding the factor D did not lower R_{adj}^2. Residuals were approximately normally distributed (with mean zero) and homoscedastic. Maximal Cook`s D was 0.04, therefore no outliers could be identified.

Individual random effects were also approximately normally distributed with mean zero and standard deviation 0.06.

We obtained the regression equation for the response y_{trans}

$$y_{trans} = 0.432 + \begin{Bmatrix} -0.249 \text{ for traffic density 50\%} \\ +0.249 \text{ for traffic density 75\%} \end{Bmatrix} + 0.004\,age - 0.00002\,A\text{–}SPAR + 0.0002\,RT$$

All factors density, age, A-SPAR and reaction time RT were significant. However, parameter estimates show that the effect of traffic density dominates: it explained 63.4% of the total variability. Age, A-SPAR and RT explained 2.7%, 2.0% and 0.9% respectively.

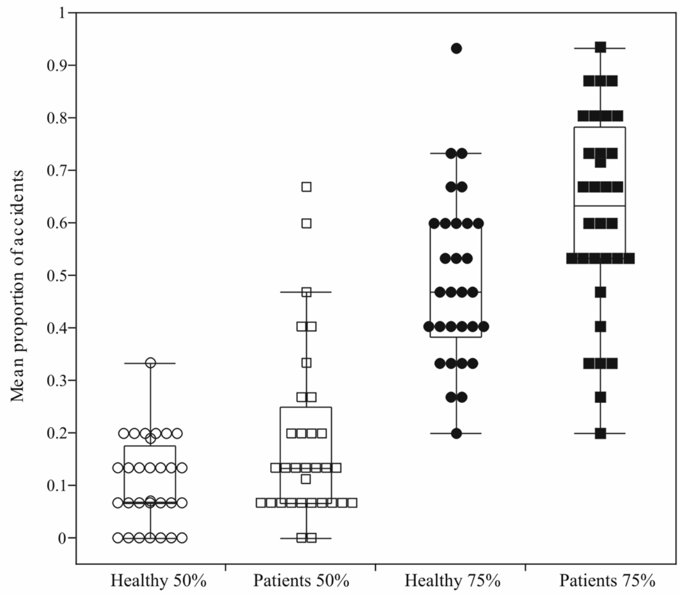


Fig. 3: Boxplots of the mean proportion of virtual accidents in the 50% and 75% traffic density. In higher traffic density, the mean proportion of accidents is considerably increased. Symbols that are not aligned are due to four cases with incomplete number of total trials (<30) because of measurement artifacts. ○ Healthy subjects in the 50% traffic density; ● Healthy subjects in the 75% traffic density; □ Patients in the 50% traffic density; ■ Patients in the 75% traffic density.

The most appropriate model *exclusively for patients* included the factors traffic density, age, A-SPAR and RT; it explained 80% of the total variability (R_{adj}^2=0.80). Adding side of lesion, D or time since lesion did not lower R_{adj}^2. Traffic density, age and RT were significant explaining 63.2%, 5.3%, 1.5% and 0.8% of the total variability. A-SPAR was not significant. The effect of traffic density as the dominant factor in the above model is demonstrated in Figure 3, where the mean proportion of accidents is presented for all study subjects in both density levels separately. In higher traffic density, the mean proportion of accidents is considerably increased. A scatter plot of the mean proportion of accidents by A-SPAR (area of sparing within the affected hemifield) is presented in Figure 4. Given high traffic density or low, A-SPAR has little effect on accident frequency. Subjects may have similar A-SPAR but widely varying accident proportions.

