Restorative Neurology and Neuroscience 26 (2008) 365–375
IOS Press

Properties of the regained visual field after visual detection training of hemianopsia patients

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Abstract. *Purpose:* To study the quality of the visual field areas that were regained after training. In those areas, we measured some of the elementary visual properties that make up the quality of visual functioning in daily-life. This was to provide information about whether the functional visual field had been enlarged.
Methods: Patients with visual field defects after a CVA were trained to detect stimuli presented in the border area of the visual field defect. Then, in the regained areas, we measured visual acuity as a measure for *spatial properties*. Secondly, to assess for *temporal properties* we measured critical flicker frequency (CFF). Finally, we studied color vision as a third property of the regained areas.
Results: Since we could not predict where restoration of visual fields would occur, we did not present pre-post comparisons. However, despite the fact that training was carried out with simple white light stimuli, we could assess acuity, CFF and color vision in the regained areas. The performance of the patients during testing of the elementary properties appeared to be almost normal when compared to control subjects and comparable to the patient's own ipsilesional visual field.
Conclusions: These results support the idea that the regained visual fields that emerged after training are actually used for processing additional visual stimuli other than those used during training.

Keywords: Cerebral blindness, visual quality, visual training, rehabilitation, recovery

1. Introduction

Cerebral blindness is a condition in which a person suffers from visual field defects due to damage in the brain. Often, the consequence is a *homonymous hemianopsia* in which half the visual field is affected in both eyes. In the last decade, visual restoration training has been proposed as a method for visual field enlargement and a substantial number of studies show that this training can lead to enlargement of the responsive visual field (e.g. Julkunen, 2003; Kasten et al., 1995; 1998a,b, 1999, 2000, 2001, 2006; Poggel et al., 2001, 2004, 2006; Sabel et al., 2000, 2005; Werth & Moehrenschlager, 1999; Zihl & Von Cramon, 1979; Zihl, 1990). In our own studies, we also found that visual detection training resulted in partial recovery of affected visual fields (Van der Wildt & Bergsma, 1998; Bergsma & Van der Wildt, 2000). However, other studies could not confirm these findings: visual field enlargements after visual restoration training were not found (Reinhard et al., 2005) and the virtues of the training are therefore still not uniformly accepted (Horton 2005a,b; Plant 2005). Saccadic eye movement training has also been applied as a method for expanding the visual field (Nelles et al., 2001; Zihl, 1981, 1995, 2006; Zihl & Von Cramon, 1986) and again, some researchers could not confirm visual field enlargement (Zihl & Von Cramon, 1986; Zihl, 1995).

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For implementation of visual training in a rehabilitation setting, it is important to know what the visual quality is of the visual field parts that have been regained after visual detection training. This quality is relevant for defining the usefulness of these regained visual fields in daily-life situations and thus the degree of visual rehabilitation after training. For example, in addition to describing field enlargements after training, researchers have also studied transfer of vision restoration training effects to color and form perception. In particular, Kasten and co-workers described this transfer to form and color perception in detail (Kasten et al., 1998, 1999, 2000; Poggel et al., 2001). Pothoff (1995) described how training with specific stimuli (color, white light and gratings) leads to field enlargements for those specific stimuli. The goal of the present study was to obtain evidence of the possible usefulness of a regained visual field area after training, using a Goldmann perimeter to define the recovered fields. We therefore studied three elementary visual functions in the regained areas of three trained patients. These were: (1) visual acuity, as a measure of *spatial* resolution of the visual system, (2) critical flicker fusion, as a measure of *temporal* resolution of the visual system and (3) color identification.

2. Methods

2.1. Subjects

Experimental subjects (patients) were all volunteers that were screened only to the degree that they had a visual field defect as a consequence of their brain damage and that they did not have other, confounding disabilities that rendered training impossible, such as sensory aphasia or visuo-spatial neglect (assessed with the Line-bisection task). Color vision was unaffected by the lesions, as confirmed by the fact that the 4 test colors could be correctly identified both in the ipsilesional field and the spared areas of the contralesional field.

Control subjects were six healthy individuals: 4 males and 2 females (Table 1). Control subjects are denoted as C1 to C6.

2.2. Training

Training was carried out monocularly, because we wanted to be able to monitor fixation visually. To do so, one eye had to be placed centrally in the perimeter so that it is visible to the experimenter. We also needed to train monocularly so that blindspot mapping could serve as a calibration of central eye fixation. Training took 30 minutes for each eye. Patients were trained by repeated trials of detection threshold measurements in the affected parts of the visual field. For presentation of stimuli a manually operated Goldmann perimeter was used, so that the stimuli could be presented very precisely on fixed retinal locations. Training on a Goldmann perimeter also provided for continuous monitoring of patient reports about visual perception of stimuli during all training sessions. Finally, the Goldmann perimeter is considered a standard in detecting visual field defects in cases of hemianopsia, glaucoma and macula degeneration (Mills, 2007; Riemann et al., 2000; Smith and Baker, 1987; Stewart, 1995; Wong and Sharpe, 2000).

