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Collision avoidance in persons with homonymous visual field defects under virtual reality conditions

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ABSTRACT

The aim of the present study was to examine the effect of homonymous visual field defects (HVFDs) on collision avoidance of dynamic obstacles at an intersection under virtual reality (VR) conditions. Overall performance was quantitatively assessed as the number of collisions at a virtual intersection at two difficulty levels. HVFDs were assessed by binocular semi-automated kinetic perimetry within the 90° visual field, stimulus III4e and the area of sparing within the affected hemifield (A-SPAR in deg^2) was calculated. The effect of A-SPAR, age, gender, side of brain lesion, time since brain lesion and presence of macular sparing on the number of collisions, as well as performance over time were investigated. Thirty patients (10 female, 20 male, age range: 19–71 years) with HVFDs due to unilateral vascular brain lesions and 30 group-age-matched subjects with normal visual fields were examined. The mean number of collisions was higher for patients and in the more difficult level they experienced more collisions with vehicles approaching from the blind side than the seeing side. Lower A-SPAR and increasing age were associated with decreasing performance. However, in agreement with previous studies, wide variability in performance among patients with identical visual field defects was observed and performance of some patients was similar to that of normal subjects. Both patients and healthy subjects displayed equal improvement of performance over time in the more difficult level. In conclusion, our results suggest that visual-field related parameters per se are inadequate in predicting successful collision avoidance. Individualized approaches which also consider compensatory strategies by means of eye and head movements should be introduced.

1. Introduction

Homonymous visual field defects (HVFDs), the loss of the field of vision in the same relative position in both eyes, are among the most frequent disorders after unilateral injury of the postchiasmatic visual pathway. Nearly 80% of patients with unilateral postchiasmatic brain lesions suffer from HVFDs (Zihl, 1995). Most common causes of HVFDs are strokes and, to a lesser extent, traumatic brain injury and tumors (Zihl, 2000). HVFDs create a marked amount of subjective inconvenience in everyday life (Gall et al., 2009; Papageorgiou et al., 2007). Patients with HVFDs may show persistent and severe impairments of reading, visual exploration and navigation, collide with people or objects on their blind side and may be deemed unsafe to drive (Trauzettel-Klosinski & Reinhard, 1998; Zihl, 2000, 2003). This has led to the belief that homonymous visual field loss is per se associated with functional impairment.

Driving has been considered to be problematic for patients with HVFDs; therefore researchers have assessed driving performance of patients with HVFDs in comparison to subjects with normal visual fields either in driving simulators or in on-road experiments. The few studies assessing the performance of patients with HVFDs in realistic or experimental driving paradigms report a variety of findings. Some authors suggest that performance of patients with HVFDs is significantly worse than that of normal subjects (Table 1, Bowers et al., 2009; Kooijman et al., 2004; Lövsund, Hedin, &

Abbreviations: HVFD, homonymous visual field defect; VR, virtual reality; A-SPAR, area of sparing within the affected hemifield; HH, homonymous hemianopia; QH, homonymous quadrantanopia.

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Table 1
List of studies assessing performance of patients with HVFDs (in descending chronological order).

Author	Study participants	Experimental setup	Results	Remarks
Wood et al. (2011)	22 patients with HH 8 patients with QH 30 controls	On-road test (interstate and non-interstate)	Patients rated as safe made larger eye movements and more head movements into their blind hemifield	Eye and head movements were assessed qualitatively by means of video footage, rather than by using a formal eye and head tracker system
Bowers et al. (2010)	12 patients with HH 12 controls	Driving simulator	Drivers with HH took a lane position that increased the safety margin on their blind side	Absolute lane position varied as the steering maneuver and location of the risk from oncoming traffic changed with road segment type
Hardiess et al. (2010)	12 patients with HVFDs 12 controls	Virtual reality (dot counting task and comparative visual search task)	8/12 patients could reach adequate performance in both tasks	In the two tasks, different patterns of compensatory gaze movements were found
Bowers et al. (2009)	12 patients with HH 12 controls	Driving simulator	HH drivers had significantly lower pedestrian detection rates on the HH-side	Wide variability among subjects and age the main factor for that. The relationship of simulator-based measures to on-road performance has yet to be established
Wood et al. (2009)	22 patients with HH 8 patients with QH 30 controls	On-road test (interstate and non-interstate)	73% of HH and 88% of QH patients received safe ratings	10 HH and 1 QH patients did not drive on the interstate, 44% of initially eligible patients did not participate in the study
Bowers, Keeney, and Peli (2008)	43 patients with HH	Follow-up questionnaires evaluating functional benefits for mobility	47% of patients were wearing the prism glasses after 12 months reporting significant benefits for obstacle avoidance	Objective measures of functional performance with and without prisms and a control or comparison treatment were not included
Martin et al. (2007)	3 patients with HH 4 controls	Naturalistic task (assembly of wooden models on a table)	No significant differences in task performance, saccade dynamics, spatial distribution of gaze	Small sample
Szlyk et al. (2005)	10 patients with HH due to occipital lobe lesions	Comparison of Fresnel prisms and Gottlieb system in the laboratory, on-road and in a simulator	Prism lenses and training in their use improved performance on visual functioning and driving-related skills	Need for data on the long-term safety of peripheral enhancement devices while driving
Racette and Casson (2005)	13 patients with HH 7 patients with QH	Retrospective chart review of occupational therapists' assessments of on-road driving test	Localized visual field loss (VFL) in the left hemifield and diffuse VFL in the right hemifield associated with impaired performance, patients with QH received no unsafe ratings	No control group, different therapists, retrospective design, lack of standardized route
Kooijman et al. (2004)	28 patients with HVFDs	On-road driving test pre- and post-training on a driving simulator	Only 4/28 patients with HVFDs passed the on-road test	No control group, referral of patients due to suspected driving safety concerns
Tant et al. (2002)	28 patients with HH	On-road driving test and neuropsychological visuospatial test performance	Only 14% of patients passed the test	Recruitment of patients whose driving was suspected to be unsafe by the caregiver or the patients themselves
Schulte et al. (1999)	6 patients with HVFDs 10 controls	Driving simulator	No differences in performance (driving speed, driving error rate, reaction time)	Small sample, restricted field of view (16° × 21°), few unexpected events
Zihl (1995)	60 patients with HH 16 controls	Dot counting task on a screen	40% of patients showed normal scanning behavior	Time since brain damage was at least 6 weeks
Szlyk, Brigell, and Seiple (1993)	6 patients with HVFDs 7 age-matched controls 31 younger controls	Driving simulator	Performance of patients worse than or similar to the older control group	3 patients had hemi-neglect, the study was performed 2 months after stroke
Lövsund, Hedin, and Törnros (1991)	26 patients with HVFDs 20 controls	Detection of static stimuli in a driving simulator at 24 positions	Only 3/26 patients with HVFDs were found able to compensate	Wide variation in the individual reaction time