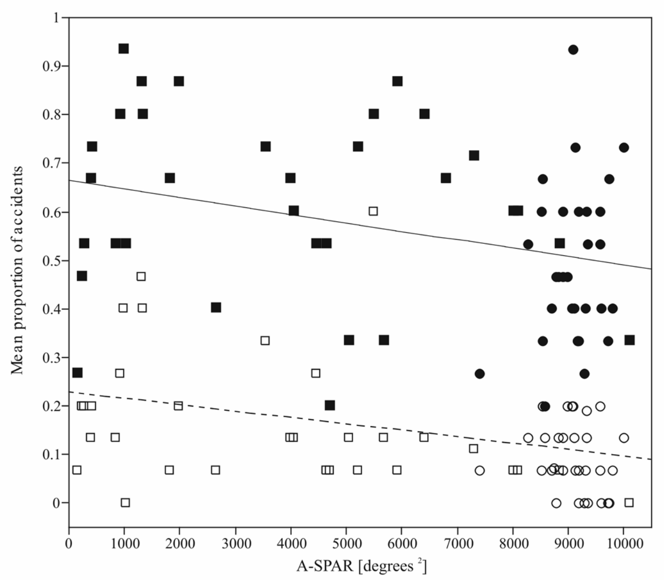


Fig. 4: Mean proportion of accidents by area of sparing within the affected hemifield (A-SPAR), data and regression lines for the mean in both traffic densities. Given high traffic density (filled symbols, solid line) or low (open symbols, dashed line), A-SPAR has little effect on accident frequency. Subjects may have similar A-SPAR but widely varying accident proportions. ○ Healthy subjects in the 50% traffic density; ● Healthy subjects in the 75% traffic density; □ Patients in the 50% traffic density; ■ Patients in the 75% traffic density.

Discussion:

Homonymous visual field defects are among the most frequent disorders after brain damage and create a marked amount of subjective inconvenience in everyday life. [21] Approximately 30% of all patients with stroke and 70% of those with stroke involving the posterior cerebral artery suffer from homonymous visual field defects. [22] In Germany there is an incidence of approximately 550,000 brain-injured patients per year, 135,000 of them suffer from visual disturbances, mostly HVFDs. [23] Many of these patients do not meet the minimum standards for a driving license, since traffic safety regulations in the European Union require a horizontal extent of the binocular visual field of 120°, and up-to-date decisions with regard to fitness to drive are often based solely on visual acuity and visual field extent. [24]

Yet there are many open questions related to visual perceptual deficiencies and driving. Numerous driving simulator studies and studies involving on-road testing of subjects with impaired visual fields have assessed the relationship between visual field loss and driving performance. A number of authors have demonstrated a worse driving simulator performance of patients with visual field defects. [4,6-8] However, performance was only weakly correlated with visual field measures in some studies. [9-11] Johnson and Keltner performed an automated visual field screening of 10.000 volunteers. Individuals with visual defects were compared with a matched normal control group. [5] Both accident and conviction rates were more than twice as high as the control group. However, this study as well as many others lacks information that quantifies severity of the defects in the binocular visual field.

In the present driving scenario, the subjects were allowed to perform eye and head movements similar to their natural viewing behavior. The most dominant variable was the traffic density, which accounted for a major portion of the total variability (Fig. 3 and Fig. 4). Although this effect seems to be trivial, it indicates that by manipulating certain experimental parameters, it is possible to achieve controlled, standardized circumstances, hence supporting the validity of driving simulators. Interestingly, the extent of the visual field defect – expressed as A-SPAR – was significant when considering the entire cohort. Since A-SPAR is an indicator of the status of the subject (patient or control), this finding points out that patients indeed caused on average slightly more accidents (Fig. 3). However, the effect exerted on driving performance was small (Fig. 4) and did not even reach significance when only the patient group was considered. This fact suggests that perimetric findings per se seem to be inadequate in predicting driving performance of hemianopic patients under VR-conditions. Furthermore, if subjects are observed individually, then there are some patients whose performance is comparable to that of the controls (Fig. 3).

Why can driving performance not be reliably predicted on the basis of visual acuity and visual field? Many authors suggest that some subjects can at least partially compensate for visual field defects by exploratory strategies using eye and head movements and thereby can achieve safe driving despite vision impairments. [3,8,9,11,14,15,25-29] Compensatory mechanisms may be also speed reduction and reduced risk-taking. [9] Jenssen et al. further suggest that drivers with homonymous hemianopsia, quadrantanopsia and homonymous scotomas develop increased attention and situational awareness, perceptual skills and decision making skills. [30] Through these strategies they did not differ significantly from an ophthalmologically healthy reference group in terms of insurance-reported accidents or self-reported accidents, even though the patient group did not compensate for their visual field defects by limiting their traffic exposure. [30] There is evidence that hemianopic patients with longstanding lesions (more than six months old) have increasingly different fixation patterns from those of normal controls, indicating evolution of a spontaneous compensatory eye movement strategy. [31] This fact is supported by cases of patients with congenital hemianopias, who adopt from birth a completely different pattern of eye- and head-movements, in order to compensate for their deficit. [32] Furthermore, several rehabilitation attempts on the training of scanning behavior in subjects with visual field defects indicate that efficient scanning techniques can be successfully trained. [29,33-36]