The stimulus, presented against a white background, was a white, circular shaped patch (diameter = 1 degree of visual angle). The luminance of the background was set at a standard 31.5 asb. ($\approx$10 cd/m^2). The luminance of the stimulus was increased with steps of 0.1 log unit change, starting with a luminance increment of 12.5 asb. ($\approx$4 cd/m^2) up to an increment of 1000 asb. ($\approx$318 cd/m^2). Patients had to respond whenever a peripherally presented stimulus was detected while fixating centrally. Because we wanted to stimulate the affected visual field, stimulus detection was not established elaborately, e.g. by a staircase method. We did not need to know the *exact* threshold values, because these stimulations were used for training purposes. The training *effect* itself was derived from Goldmann dynamic perimetry according to the methods described by Frisén (1990). For dynamic perimetry we used Goldmann stimulus size IV with maximum luminance (4e = 1000 asb.) against a constant background luminance of 31.5 asb. The stimulus was moved from the blind field in the direction of the seeing field. Dynamic perimetry was carried out perpendicularly to the visual field border on 10 locations for patients WV and MS and was repeated 3 times on each location. For patient LV the dynamic test stimulus was moved from the periphery to the fixation point on 25 meridians in the left visual field. LV had to report the appearance, disappearance and reappearance of the stimulus. Measurements were repeated 3 times on every meridian.

It should be mentioned that Goldmann dynamic perimetry is limited due to the fact that it is prone to low inter-examiner reliability. Perimetry was carried out by one examiner, who carefully followed the perimetry-instructions laid out by Frisén (1990) and who repeated

Table 1
Subject Sample

Subjects	Sex	Age	Time since lesion	Training sessions	Damage	Type of field
1. WV	M	52	4 yrs	55	Infarct of the left a. carotis	Homonymous Hemianopia Right
2. MS	M	50	2 yrs	40	Stroke in left parietal lobe	Incomplete Hemianopia Right
3. LV	M	48	5 yrs	40	Vertebrobasilar stroke	Incongruous Hemianopia Left
4. C1	F	16	–	–	None	Healthy
5. C2	M	23	–	–	None	Healthy
6. C3	F	24	–	–	None	Healthy
7. C4	M	25	–	–	None	Healthy
8. C5	M	42	–	–	None	Healthy
9. C6	M	62	–	–	None	Healthy

the measurement 3 times at each meridian to minimize intra-examiner variability.

During the training period, fixation was monitored visually, so that visible eye-movements could be detected. Before starting perimetry, the boundaries of the blind spot were measured to calibrate the gaze direction of the patient so that we could reliably monitor fixation. After calibration, fixation deviations of 2° and more can easily be detected. Patient 1 received 55 sessions of training, patients 2 and 3 received 40 training sessions of about 1 hour respectively. These different amounts of training reflect the different moments at which training seemed to have reached its maximum effect. Training was carried out once a week. After all training sessions were completed, we measured three basic visual properties in the regained areas that had been formed in the visual field.

2.3. Testing

A. Peripheral Visual Acuity was used as measure for the spatial properties of the regained field. We could not carry out a pre- vs. post-training comparison, because it is not possible to predict prior to training which areas are likely to improve. Instead, a post-training measurement of a visual property was collected in a visual field area which had no light-detection before training. According to several researchers, training with white light stimuli improves color and form perception (Kasten et al., 1998, 1999, 2000; Poggel et al., 2001). Acuity can be thought of as form perception, so a visual field enlargement after training – which has in essence recovered white light stimulus detections in the enlarged area- could be reflected as measurable acuity (improvement) in those areas as a result of transfer of training effect. With increasing eccentricity, visual acuity decreases so quickly that after 15° it can hardly be measured. Therefore, we measured acuity in the regained area at eccentricities 2.5°, 5°, 10° and 15°. Because acuity is independent of the meridian it is tested at, we chose test eccentricities such that they were located in regained area. Peripheral visual acuity was measured under photopic conditions as a campimetric test. Single Landolt's C's of different sizes were presented binocularly on different eccentricities with a maximum of 15° in both hemifields. The center of the 'C' was placed on the test location. All 4 orientations of the 'gap position' in the C were presented. A 100% score on presentation of a 'C' led to presentation of the next test stimulus: a smaller size 'C'. The smallest 'C' of which the patient could detect the gap position in all orientations determined the acuity at the eccentricity under scrutiny. Fixation was monitored visually.