Törnros, 1991; Szlyk, Brigell, & Seiple, 1993; Tant et al., 2002). On the other hand, other studies report that there are no performance differences between patients with HVFDs and control subjects (Table 1, Martin et al., 2007; Schulte et al., 1999; Wood et al., 2009). The majority of studies have highlighted poor steering control, incorrect lane position and difficulty in gap judgment as the primary problems of drivers with HVFDs (Bowers et al., 2009, 2010; Szlyk, Brigell, & Seiple, 1993; Tant et al., 2002; Wood et al., 2009). An additional question concerned the underlying factors affecting performance of patients with HVFDs. It has been a matter of debate whether driving performance of patients with longstanding HVFDs is primarily determined by visual field measures, e.g. the extent of the visual field along the horizontal meridian, the Esterman score (Johnson & Keltner, 1983), or affected by additional factors, such as aging, side of brain injury and compensation by eye and head movements (Pambakian et al., 2000; Wood et al., 2011; Zihl, 1995).

Rather than making general statements on the average performance of patients with HVFDs, recent evidence suggests that functional assessments to evaluate each patient individually should be introduced, because a significant portion of patients have the potential to compensate and wide variability among them occurs (Bowers et al., 2009; Hardiess et al., 2010; Wood et al., 2009, 2011). In order to enable individual assessments in driving scenarios, it has been argued that studies should address specific questions at specific road segments and in relation to specific visual impairments (Mandel et al., 2007). One aspect of driving behavior, which has not been studied adequately, is performance of patients with HVFDs at intersections. Hence, Bowers et al. (2009) investigated detection of stationary pedestrians at intersections and along the roadside on city and rural roads in a driving simulator, and found that HH (homonymous hemianopia) drivers exhibited significantly lower pedestrian detection rates on their blind side at intersections. However, collision avoidance ability of patients with HVFDs at intersections, in terms of detecting and appropriately responding to dynamic collision-relevant obstacles (i.e. cross-traffic vehicles), has not been studied yet.

Therefore, the aims of the present study were (i) to assess the performance of patients with HVFDs in comparison to normal-sighted control subjects in a dynamic collision avoidance task while crossing an intersection, and (ii) to investigate whether their performance can be explained by visual field indices. We evaluated performance of patients with longstanding HVFDs due to cerebrovascular lesions, in a collision avoidance task under virtual reality (VR) conditions and compared them to normal-sighted age-matched subjects. We hypothesized that patients with HVFDs would demonstrate poorer performance in terms of collision avoidance at an intersection. In particular, we expected that patients would collide more often with vehicles on the blind than the seeing side and there would be no difference in collision rates between the seeing side of patients and the normal-sighted subjects. However, we speculated that performance would not be solely explained by visual field-related parameters and therefore expected contribution of additional factors, e.g. age, side of brain lesion and time span since lesion onset. Literature on spatial cognition often reports gender differences, with males typically performing better in tasks involving mental rotation, three-dimensional figures and spatial orientation (Voyer, Voyer, & Bryden, 1995; Wolf et al., 2010). Therefore the effect of gender on collision avoidance was also investigated.

A driving scenario was chosen as a paradigm that concerns a familiar everyday situation. Driving consists of several subtasks (e.g. steering and lane positioning, visual exploration of the scenery, navigational considerations). However, we have isolated one central aspect, namely collision avoidance while crossing an intersection, in order to systematically address one type of error and the relevant visual requirements. Furthermore, collision avoidance is associated with daily living tasks such as crossing a road, walking in a crowd, or driving through an intersection, which often require pedestrians and drivers to adapt their behavior to the displacement of other objects in their environment (Lobjois et al., 2008). At an intersection, a driver must estimate the time interval that it will take for his car to cross the road before an oncoming vehicle will arrive there (i.e. time-to-contact, TTC) (Lobjois, Benguigui, Bertsch, & Broderick, 2008; Matsumiya & Kaneko, 2008; Schiff & Detwiler, 1979; Schiff & Oldak, 1990). This task requires oculomotor adaptation, head movements and visuo-motor calibration, which consists of perceiving the size of the gap between the cross-traffic vehicles in terms of time to (re)act (Lee, 1976; Simpson, Johnston, & Richardson, 2003). Yet the effect of homonymous visual field loss on the completion of such a cognitively challenging task has not been assessed previously.

Virtual reality was used in order to achieve standardized, repeatable and completely programmable experimental conditions and avoid any safety concerns and driving licensure issues that may be encountered in on-road studies. In contrast to a real driving scenario, we simplified our task by omitting steering, lane positioning, and navigational considerations. Here, only the active avoidance of a potential collision while approaching an intersection with variable number of cross-traffic vehicles has to be accomplished. The intersection task was constructed so as to enable simulation of all possible scenarios that may occur in reality (i.e. two lanes for traffic vehicles moving in opposite directions, variability in traffic density, speed control of the approaching car, a large field of view for the subjects, and scanning of the scenery by means of head and eye movements). In order to enable comparability between subjects we allowed speed adjustments within defined limits (i.e. no infinite acceleration and deceleration were possible) and we restricted the velocity of the cross-traffic vehicles to a fixed value. Usually (in real traffic scenarios), drivers can and have to stop in front of an intersection in order to prepare passage through the intersection when all other vehicles are out of the time-to-collision range. Clearly, this circumstance is not satisfied in our experimental design due to the need for detecting performance differences between study participants. However, our subjects never felt uncomfortable or overwhelmed with this adaptation. Additionally, the available period to react at an intersection is not always unlimited even in real world, because different categories of road users interact in these limited areas with crossing trajectories. The result is that in 2007 at least 22% of fatal accidents in the USA occurred at intersections (Fatality Analysis Reporting System Encyclopedia, 2007). Therefore, we believe that our intersection task is an adequate representation of the type of situation people face at (real) intersections.

2. Materials and methods

2.1. Subjects

Potential participants with hemianopia or quadrantanopia were recruited from the Department of Neuro-Ophthalmology and the Neurology Clinic at the University of Tübingen (Germany), as well as the Neurology Clinic of the Bürger Hospital in Stuttgart and the Bad Urach Rehabilitation Center. Normal-sighted control subjects were recruited from the Tübingen region and comprised group-age-matched volunteers from friends and relatives of the authors, the staff and the patients in the Department of Neuro-Ophthalmology at the University of Tübingen.