Another explanation for the lack of predictive power of the above-mentioned visual parameters is that driving is a multilevel task comprising numerous central factors as mental ability, attention, visual perception, memory and physical state, which combine with driving experience and exposure, personal skills, sensory, motor and compensatory abilities, in order to promote decision-making and action into a more or less complex driving task and environment. [37] An important additional source of variability in reports of visual field and driving performance is the large degree of individual variations in developing compensatory strategies, which is also highlighted within our sample (Fig. 4). [6,13,28] These factors are not addressed by standard ophthalmologic assessments, so it is not surprising that the observed relationships between vision and accident causation is weak.

Additionally, the driving ability of the older population is likely to become a major concern, since the elderly comprise the fastest growing sector of the driving population and their mobility may be critically dependent on the use of a vehicle. [38] This is important because older drivers have more traffic convictions and accidents per kilometer driven than any other age group. [39] The prevalence of eye disorders and cerebrovascular disease increases significantly with age and there are also normal age-related changes, like a decline in cognitive abilities and a slowing down of information processing, which may affect driving ability. [39] As a result, many studies report a deterioration in simulated driving performance or on-road assessment with increasing age. [6,9, 38,40,41] In the present study, it was also demonstrated that age has a slight impact on the frequency of crashes, which was stronger in the patient group. Similarly, a weak effect was revealed about perimetric reaction time (RT). RT is conceptually related to processing speed in the visual system, in particular on the lower level. [42] Driving performance, especially in a simplified scenario like the presented one, is presumably also dependent on visual temporal processing abilities, since the information input is mainly visual.

Concerning the side of the brain damage no differences were revealed between left- and right-hemispheric lesions. Some studies indicate that patients with right-hemispheric lesions perform worse on performance measures and driving tasks, presumably because of a higher incidence of visuo-spatial deficits like neglect. [43-45] Cortical damage in the vicinity of the temporo-parietal lobe or – according to recent findings – in the right superior temporal gyrus, often results in unilateral hemi-neglect in which the patient fails to respond to stimuli presented contralateral to the lesion. [46] In the present study, patients with clinical evidence of neglect or signs of impaired lateralized attention in the paper-and-pencil tests were excluded. Additionally, the brain lesions in our patient group were primarily restricted to the occipital lobes after an infarct of the posterior cerebral artery, where the two hemispheres are represented functionally fairly equivalent. [41] Therefore there was no evident reason for a worse performance of patients with right-sided lesions.

Regarding time since onset of the lesion, it was also not expected that any significant effect would be revealed, because the time span after lesion onset was at least six months in our patient group. As suggested above, six months post injury is the time span, after which patients have adapted a different compensatory eye movement strategy. [35] Recent quantitative studies of visual field recovery also suggest that spontaneous improvement of homonymous hemianopia is seen in at least 50% of patients within one month of injury and in most cases the improvement occurs the first three months from injury. [47,48] Therefore an improvement in the visual field of our patient group, which could have an impact on the exploratory strategy, would be rather unlikely.

Our results must be treated with caution, given that cerebro-vascular accidents are likely to affect other higher-order aspects of the driving task in addition to the extent of the visual field. Moreover, our experiment was just a simplification of only one real-world driving situation, obtained with a driving simulator and therefore the findings cannot be uncritically transferred in real-life scenarios; the additional consideration of visual exploration in this group of patients and its effect on predicting driving performance represents the main issue for a future analysis.

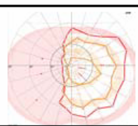
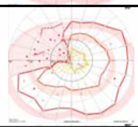
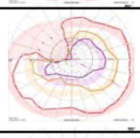
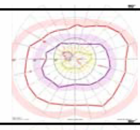
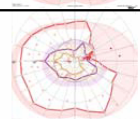
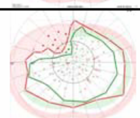
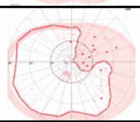
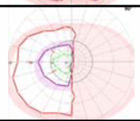
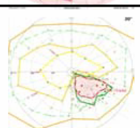
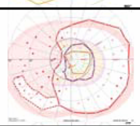
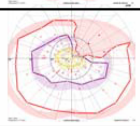
In conclusion, some patients with HVFDs demonstrate sufficient compensatory driving behavior during a simulated test ride and may partially overcome their visual field deficit, presumably by eye and head movements. Therefore, the visual field-related parameters should not be taken as the sole indicator of driving fitness. We suggest that studies in the future should attempt to find predictors of visual compensation in driving tasks and measure not only the extent of the visual field defect, but also the extent to which impaired drivers adopt compensatory, exploratory viewing strategies.