B. Critical Fusion Frequency was used as a measurement of the temporal properties of the visual system. Here, we measured the frequency at which a flickering on/off modulating white stimulus (diameter 1°) fuses into a stable stimulus. Stimulus contrast with the background was set at its maximum. This frequency was measured at eccentricities 10° 20°, 30° and 40° with increasing and decreasing frequencies. Averaging these two values determined the CFF for the eccentricity under scrutiny. Tyler (1987) showed that there are small meridional effects on CFF. Because CFF is only weakly depending on the meridian it is tested at, we chose test eccentricities such that they were located in regained area. A Tübinger perimeter was used for presentation of the stimuli. The difference that can be found between automated static perimetry (short stimulus presentations) and manual dynamic perimetry (long stimulus presentations) in showing the training effect of a single patient, gave us the impression that a hemianopic patient is not able to process very short stimulus presentations. We therefore expect that CFF will be lower on the affected side. The stimulus was presented in the regained and the unaffected areas, so the patient had to observe the stimulus peripherally.

C. Color Perception. Colored light stimuli (diameter 1°) were also presented in the regained areas of the vi-

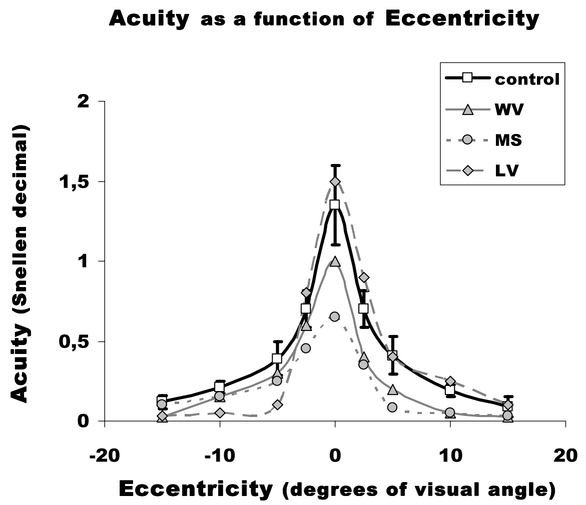


Fig. 1. Peripheral Visual Acuity. Acuity expressed as Snellen decimal. Eccentricity is displayed in degrees. The bold curve with error bars indicates the mean performance of the control subjects. The other curves indicate the performance of the patients. Eccentricities with a minus sign are in the Left Visual Field. Error bars depict 1 S.D.

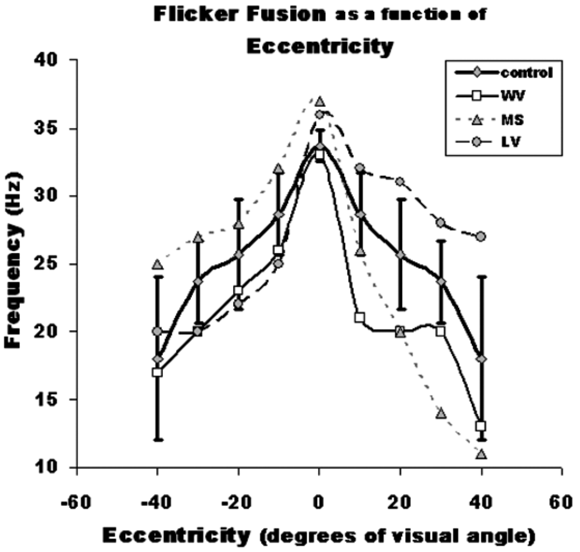


Fig. 2. Critical Fusion Frequency. Eccentricity in degrees. The bold curve with error bars indicates the mean performance of the control subjects. The other curves indicate the performance of the patients. Eccentricities with a minus sign are in the Left Visual Field. Error bars depict 1 S.D.

sual field. Test targets were circular shaped light stimuli (diameter 1° of visual angle) in the colors green, red, yellow or blue. They were presented in the regained areas. The patient had to name these colors with peripheral view. Standard color stimuli of the manual Tübinger perimeter presented with maximum luminance were used as test stimuli. Based on other investigations (Kasten et al., 1995, 1998a,b, 2000), we expect to see transfer of the white stimulus training effect to color perception. Therefore, we expect color stimuli to be identifiable in the regained areas.

For presentation of both the colored and the CFF stimuli, a Tübinger perimeter was used. *Acuity and CFF* were tested binocularly because this resembles daily-life performance more than monocular findings. Visual fixation monitoring was therefore somewhat more difficult but as can be seen in figures 1 and 2, both the acuity curve and the CFF curve have their maximum at the fovea, suggesting that fixation was carried out properly. Although training was carried out monocular, test locations were chosen such that the stimuli were presented in both monocular measured regained visual fields. *Color identification* was tested monocular. Because color identification is difficult to quantify, the only way to present the results is to place them in the graphs of the patients' visual fields. For obvious reasons, it was therefore necessary to measure patient LV monocularly. We did the same with the other two patients, but in their case, both monocular findings were virtually identical: here, the monocular fields closely resemble the binocular fields.