To be included in the study, all participants were required to be at least 18 years old, to have best corrected monocular (near and distant) visual acuity of at least 20/25 and normal function and morphology of the anterior visual pathways as evaluated by ophthalmological tests (fundus and slit-lamp examinations, ocular alignment, ocular motility). The group-age-matched control subjects should additionally have normal visual fields and no history of brain injury, physical or cognitive impairment. Patients should have a homonymous visual field defect, varying from complete homonymous hemianopia to homonymous paracentral scotomas, due to a unilateral vascular brain lesion, which was documented by neuroradiological examinations (magnetic resonance imaging or computerized tomography). Exclusion criteria for patients were as follows: visual hemi-neglect as determined by horizontal line bisection, copying of figures, and by means of the "Bells test" (Gauthier, Dehaut, & Joannette, 1989), evidence of cognitive decline, aphasia, apraxia, visual agnosia or physical impairment, cerebral tumor, multiple sclerosis, Alzheimer's disease, Parkinson's disease, and previous scanning training. The time span between the brain lesion and the examination date should comprise at least 6 months.

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. Following verbal and written explanation of the experimental protocol all subjects gave their written consent, with the option of withdrawing from the study at any time.

Of the 41 potential participants with hemianopia or quadrantanopia, two patients with unilateral neglect and seven patients with bi-hemispheric cerebral lesions leading to HVFDs in both hemifields were excluded. Two further patients withdrew after experiencing symptoms of motion sickness. Thirty eligible patients with HVFDs (20 with hemianopia and 10 with quadrantanopia) and 30 normal-sighted group-age-matched control subjects were finally enrolled into the study.

The etiology of the HVFD was in all cases a unilateral cerebrovascular lesion due to ischemia (21 patients), hemorrhage (one patient), rupture of intracerebral aneurysm (two patients), arteriovenous malformation (two patients) or hemorrhage after trauma (four patients). Time since lesion onset was at least 6 months (median: 20 months, range: 6 months to 18 years). There were 15 patients with right-hemispheric and 15 patients with left-hemispheric lesions, which were in the majority of cases located in the occipital lobe. The demographic characteristics of each of the 30 patients are listed in Appendix A.

2.2. Visual field assessment

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). Visual fields within the central 30° were performed with appropriate near correction. In the patient group – in accordance with a recent study of Wood et al. (2009) – homonymous visual field loss was classified as left vs. right and complete vs. incomplete. For patients with quadrantanopia, field loss was further classified as superior vs. inferior.

2.3. Experimental design

Performance in the collision avoidance task was assessed under VR-conditions. The VR environment was displayed on a 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 (Fig. 1).

The visual environment and the experimental procedures were programmed in the SGI OpenGL Performer™. The spatial resolution of the projected images was 2048 × 768 pixels displayed with a frame rate of 60 Hz.

2.4. Experimental task

The subject was instructed to "drive" along a straight road (Fig. 2A and B) and finally to drive through a virtual intersection with cross traffic without causing a collision.

The virtual driving distance to the intersection was 172.5 m and only straightforward movement of the virtual vehicle was possible. Subjects started each trial in a tunnel (Fig. 2A). After leaving the tunnel they could adjust their driving speed between 18 and 61.2 km/h (11.2–38 mph) by means of a joystick in order to avoid a collision with the cross traffic at the intersection. During the driving period it was not possible to stop the car. The subject should therefore estimate the time interval when the oncoming vehicle will arrive at the intersection. At the same time, the subject also needed to estimate the time interval that it will take for his/her vehicle to cross the road at the intersection (Matsumiya & Kaneko, 2008) and could adjust the speed in order to achieve the goal of preventing a collision. When subjects reached a white line 22.5 m before the intersection (Fig. 2B), they were not allowed to adjust their speed anymore. After this line they were automatically driven across the intersection with the last adjusted speed without further visual input. A potential collision was then calculated by the simulation program and was delivered to the examiner at the end of the experiment. Even in case of a collision, participants did not experience a virtual crash and did not receive any feedback about their performance, in order to maintain identical conditions for each trial.

All cars of the cross traffic had a constant speed of 50 km/h (31.1 mph) and on average there were equal numbers of vehicles from the left and right side. The experiment was programmed at two traffic density levels of ascending difficulty, which would generate collisions in 50% or 75% of the trials respectively – in case that a subject would begin the trial at a random position and would drive with random speed (i.e. chance level).

Subjects performed 30 trials: 15 trials for each density level in the same randomized order – and were free to perform head and eye movements. Prior to the start of the experiment all subjects underwent a training session lasting 5–10 min in order to understand the experimental demands and become familiar with the use of the equipment and the joystick. The experiment started after the participant reported that he/she has understood the task and has completed at least three "collision-free" trials at each of the two density levels. After each trial the simulation program recorded whether there was a collision or not. Participants were

Fig. 1. Image of the experimental set-up. Study participant performing collision avoidance in front of the projection screen.

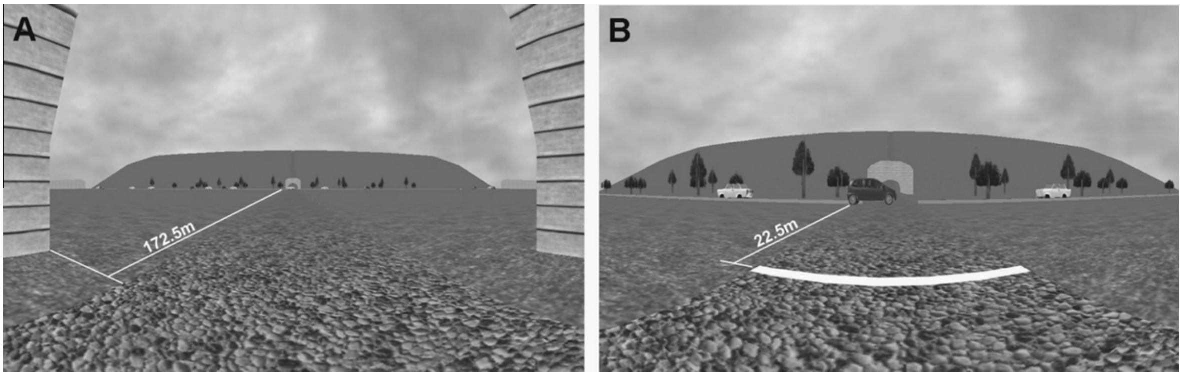

Fig. 2. (A) Start position of the virtual vehicle in the tunnel. The distance to the intersection (172.5 m) is depicted. (B) End position of the virtual drive at the white line 22.5 m before the intersection. The cross traffic at that moment is depicted (two cars driving from right to left and one car driving to the right).

not given feedback about their performance until the end of the experiment. Participants were encouraged to take breaks at will; testing resumed when the participant indicated they were ready. The time to complete the whole experiment ranged from 40 to 50 min.