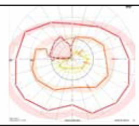
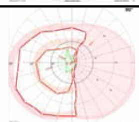
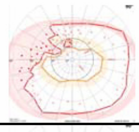
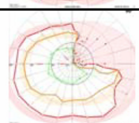
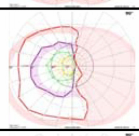
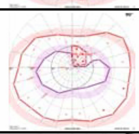
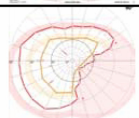
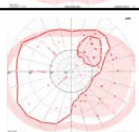
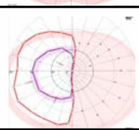
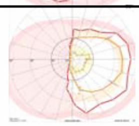
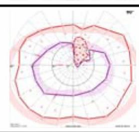
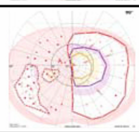
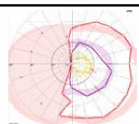
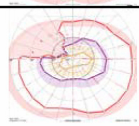
Appendix:

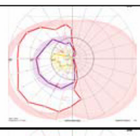
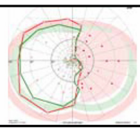
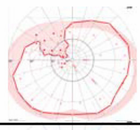
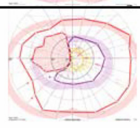
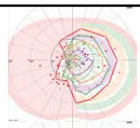
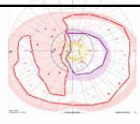
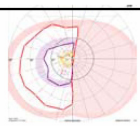
Papageorgiou et al: Driving performance in patients with homonymous visual field defects and healthy subjects in a standardized virtual reality environment

Patient identification (Pat-ID), gender, age at time of examination (Age), time span between brain lesion and neuro-ophthalmological examination (Δt), pathogenesis of brain lesion, site and extent of lesion, side of brain lesion (R=right, L=left), appearance of homonymous visual field defect (HVFD, assessed with semi-automated kinetic perimetry = SKP under binocular conditions*), area of sparing within the affected hemifield (A-SPAR in degrees^2), minimum linear distance between the central fixation point and the defect border (D in degrees of visual angle), perimetric reaction time (RT in milliseconds-ms).

*The area of absolute visual field loss is shaded in light red and the III 4e isopter is depicted as a dark red line. As recommended in kinetic perimetry, two additional isopters within the III 4e isopter were tested in most of the cases.

Pat-ID	Gender Age [yrs.]	Δt [yrs.]	Pathogenesis Site / Extent of lesion Side of brain lesion	HVFD (90 ° eccentricity, both eyes)	A-SPAR [degrees^2]	D [degrees]	RT [ms]
01	m 51	3.5	Ischemia parieto-temporo-occipital R		1301.1	12.5	1370
02	w 58	2.5	Hemorrhage temporo-occipital R		4450.2	4.9	280
03	w 65	9.9	Hemorrhage (Aneurysm) occipital R		5920.6	7.4	945
04	w 27	0.8	Ischemia occipital R		6401.8	5.5	1108
05	m 70	1	Ischemia occipital L		4632	19	305
06	m 66	1	Ischemia temporo-occipital R		5052.3	21.7	332
07	m 48	1	Ischemia occipital L		4041.7	1.1	259
08	m 57	7	Ischemia occipital L		243.1	3.2	374
09	m 37	0.5	Ischemia occipital L		10105	2.8	319
10	m 64	1.6	Ischemia occipital R		3549.7	13.6	291
11	w 46	3	Ischemia occipital L		7300.9	11.6	281