2.4. Control measurements

The results of the measurements of the three basic visual properties in the regained fields were compared with measurements of the same visual properties in the contralateral, unaffected visual field. So the patients were their own control subject, which enabled a perfect match. The results are also compared with the performance of 3 healthy control subjects (C1, C4 and C6) in the case of Critical Flicker Fusion, and to the performance of 6 healthy control subjects (C1–C6) in the case of Peripheral Visual Acuity (see Table 1). The ages of the control subjects are spread out from 16 to 62. It could be argued that age-effects make comparison troublesome. Klein et al. (1996) show in their study that decreased visual acuity (20/40 to 20/200) is a common finding among individuals older than 75 but persons of 43–54 years have 78 times *less* chance of the same decreased visual acuity. A study of Attebo et al. (1996) mentions decreased visual acuity in 0.8% of individuals between 49 and 54 and in 42% of individuals older than 85. A thorough study of Frisén and Frisén (1981) considers all ages between 11 and 75. Their data suggests that acuity declines from the age of 25. This decline is 0.3 (Snellen decimal) between 25 and 60 years. Only after the age of 60 the decline was steeper. All control subjects and patients in this study have central acuity of 0.7 or higher, so we do not need age-correction and we assume they can be compared. Essentially, the same applies to CFF: in a study population of 130 subjects, aging 9 to 86, the mean CFF of a stimulus with 1° diameter changed from 34 Hz to 31 Hz. Around age 60, these values are still at 33 Hz (Lachenmayr et al., 1994). Tyler (1989) showed that there is a clear age-effect for contrast-sensitivity in flicker perception, especially for the higher frequencies. In our test, the stimulus was set at the maximum luminance and was flickered on-off (100% modulation depth) so that this age-effect for sensitivity is minimized. Age-effects cannot be ruled out, however. As can be seen in Figs 1 and 2, the control measurements are averaged into one curve. The average age of the control group is 32 years. Since our experimental subjects are 48, 50 and 52 yrs, respectively, one could argue that the performance of the subjects is actually somewhat underestimated when compared to the control group. We therefore argue that our control subjects, however widespread in age, can be used for comparison with our patients.

In color perception, increasing age can lead to confusing colors (white/yellow, purple/dark red, dark blue/black). However, our patients were all able to correctly identify the colors used in their unaffected field. In this variable, patients serve as their own control.

3. Results

3.1. Peripheral visual acuity

Because it is an important measure of general visual functioning, we chose peripheral acuity as first measure of regained visual field quality. As mentioned in Methods, acuity was measured binocular because it resembles daily-life performance more closely than monocular testing. The peripheral acuity performance of patients **1** (WV), **2** (MS) and **3** (LV) are shown in Fig. 1. The solid line with the error bars depicts the mean performance of 6 control subjects (C1–C6). The size and location of the regained visual fields are shown in Figs 3–5 as gray areas.

Figure 1 shows that the acuity performances of the patients are comparable to the performance of the control subjects when central acuity and peripheral acuity in the unaffected visual field are considered. Peripheral acuity values in the hemianopic visual are significantly lower than normal peripheral acuity, as can be seen by the error bars of the control measurements. These asymmetries in the patient curves show that acuity in the regained visual fields is clearly not comparable to normal acuity and that it is also worse than the premorbid performance, as shown by the acuity values on the unaffected side. However, acuity could reliably be measured in the regained areas, implying that these areas can be used for (rudimentary) form-perception.

3.2. Critical fusion frequency

The second variable, CFF, gives an impression of the temporal characteristics of the regained areas. Figure 2 shows the CFF-performance of the 3 patients and the performance of subjects C1, C4 and C6. The curves show at what frequency a flickering stimulus fuses into a stable, non-flickering stimulus at different eccentricities.

As with peripheral acuity, the CFF performance of the patients is comparable to the performance of the control subjects when central CFF and peripheral CFF in the unaffected visual field are considered. In the affected visual field the CFF values are significantly lower than normal, as can be seen by the error-bars. As with acuity, these asymmetries in the patient curves mean that performance in the regained visual fields is not comparable to normal performance, which is based on the performance on the unaffected side and the performance of the control subjects. So, a CFF could be measured in the regained areas, implying that these areas can be used for processing fast changes in visual information, but not as quickly as in normal vision.

3.3. Color perception

Another possibility to qualify visual performance in the regained areas after training is to observe the ability to recognize colors in those areas. Patients had to identify the stimulus color that they perceived while fixating centrally. These verbal responses were compared to the reports of the same patient of stimuli presented in the contralateral stimulus locations. The reason for this is that at a certain eccentricity the perception of colors changes, and this is also true in healthy subjects. However, because this distance can vary from one person to the next, the comparison between the two conditions had to be carried out for each subject individually.