2.5. Statistical methods

2.5.1. Visual field evaluation

From the binocular semi-automated 90° kinetic perimetry (SKP) we calculated the area of sparing within the affected hemifield (A-SPAR in deg^2) for the stimulus III 4e (background luminance 10 cd/m^2, angular velocity 3°/s, Fig. 3). Additionally, the area of sparing within the central 30° of the affected hemifield (A-30-SPAR) was also calculated (Fig. 3). This is the area most likely to be used during the collision avoidance task or when looking through the windshield of a car. An intact central 30° visual field is also recommended by the German ophthalmological society as a prerequisite for driving license. A software tool available on the OCTOPUS 101 Perimeter enables automatic calculation of the area within a specific isopter (in deg^2). In order to calculate the area of sparing for subjects with normal vision, they were arbitrarily assigned the right hemifield as the "affected" one, since any difference between the two hemifields in this case would be negligible. The A-30-SPAR was identical for all normal subjects. 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 (Schiefer et al., 2000).

2.5.2. Data analysis and statistics

Overall performance in the task was quantitatively assessed as the number of collisions for the 15 trials per density level. Data were analyzed using the statistical software JMP® (SAS Institute Inc., Cary, NC, USA) [www.jmp.com]. Since the number of collisions followed a Poisson distribution we applied a square root transformation in order to stabilize variances. We applied multifactorial analyses of variance with fixed factors group and traffic density and as random factor the individual nested under the factor group. The factor group refers to the division of participants in patients and normal subjects. Since the interaction terms between the fixed factors turned out to be non-significant, they were not included into the final models. The results are given as Hölder means together with the corresponding 95% confidence intervals. In our case the Hölder mean is the square of the arithmetic mean of the square roots of the observations.

In order to identify factors that might affect performance of patients, the effect of A-SPAR, age, gender, and traffic density on the number of collisions was investigated by means of fitting an analysis of covariance model stepwise by starting with the full model, setting the critical p-values at 5%, and eliminating all non-significant factors and their interactions. In order to stabilize the variances we took the square roots of the number of collisions. For Poisson distributed variables this results in a constant standard deviation of 0.5. The observed root mean square error was 0.54 which agrees well with the expected value. The final result of this stepwise procedure yielded a simple model, which contained all four main effects but without their interactions.

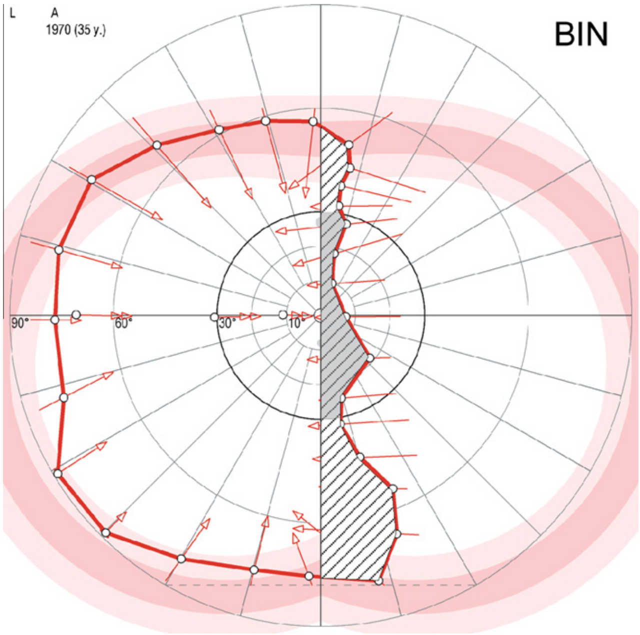

Fig. 3. Binocular visual field of a patient with a homonymous hemianopia to the right: Graphic representation of the area of sparing within the affected hemifield (A-SPAR as *hatched region*, obtained with stimulus III4e, angular velocity 3°/s) and the area of sparing within the central 30° of the affected hemifield (30-A-SPAR as *gray hatched region*).

3. Results

3.1. Demographic data

The demographic summary statistics of patients and controls are given in Table 2. The ratio males/females for patients was 2.0 and for control subjects it was 1.5. There were no differences in age ($p = 0.79$, t-test) and gender ($p = 0.79$, Fisher's exact test) be-

Table 2
Demographic summary statistics (age and gender) of patients with HVFDs and control subjects.

	Hemianopia ($n_1 = 20$)	Quadrantanopia ($n_2 = 10$)	Combined ($N = 30$)	Controls ($N_o = 30$)
Age, mean (SD)	45.9 (16.4)	46.9 (16.1)	46.2 (16.0)	45.1 (15.4)
Gender, *N* (%)				
Female	5 (25)	5 (50)	10 (33)	12 (40)
Male	15 (75)	5 (50)	20 (67)	18 (60)
Side of lesion, *N* (%)				
Right	9 (45)	6 (60)	15 (50)	
Left	11 (55)	4 (40)	15 (50)	

tween patients and control subjects, reflecting group-matching with respect to age and gender. Additionally, a one-way ANOVA yielded no differences in regard to age ($F(2,57) = 0.079$, $p = 0.924$) between patients with right HH (45.3 ± 17 years, mean ± SD), patients with left HH (47.1 ± 15.5 years, mean ± SD) and control subjects (45.1 ± 15.4 years, mean ± SD).

3.2. Task performance analysis

The number of collisions of all subjects is shown in Fig. 4 separately for each traffic density level. Increasing the traffic density from 50% to 75% increases the mean number of accidents for controls by about 6 and for patients by about 7 ($p < 0.0001$, *F*-test). The difference between the controls and patients is about 1 for 50% density and 2 for 75% density ($p = 0.0061$, *F*-test).

Patients with hemianopia had significantly higher collision rates than controls in both traffic density levels, while there were neither significant differences in the collision rates of quadrantanopia patients compared with normal subjects nor with hemianopia patients (Fig. 5).