12	m 43	1	Ischemia occipital R		8013.7	3	415
13	m 73	1.1	Ischemia occipital L		976.7	6.7	270
14	m 29	1.8	Ischemia occipital R		5671.3	18.6	777
15	w 21	3.9	Ischemia parieto-occipital L		4710.7	1.7	267
16	w 35	11.2	Ischemia occipital L		1335	7	344
17	m 46	1	Ischemia temporo-occipital L		8090.4	2.5	670
18	m 64	0.5	Ischemia occipital L		1986.6	15.4	518
19	m 19	1.7	Hemorrhage (Trauma) parieto-occipital L		2640.4	21.7	391
20	m 30	1.6	Hemorrhage (Aneurysm) parietal L		149.4	0	357
21	m 32	3.5	Brain surgery (AV malformation) parieto-occipital R		414	3.2	1062
22	w 40	2.7	Ischemia occipital L		8853.2	4.7	311
23	m 51	0.7	Ischemia parieto-temporo-occipital, R		1810.3	2.7	390
24	m 40	4.9	Brain surgery (AV malformation) occipital R		923.7	2.3	299
25	m 60	3.6	Ischemia occipital R		5496.4	8	387

26	w 45	16	Hemorrhage (Trauma) parieto-occipital L		391	2.1	442
27	w 32	1.1	Ischemia occipital L		845.5	4.5	260
28	m 64	0.7	Ischemia occipital R		6790.6	7.8	348
29	w 43	5.9	Hemorrhage (Trauma) occipital R		5208.6	3.7	262
30	m 18	1.8	Hemorrhage (Trauma) Parieto-temporo-occipital R		1019	16	566
31	m 53	2	Ischemia occipital R		3987.2	13	449
32	w 60	1.1	Ischemia occipital L		280.2	2	346

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Summary

During the first part of this PhD-project a new projection device, appropriate for presenting visual stimuli over a large area to a sitting subject, was established and constitutes the methodological basis for all further investigations. Psychophysical experiments comprising virtual scenarios could be performed with this novel setup whereby subjects were free to move their eyes and the head in a natural manner. Furthermore, the tracking of the subjects' eye and head movements could be successfully integrated.

Concerning the visual limitations, existing naturally or incurred additionally by affections of the vision related brain regions, humans can develop gaze related strategies in order to adapt their behavior to the demands required by a specific task. In the comparative visual search paradigm, performed in order to investigate gaze adaptations in healthy subjects under different cost requirements, the influence of working memory limitation due to the process of generating task dependent eye and head movements for visual search became obvious: As long as the costs for gaze movements remained in a lower range, the memory involvement was restricted. However, in adaptation to increased movement costs for acquiring information, subjects performed fewer gaze movements and their search strategy was shifted towards memory use. Further gaze related adaptations were identified in some hemianopic patients. Due to their visual field restrictions, advanced compensatory eye and head movements needed to be developed. In more complex tasks, the majority of the hemianopic patients tended to maximize their information intake by performing more fixations in the hemifield related to the visual field loss and by shortening the saccadic amplitudes as indicated by the rapid gaze jumps between the regions selected for acquiring information. Another group of hemianopic patients showed these compensations in conjunction with an elevated number of re-fixations already for the not cognitively demanding visual sampling task. These findings reveal for a fundamental capability of healthy and visually impaired subjects, to adapt the vision related functions in order to behave adequately in terms of memory and/or visual field limitations.

Concerning the varying task performance of the visually impaired hemianopics in the varying paradigms of the experimental toolbox, no connections to the clinical and demographic data could be identified. Thus, only the acquired and advanced gaze related adaptations serve to perform in different tasks in a more or less adequate way. Furthermore, against the unalterable nature of the clinical and demographic attributes, patients with a hemianopic field loss possibly can influence and enhance their compensation level to overcome the restriction of their visual field.

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Meine Diplomarbeit fertigte ich an der Universität Bayreuth mit dem Schwerpunkt Elektrophysiologie der Geschmackssensillen von Termiten an. Das darauf folgende neue Forschungsvorhaben hinsichtlich meiner Doktorarbeit in Tübingen stellte für mich damals einen herausfordernden und nachhaltigen Themawechsel dar. Heute, nach den Jahren meiner Doktorarbeit und um viele Erfahrungen reicher, bin ich sehr glücklich, diesen Schritt in ein neues und überaus interessantes Forschungsgebiet gewagt zu haben. Doch dies alles wäre mir sehr viel schwerer gefallen wenn nicht gar unmöglich geworden, wenn nicht viele liebe und wissenschaftlich interessiert und motivierende Menschen um mich herum gewesen wären.

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Lebenslauf

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