In Figs 3–5, the gray areas are the regained areas. In these areas, colored stimuli were presented at the end of the training period. Test colors were presented on 5 different days. The locations at which the colors were

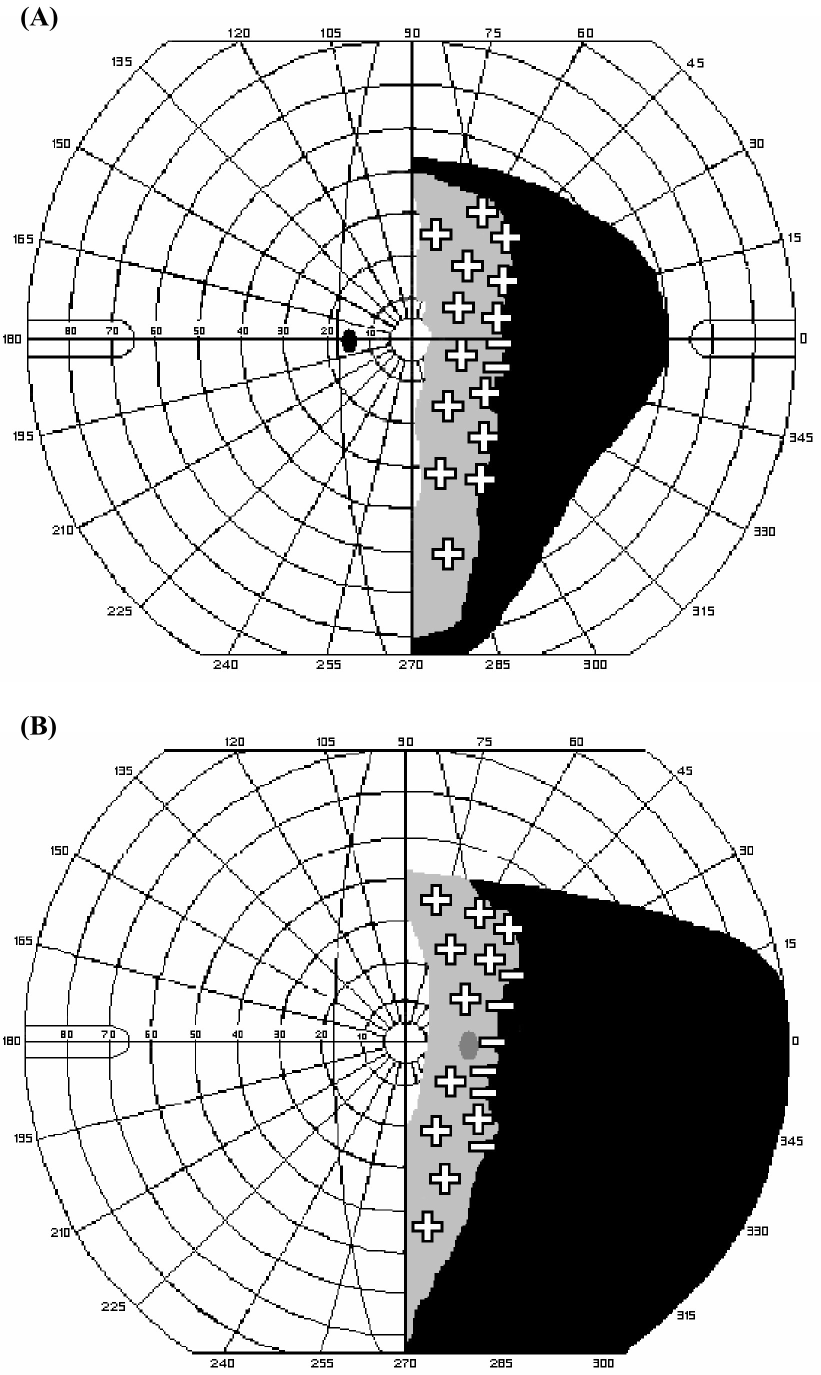
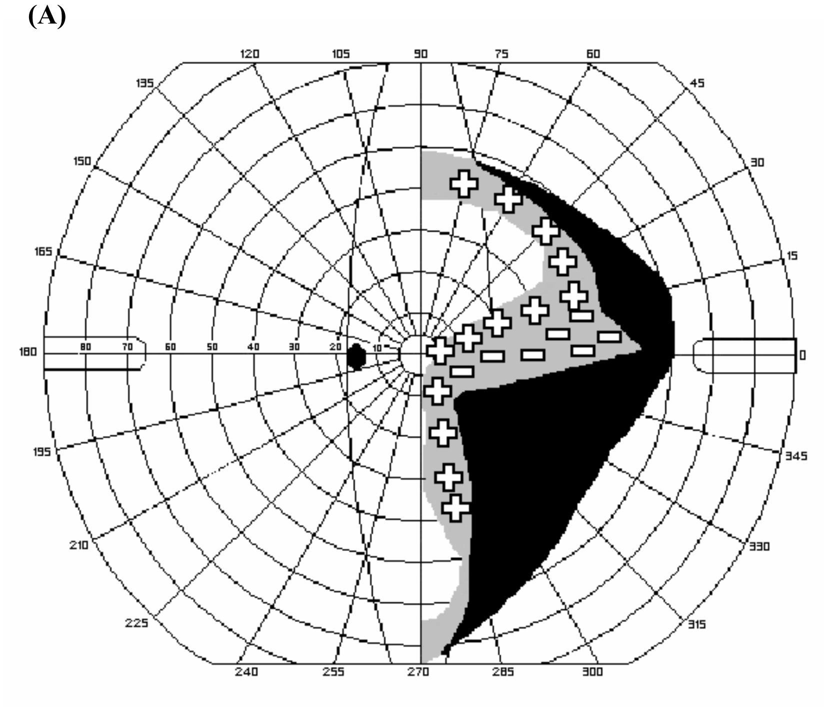