3.3. Side of collision

In order to compare the number of collisions between two hemifields within the same group, e.g. blind vs. seeing in patients, we used the matched pairs *t*-test. For comparisons between different groups we applied a one-way ANOVA. The data from four participants (three normally-sighted participants and one patient) with respect to the side of collision were not available due to spo-

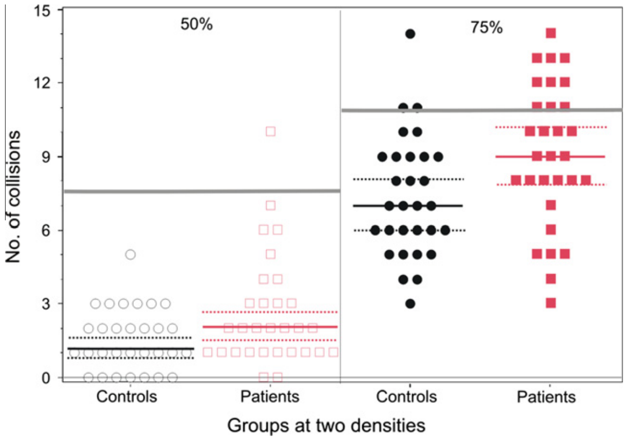

Fig. 4. Scatterplots of the number of virtual collisions at the 50% and 75% traffic density. The continuous black and red lines show the Hölder means and the dashed lines show the corresponding 95% confidence intervals. The red squares correspond to patients and the black circles refer to control subjects. The markers are open for density 50% and closed for density 75%. Increasing the traffic density from 50% to 75% increases the mean number of accidents for controls by about 6 and for patients by about 7 ($p < 0.0001$). The difference between the controls and patients is about 1 for 50% density and 2 for 75% density ($p = 0.0061$). The gray lines show the expected number of collisions in case that the subjects began the trials at a random time point and drove with random speed (i.e. with closed eyes): 7.5 collisions for 50% density and 11.25 collisions for 75% density. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

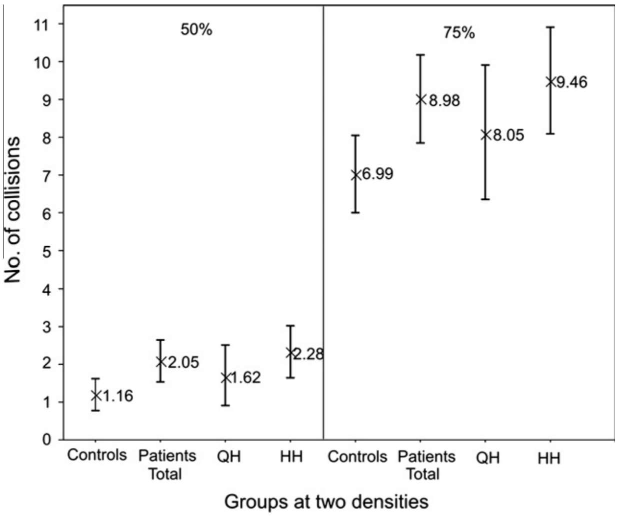

Fig. 5. Hölder mean number of collisions in controls, in the total patient group ("Patients total"), in patients with homonymous quadrantanopia (QH) and patients with homonymous hemianopia (HH) together with 95% confidence intervals. The means were estimated by a multifactorial analysis of variance with the fixed factors "group" (three levels) and "density" (two levels) and the random factor "individual", nested under the factor "group." The interaction between the two fixed factors was not significant ($p = 0.4546$) and was therefore ignored in the final model.

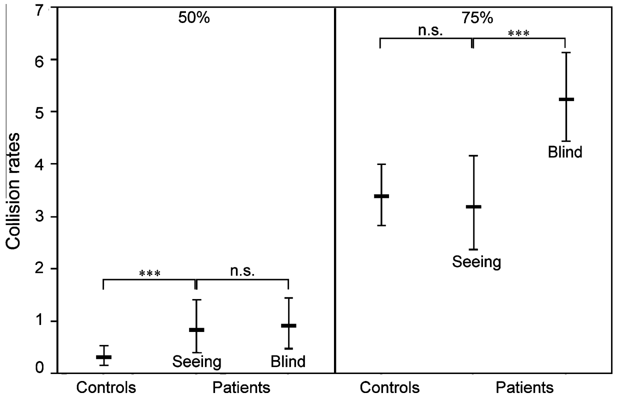

Fig. 6. Collision rates (number of collisions divided by the number of subjects at risk) together with their exact 95% CI based on the Poisson distribution in controls and patients for density 50% and 75%. Results of comparisons between groups (controls and patients) and between two hemifields within the same groups are shown. Due to missing data from four participants (three normally-sighted participants and one patient) with respect to the side of collision, analyses were carried out on 27 controls and 29 patients.

radic missing values in the recording process. While in the easier task (traffic density 50%) there were no differences in the number of collisions between patients' blind and seeing hemifield ($p = 0.821$), in density 75% patients collided more often with vehicles approaching from their blind side ($p = 0.002$). In terms of performance on patients' seeing side compared to normal subjects, in density 50% patients collided more often than normal subjects to their seeing hemifield ($p = 0.033$). However, in density 75% the number of collisions on patients' seeing side was similar to the number of collisions experienced by the normally-sighted ($p = 0.716$). These results are depicted graphically in Fig. 6.

3.4. Area of sparing

The effect of A-SPAR (area of sparing within the affected hemifield) and A-30-SPAR (area of sparing within the central 30° of the affected hemifield) on collision rate is presented in Fig. 7 as scatterplot of the number of collisions by A-SPAR and A-30-SPAR respectively. The slope of the curve for A-30-SPAR (−5/10,000 A-30-SPAR) was larger than the slope of the curve for A-SPAR (−0.6/10,000 A-SPAR), indicating a stronger negative correlation of A-30-SPAR with the number of collisions. However, this finding was expected, because the *Y*-axis values (number of collisions) are identical for both diagrams, while the *X*-axis values (A-SPAR or A-30-SPAR in deg^2) differ by almost one order of magnitude. Additionally, although the effect of both A-SPAR and A-30-SPAR were significant, there are large individual differences within our sample. It is noteworthy, that there are patients with almost identical A-SPAR or A-30-SPAR but considerably different collision rates. Furthermore, there are also some patients with even low A-SPAR or A-30-SPAR, who exhibit similar performance with that of normal-sighted control subjects.