Fig. 3. *Patient WV*. Figure 3a: OS (left eye). Figure 3b: OD (right eye). Black areas: absolute defect or non-responsive areas after training. Gray areas: regained areas after training. '+': normal color perception. '−': impaired or absent color perception.

presented were unchanged within each subject but differed between subjects depending on their visual field size. The '+'s indicate locations with normal color perception as compared to control measurements. Normal color perception means that 100% of the stimulus presentations were identified correctly. In the locations, 100% of the presented stimuli were detected, but color perception was impaired (patients report yellow and

(A)



(B)

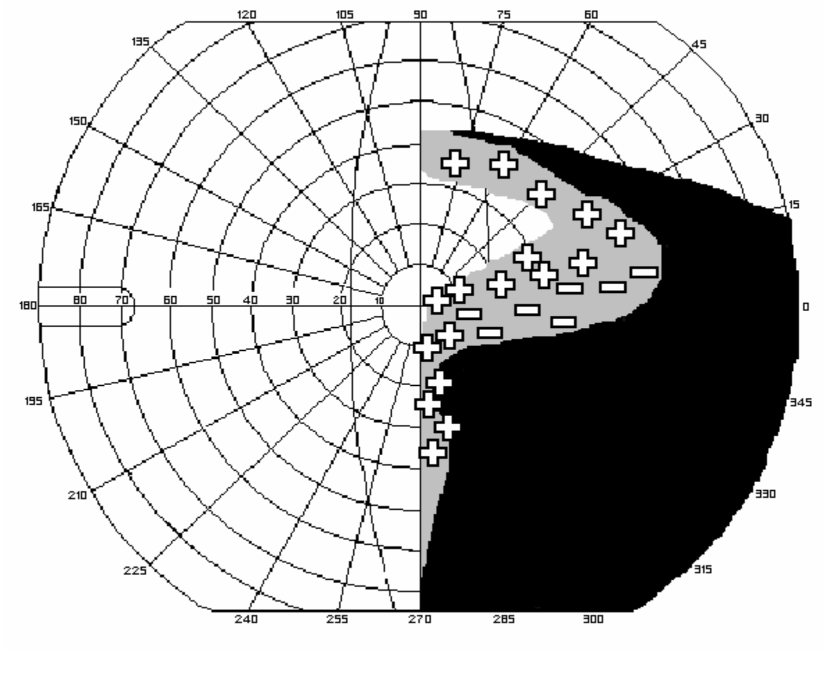


Fig. 4. *Patient MS*. Figure 4a: OS (left eye). Figure 4b: OD (right eye). Black areas: absolute defect or non-responsive areas after training. Gray areas: regained areas after training. '+': normal color perception. '−': impaired or absent color perception.

green to be white, red as orange or yellow, blue can be seen as dark green) or absent (stimuli are gray or 'have no color'). The fact that patients reported these aberrant colors implies that they did not give their response on the basis of non-equiluminance of the test targets.

Figure 3 shows the color identification of patient WV.

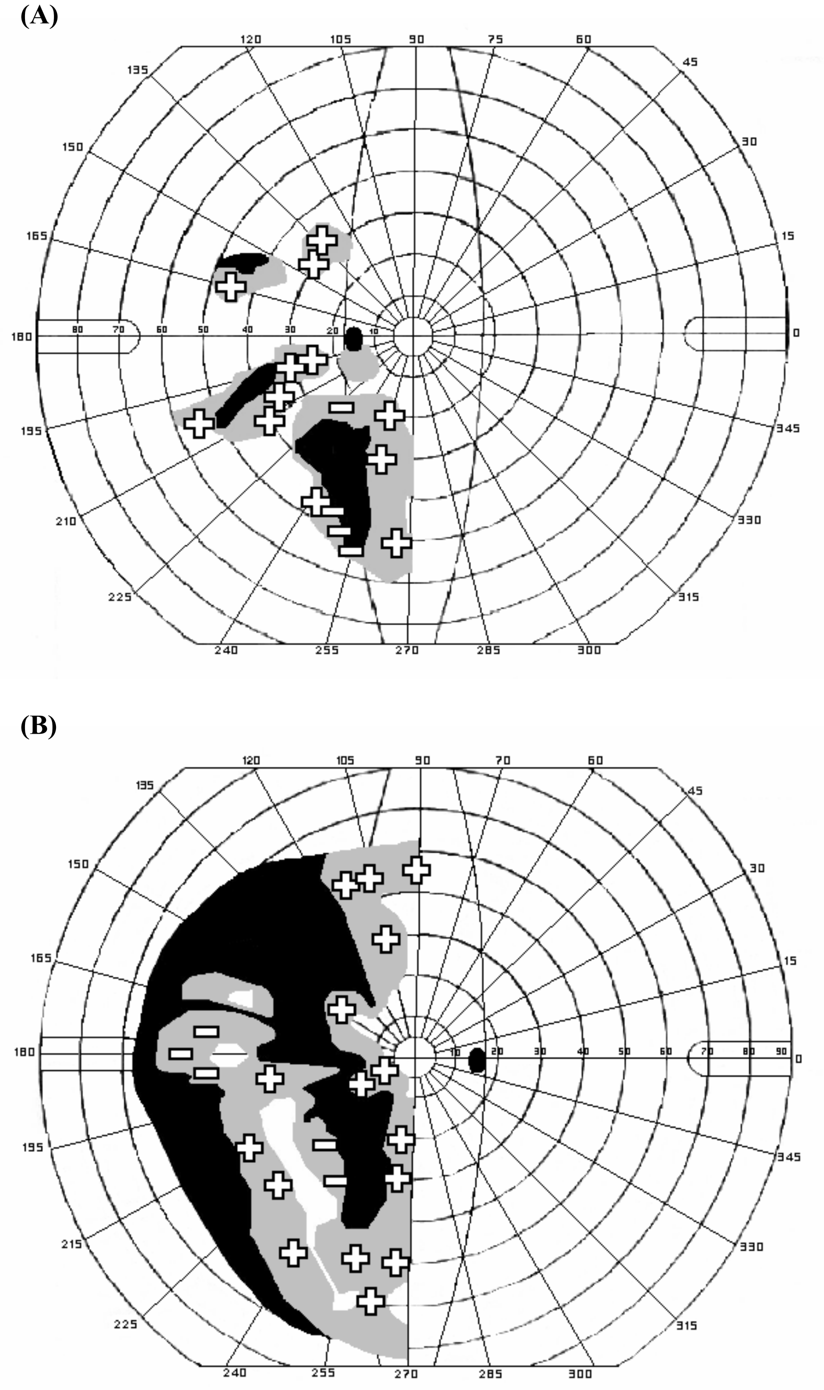


Fig. 5. *Patient LV*. Figure 5a: OS (left eye). Figure 5b: OD (right eye). Black areas: absolute defect or non-responsive areas after training. Gray areas: regained areas after training. '+': normal color perception. '−': impaired or absent color perception.

As can be seen, most stimuli are identified correctly. Only those stimuli that were presented near the visual field border with the blind area were identified incorrectly (stimuli were reported to be perceived as white or 'grayish white'). So while the performance in the regained areas is not as good as it is in the unaffected areas, it is comparable, and for the most part the area can be used for color identification.

Figures 4a and 4b show the color identification results of patient MS. Here, a part of the regained field after training revealed a peculiar characteristic: in this area, patient MS could never *decide* if a stimulus had been seen or not. As a consequence, neither a positive nor a negative response was given. This concerns the regained area where '−'s are shown. The '+'s in the rest of the regained fields depict normal color recognition. However, when patient MS was urged to respond quickly his responses showed great improvement: colors were named correctly in more than 75% of the trials. To the perception of patient MS, however, these responses seemed to be unreasonably wild guesses since there was 'no information to work with'. So, patient MS showed improved performance on the basis of unaware visual information, or 'agnosopsia'. Unfortunately, the unawareness of the visual information made it impossible for patient MS to learn to respond to it, and '−'s remained the result in this part of the regained visual field.

As can be seen in Figs 5a and 5b, patient LV has a very irregular visual field: an incongruous hemianopsia. Figure 5a shows the left eye (OS), 5b the right (OD). Again, *black* areas are absolute visual field defects, in which the patient does not respond to the stimuli used. The *gray* areas are the regained areas after training. There are actually only two areas in OD and OS that show '−'s. In the majority of the regained area, color perception is normal.

4. Discussion

In our study of visual restoration training effects on the size of the visual field we found that the visual field border between the intact and the defect visual field shifts into the direction of the defect after training, i.e. our study confirms that the training can enlarge the visual field. In this paper we describe the degree to which the visual field area that is regained by training can be used for visual functioning. The visual field was enlarged with the use of white light stimuli and the transfer of training effects to the perception of other stimuli was tested. This quick glance into the visual quality of the regained areas should give us a general insight in their degree of usefulness. How this usefulness is related to improved visual functioning in daily life should be answered by using additional questionnaires or real-life observations.