3.5. Age and gender

The effect of age and gender on the total number of collisions is exhibited in Fig. 8. The data were modeled by square root transformed numbers of collisions. Backward stepwise regression anal-

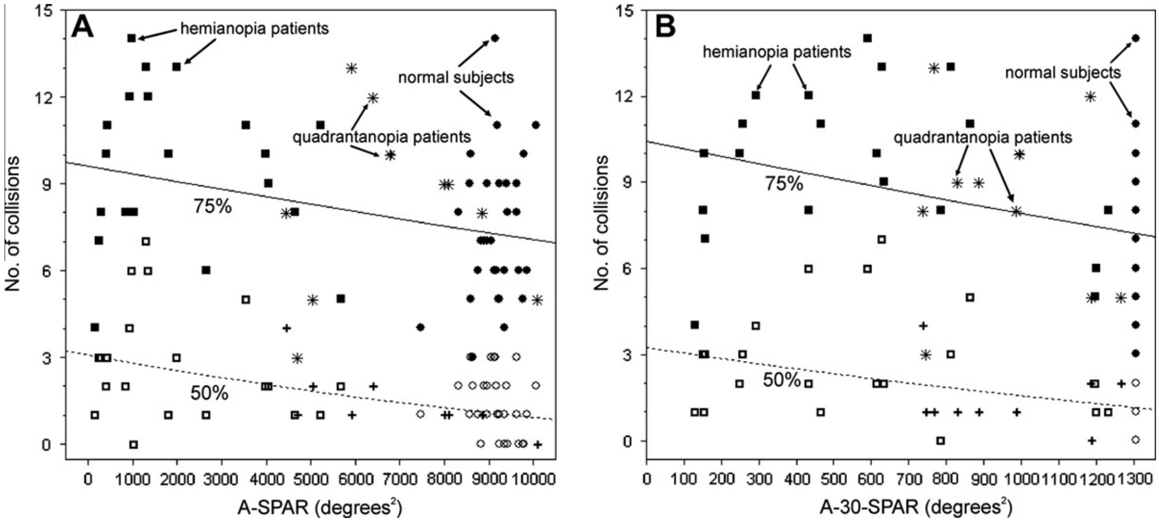

Fig. 7. Number of collisions by area of sparing (A: within the affected hemifield; B: within the central 30 deg^2 of the affected hemifield), data and regression curves for both traffic densities. The dots are labeled according to type and density. For 50% densities all labels are open and for 75% density they are filled. Normal subjects are shown by circles, hemianopia patients by squares and quadrantanopia patients by stars for 75% density vs. crosses for 50% density. (A) Because the intercepts differ for the two densities, the slopes of the linear component of the two curves are different though for the square roots the slopes are identical: −0.6/10,000 A-SPAR (95% CI −0.9 to −0.3/10,000 A-SPAR). (B) For the area of sparing within the central 30° of the affected hemifield (A-30-SPAR), the slope is −5/10,000 A-30-SPAR (95% CI −7/10,000 to −3/10000 A-30-SPAR).

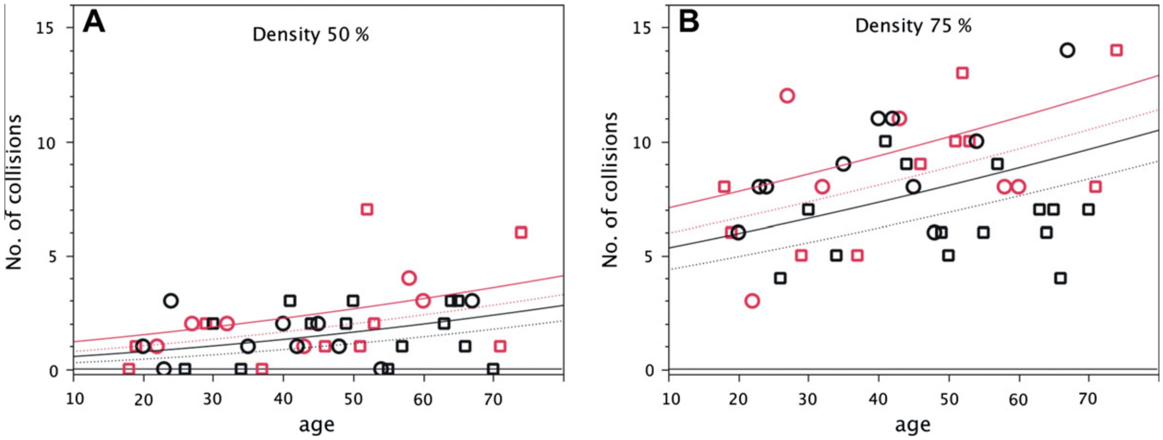

Fig. 8. The effect of age and gender on the number of collisions by traffic density in the total study population (A: density 50%; B: density 75%). Females are denoted by a circle and males by a square. The red markers (and lines) correspond to patients and the black markers (and lines) refer to control subjects. The continuous theoretical curves refer to females and the dashed lines to males. The number of collisions increases quadratically with age. Only the intercepts differ by gender, group and density for the square roots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

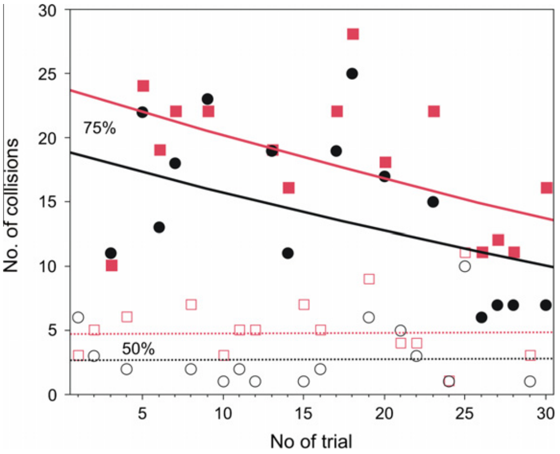

Fig. 9. A learning effect could only be seen at density 75% for patients and control subjects. The markers are the same as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ysis with fixed factors group (patient or normal), density (50% or 75%), gender and age, revealed non-significant interaction terms between them. All the main effects were significant: The number of collisions increases quadratically with age. The age effect is highly significant ($p = 0.0001$). The effects of group ($p = 0.0007$) and density ($p < 0.0001$) are discussed in Section 3.2. The gender effect is marginally significant ($p = 0.0456$). The age effect is not influenced by the other main factors (group, density and gender).

3.6. Brain lesion

Patients were divided into two subgroups by the median of their performance in both density levels using the median split method (Cohen, 2003): "performance above average" and "performance below average". Above average patients were compared with below average patients regarding the time span since brain lesion and side of brain lesion. Patients with performance above average did not differ from patients with performance below average regarding the side of brain lesion ($p = 1.00$, Fisher's exact test for dichotomous variables). Similarly, there was no difference in and time since brain lesion between patients with performance above average (3.49 ± 4.81 years, mean ± SD) and patients with performance below average (3.72 ± 4.57 years, mean ± SD) patients ($t(28) = -0.19$, $p = 0.85$, t-test for log transformed continuous variables). Data regarding the effect of brain lesion site on collision avoidance are reported elsewhere (Papageorgiou et al., 2011).

3.7. Learning effect

Performance of participants over time was investigated, in order to find out if participants decrease their collision rate over time. A learning effect was revealed for both patients and control subjects only in density 75%. The learning effect is exhibited in Fig. 9. The learning effect was not influenced by age and gender (data not shown).

4. Discussion

The goal of this study was twofold. First, it was designed to examine differences in performance between patients with HVFDs and normal-sighted control subjects in a collision avoidance task with moving obstacles. Second, we aimed to investigate the impact of the extent of the HVFD on collision avoidance, with the hypothesis that performance would not be solely explained by visual field-related parameters. Therefore we expected contribution of additional factors, e.g. age, gender, side of brain lesion and time span since lesion onset. We have examined a large homogenous patient group (regarding cause of HVFD) in comparison to an age-matched control group under standardized, repeatable VR-conditions.

4.1. Effect of HVFD

As hypothesized, subjects with HVFDs had on average more collisions than subjects with normal vision and in density 75% they experienced more collisions with vehicles approaching from the blind side than the seeing side. Additionally, in density 75%, the number of collisions on the seeing side of subjects with HVFDs was similar to the number of collisions experienced by normal subjects. In the easier task (density 50%) differences in collision rates between the blind and seeing hemifield were not obvious probably due to decreased visual and cognitive demands. These results suggest that patients with HVFDs are less efficient and experience difficulties in collision avoidance under VR-conditions, and are partly in accordance with a recent study of Bowers et al. (2009). They examined the effect of HH on detection of pedestrian figures within the controlled environment of a driving simulator. They concluded that detection rates of HH drivers for pedestrians on the blind side were significantly lower than detection rates for pedestrians on the seeing side and were significantly lower than those of drivers with normal vision. However, the experimental task in the study of Bowers et al. (2009) included detection of stationary pedestrians. Therefore the authors assumed that this may have resulted in lower detection rates than if the detection 'target' had been a moving car. In the present study, moving vehicles at an intersection were used in order to achieve more realistic circumstances in terms of collision avoidance. For this reason probably performance differences between patients and normal-sighted subjects were not as large in our sample as in the study of Bowers et al. (2009). Therefore, our results suggest that patients with HVFDs may achieve better ratings on collision avoidance tasks with moving obstacles than on detection of stationary targets at intersections. This may be related to the Riddoch phenomenon of statokinetic dissociation, whereby patients perceive moving but not static objects (Schiller et al., 2006). Statokinetic dissociation is often noted in recovering occipital lesions and has been commonly attributed to preserved islands of function within the occipital cortex. Variable degrees of dissociation of perception between moving and nonmoving stimuli have been also demonstrated in normal subjects and in patients with compression of the anterior visual pathways (Safran & Glaser, 1980). An additional explanation is provided by the division of the retino-cortical projection in two parallel pathways, the parvo- and the magno-cellular system (Nassi & Callaway, 2009). Magno-cellular neurons predominate in retinal periphery and are believed to mediate fast flicker and motion detection (Merigan, Byrne, & Maunsell, 1991; Merigan & Maunsell, 1990). Therefore, peripheral vision is much more sensitive to flicker perception than foveal vision, and this phenomenon might underlie our findings as well (Chapman, Hoag, & Giaschi, 2004; Schiller, Logothetis, & Charles, 1990).

Our findings cannot be directly contrasted to the results of Bowers et al. (2009), because the task requirements and the expected responses are different. In the study of Bowers et al. (2009) the subjects had to indicate detection of pedestrians by honking the car horn without any time constraints (i.e. even after they completed a turn at an intersection). At the same time they had to steer the virtual vehicle and operate all vehicle controls. We rather investigated subjects' ability to detect moving obstacles and avoid a collision in a strictly timely manner. Estimates of collision avoidance involve primarily perception of time-to-contact (Lee, 1976), i.e. the amount of time before a perceived object would reach the observer, the ability to detect the potential collision object and switch attention towards it, the ability to determine an appropriate avoidance response, and the ability to actually control the vehicle to avoid the collision under continuous demand on working memory (Horrey et al., 2007; Olson, 2002). Therefore, we did not offer the possibility of bringing the vehicle to a halt at the intersection. At most intersections without traffic lights, drivers would normally slow down on approach to the intersection and make a gap judgment either as they were slowing down (yield sign) or from a stationary position (stop sign). They would then choose an appropriate speed and time point at which to go through the intersection. While the inability to stop the vehicle might be a limitation in the study design, it was adopted in order to investigate how subjects perform in time-constrained collision avoidance situations and to quantify performance as the number of collisions by eliciting a "forced choice response."

One might argue against the choice of collisions as a measure of performance, because collisions are relatively infrequent events in real-world situations; however, intersections are challenging even for normal subjects (Bowers et al., 2009) and the available period to react, namely to perceive the size of the gap in terms of time to act (Simpson, Johnston, & Richardson, 2003), is not always unlimited – even in real world. In 2007, at least 22% of fatal accidents in the USA occurred at intersections (Fatality Analysis Reporting System Encyclopedia, 2007). Injury accidents at intersections account for 41.2% in Germany, which is quite close to the European median (43%), and 50.1% in the UK. This is due mainly to the fact that accident scenarios at intersections are among the most complex ones and different categories of road users interact in these limited areas with crossing trajectories (Cooperative Intersection Safety, 2009).