We described 'visual quality' in terms of three basic visual properties, namely *spatial properties* (peripheral acuity), *temporal properties* (peripheral CFF) and *color perception*, and found that the performance of the patients for these functions was significantly impaired compared to control measurements. However, these properties were of such quality, that one could argue that visual functioning in these areas is more than just detection of contrast or contrast differences (the training stimuli): patients can distinguish different colors, see fast movements and show peripheral acuity with a resolution that is large enough to be useful in daily-life practice. These results support the idea that the functional visual field is actually expanded by this training, because these three functions are well measurable in the visual fields that were regained after training, while there was no response to pre-training presentations of stimuli in the same visual field areas. In other words, the training produces a visual field that could well be used in daily life.

Since in all measured functions there is an asymmetry across the visual hemifield, performance on these measures is clearly not exactly the same as the assumed pre-morbid levels (as measured in the non-affected visual field), or as the control measurements. However, the presence of visual functioning in the regained areas, albeit diminished, could be enough to support general visual behavior. As long as there is a peripheral signal, the patient could turn eyes, head and attention towards the signal, so that it can be processed with central vision.

It also became clear that, although the type of visual field defect was varying, a training effect was found in each patient. Also, after training there appeared to be transfer of training effect to the perception of other test stimuli. An explanation for these observations could be that the patients are learning something during training that has an effect on other perceptional processes. Visual attention could be the mechanism that is trained, with the perception of form, color and movement improving because of it. It is known from literature that directed visual attention improves detection of stimuli that are presented in the transition zone between the unaffected and the blind area (cued VRT) (Poggel et al., 2004, 2006). In this paper, the authors propose that "top-down signals preactivate partially damaged areas of V1 (. . .) with the effect of permanently increasing conscious visual perception". This principle may also apply to other stimuli than white light targets: during training, attention is forced to be focused on the transition area (where visual input is kept subconscious before training because all attention is directed to the healthy visual field) and, as a consequence, the visual input is processed to get a conscious impression of the transition area. This information can now reach higher cortical areas again, making form and color recognition possible (Kasten et al., 2000). This same principle could also explain why there was a lack of training effect with some patients (and thus no transfer effects). If there is little or no transition zone, then the top-down mechanism of improved attention will not have many partially damaged areas in V1 to reactivate, and no or little conscious visual perception will be permanently increased.

It is interesting to corroborate our results by administering tests that appeal, amongst others, to visual attention (e.g. visual search tasks; judgment of peripherally presented stimulus parameters). For example, patients with homonymous field defects often show defective visual scanning behavior. This can have its origin in parieto-occipital lesions (Werth & Moehrenschlager 1999), which are also liable to cause attentional disturbances. Improved visual attention, induced by the visual restoration training method, could then have a positive effect on scanning behavior. Also, field defect related reading problems could be diminished after training because of increased visual attention capacity. Visual field enlargement can provide the patient with previously inaccessible information about the location and length of words to the right of the fixation point. This could enable the patient to anticipate fixations more efficiently and read a line with less and larger saccades. More information to the left of the fixation point can enable the patient to read the beginning of words without having to skip back (regressions) and to find the beginning of a new line faster. These variables can be measured before and after training, without actually rehearsing them.

Although improving visual attention seems a plausible explanation for the training effect, it is also interesting to think of other forms of brain plasticity as the underlying mechanism of a growing responsive visual field (Johansson, 2000). Partially surviving neurons near the lesion could account for plasticity because their receptive fields may change their location and size following injury (Sabel & Kasten, 2000) or could enlarge their refinement in information processing (Kasten et al., 1999). Reorganization of neuronal networks may be involved, including axonal sprouting or increased synaptic efficacy, both at low level visual areas as at higher-level attention related areas (Sabel & Kasten, 2000). Finally, improved visual attention *itself* could also be seen as brain plasticity. In any case, if surviving brain tissue is compensating for the loss of function, or if some other form of functional reorganization is taking place, then functional magnetic resonance imaging (fMRI) before and after training can produce interesting results. Recently, a study performed by Marshall et al. (2007) identified brain regions in which altered brain activity could be associated with a shift of attention to the trained borderzone after visual restoration training (VRT). The alteration in brain activity was measured after a month of VRT, a period that normally is too short to display an effect in the visual field. So, no visual field enlargements were associated with the change in brain activity. Therefore, in a new study we include fMRI measurements before and after training.

Acknowledgements

The work described in this paper was made possible by the financial supports that were granted by the following Dutch foundations:

Hersenstichting (proj. 9F01.20); **Stichting RVVZ** (proj.doss.795); **Stichting NUTS-OHRA** (proj. SNO-T-08-30) and **Stichting Blinden-Penning**.

We like to thank patients WV, MS, LV and the control subjects for their voluntarily participation.

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