The presence and extent of the HVFD, expressed as a lower area of sparing in the affected hemifield (A-SPAR) or in the central 30° of the affected hemifield (A-30-SPAR), is associated with worse performance in the present collision avoidance task. This is additionally illustrated by the finding that patients with hemianopia displayed worse performance than those with quadrantanopia (Fig. 5). The negative correlation of A-30-SPAR with the number of collisions was stronger than that of A-SPAR, indicating that the central visual field is more relevant for collision avoidance under VR-conditions. This finding is in agreement with recent European standards for the visual field of drivers, stating that no defects should be present within the central 20° for holders of ordinary driving license, or within the central 30° for heavy goods vehicle and public service vehicle licence holders (Changes to Annex II of the 2nd EC Directive on Vision and Driving, 2011). These field values are based on the observation that this area is of particular importance for visual perception during driving (Schiefer et al., 2000). However, the weak relationship between A-SPAR or A-30-SPAR and the number of collisions, as shown by the slope of the regression curves (Fig. 7), suggests that perimetric findings per se are inadequate in predicting collision avoidance among patients with HVFDs under VR-conditions. Few studies have assessed the impact of the extent of the HVFD on performance by using different performance measures and study designs. Hence, comparing our results with previous findings may only provide indicative data. In agreement with Racette and Casson (2005) we concluded that hemianopia tended to have a worse impact on driving performance than quadrantanopia, while quadrantanopic drivers did not differ in their performance from normal-sighted subjects (Fig. 5). Furthermore, in the present study 23 out of 30 patients with HVFDs (76.7%) performed within the range of normal subjects in both difficulty levels, if the outlier normal subject with excessively high collision rates is excluded (Fig. 4). These findings are consistent with a recent on-road study (Wood et al., 2009), where 88% of quadrantanopic patients and 73% of patients with HVFDs received safe ratings (Wood et al., 2009). On the other hand, our results appear to be at odds with the on-road studies of Tant et al. (2002) and Kooijman et al. (2004), because in these studies subjects had been referred due to suspected driving safety concerns.

4.2. Variability among patients with HVFDs and among various studies

The predictive power of A-SPAR is additionally limited by the fact that large individual variability occurs (Fig. 6). A high degree of between-subject variability in patients with HVFDs in VR or on-road driving tasks has been reported in other studies as well, and may reflect aging processes (see Section 4.3), individual compensation capacity and working memory availability (Bowers et al., 2009; Hardiess et al., 2010; Lövsund, Hedin, & Törnros, 1991; Racette & Casson, 2005; Wood et al., 2009). Other factors that may account for the great variability in the performance of patients with HVFDs among studies are the differences in the experimental design (naturalistic tasks, virtual reality or on-road driving assessments) and the performance measures, the presence of a normal-sighted control group, the reason for participation in the study, the sample sizes and the inclusion criteria of subjects – i.e. time after lesion onset, presence of hemi-neglect (Table 1). We have tried to minimize these limitations, since our subject group was relatively large, homogenous in regard to the etiology of the HVFD and free of selection bias, there were no safety concerns and our study did not include a driving test, but an assessment of performance in a cognitively challenging task under repeatable VR-conditions. However, the observed variability highlights the need for development of a standardized, functional task which could also be used as an outcome measure in rehabilitation training programs (Bowers, Keeney, & Peli, 2008; Szlyk et al., 2005).

4.3. Age effect

Increasing age in the present collision avoidance task was associated with decreasing performance. Previous studies have reported deterioration in simulated tasks or on-road assessments with increasing age (Lövsund, Hedin, & Törnros, 1991; Szlyk, Brigell, & Seiple, 1993; Wood, 2002). However, there is little work investigating how age affects performance in time-constrained collision-avoidance situations. Bowers et al. (2009) found that older HH drivers had lower pedestrian detection rates than younger HH drivers, indicating a reduction in the ability to compensate for the field loss with increasing age. Szlyk, Brigell, and Seiple (1993) also suggested that age-related losses, when compounded by stroke-associated impairments, significantly influenced visuospatial driving-related skills. A recent study suggested that collision avoidance situations are increasingly difficult with advancing age and older adults are less efficient at perceiving an affordable gap when spatiotemporal relations are of importance (Lobjois et al., 2008). Our findings confirm these results and extend the age effect in collision avoidance tasks for patients with HVFDs as well. Interestingly, there was no interaction of age and the presence of HVFDs, thus indicating a similar (highly significant) age effect in both patients and normal-sighted subjects. Age-related changes, like a decline in cognitive abilities, a slowing down of information processing or even a deterioration of exploration ability, may probably affect object detection and subsequent reaction ability in such interactive scenarios (Ryan, Legge, & Rosman, 1998).

4.4. Learning effect

During the short-term exposure to the more challenging conditions of higher traffic density, both visually-impaired and normally-sighted participants had similar learning curves, which should be attributed to task learning.

4.5. Brain lesion

Consistent with previous findings (Bowers et al., 2009), we did not find any differences in the time span since the brain lesion between patients with "performance above average" and "performance below average". The reason is probably that our patient group was homogenous regarding cause of the brain lesion, and the time span after lesion onset was at least 6 months. Recent studies suggest that 6 months postinjury is the time span after which spontaneous recovery of visual field is unusual following vascular lesions, when patients have adapted a different compensatory eye movement strategy (Pambakian et al., 2004; Zhang et al., 2006).

Concerning the side of the brain damage, one might expect that patients with right-hemispheric lesions would perform worse, presumably because of a higher incidence of visuo-spatial deficits like neglect (Korner-Bitensky et al., 2000; Meerwaldt & Van Harskamp, 1982). However, no differences in performance were revealed between patients with left- and right-hemispheric lesions in agreement with earlier studies (Bowers et al., 2009; Szlyk, Brigell, & Seiple, 1993; Wood et al., 2009; Zihl, 1995). This may be due to the fact that patients with clinical evidence of neglect or signs of impaired lateralized attention in the paper-and-pencil tests were excluded from the present study. Another possible explanation is that both hemispheres play equivalent roles in the spatial guidance of visual searching (Ratcliff & Newcombe, 1973; Zihl, 1995).

5. Conclusion

Our results for patients with HVFDs seem to extend the findings of a recent study on impaired detection of stationary objects (Bowers et al., 2009), to impaired collision avoidance of moving obstacles at intersections as well. However, the extent of HVFDs is weakly associated with performance in the present collision avoidance task under VR-conditions. Performance of some patients is similar to that of normal subjects, which may be attributed to the development of compensatory viewing behavior (Hardiess et al., 2010; Wood et al., 2011). Due to this wide between-subject variability, generalization of the findings regarding the impact of HVFDs is misleading and individualized approaches of compensatory functional behavior of patients with HVFDs are necessary. In future studies we will attempt to find predictors of visual compensation in realistic tasks and measure not only the extent of the visual field defect, but also the extent to which impaired individuals adopt compensatory viewing strategies. Assessment of visual exploration (head and eye movements), functioning in everyday life and multimodal approaches (performance in different tasks) may play an important role in determining the visual capacities of patients with homonymous field loss (Hardiess et al., 2010; Wood et al., 2011).

Disclosure

Ulrich Schiefer is consultant of HAAG-STREIT, Inc., Koeniz, Switzerland, he holds patents, related to the semi-automated kinetic perimetry.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.visres.2011.10.019.

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