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Low-level phenomenal vision despite unilateral destruction of primary visual cortex

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Running head: Phenomenal vision without V1

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Abstract

GY, an extensively studied human hemianope, is aware of salient visual events in his cortically blind field but does not call this 'vision'. To learn whether he has low-level conscious visual sensations, or whether instead he has gained conscious knowledge about, or access to, visual information that does not produce a conscious phenomenal sensation, we attempted to image-process a stimulus s presented to the impaired field so that when the transformed stimulus $T(s)$ was presented to the normal hemifield it would cause a sensation similar to that caused by s in the impaired field. While degradation of contrast, spatio-temporal filtering, contrast reversal, and addition of smear and random blobs all failed to match the response to a flashed bar s_f, moving textures of low contrast were accepted to match the response to a moving contrast-defined bar s_m. Orientation and motion direction discrimination of the perceptually matched stimuli (s_m and $T(s_m)$) was closely similar. We suggest that the existence of a satisfactory match indicates that GY has phenomenal vision.

Introduction

A lesion that destroys the striate cortex (V1) produces a visual field defect in the contralateral hemifield. Its extent is perimetrically mapped by asking the patient where a visual target is visible, and its density is assessed by varying the intensity or contrast of the target and asking the patient whether or not it is detectable within the defective area. An absolute defect is one in which the target cannot be (consciously) seen at any intensity below a 'straylight detection threshold'; stimuli of higher intensity can be detected on the basis of intra- or extraocular light scattered into the normal visual field. In contrast, vision in a relative defect does not depend on straylight visible in the normal field. This residual vision is conscious but thresholds are increased relative to the normal visual field, and transients such as on- and off-sets, flicker and fast motion are exclusively, or more readily, detected than stationary targets (Riddoch, 1917).

GY, the subject of this study, has suffered destruction of his left visual (striate plus extrastriate) cortex, which caused a hemianopia with up to 4° of macular sparing (Fig.1). GY is the most extensively studied hemianopic patient to date (e.g. Azzopardi & Cowey, 1997; 2000; Barbur *et al.*, 1980; Benson & Blakemore, 1998; Brent *et al.*, 1994; Finlay *et al.*, 1997; Guo *et al.*, 1998; Kentridge *et al.*, 1999; Morland *et al.*, 1996; 1999; Weiskrantz *et al.*, 1995; 1999). Interestingly, he not only shows implicit processing of visual information, being able to detect and discriminate a variety of visual features without being consciously aware of them, but is aware of salient visual stimuli, for instance fast moving or high-contrast targets (Barbur *et al.*, 1980; Weiskrantz *et al.*, 1995; Zeki and ffytche, 1998), even when these cannot produce any detectable scatter in the normal field. His hemianopic field is thus relatively blind, challenging the assumption that all residual conscious vision requires residual V1 (striate cortical) activation. Indeed, no such activation has been detected with Positron Emission Tomography (PET) (Barbur *et al.*, 1993) or functional Magnetic Resonance Imaging (fMRI) (Baseler *et al.*, 1999; Goebel *et al.*, 2001; Kleiser *et al.*, 2001; Sahraie *et al.*, 1996), and two groups have used fMRI on GY in attempts to differentiate between the neuronal basis of blind and residual conscious vision (Sahraie *et al.*, 1996; Zeki & ffytche, 1998).

In view of the many reports published on GY's residual visual capacities, the far-reaching conclusions drawn from them, and the general interest in the architecture and neuronal basis of conscious vision, we thought it worthwhile to investigate whether GY's residual conscious vision is phenomenal, giving conscious visual qualia. GY himself has always been reluctant to call his visual functions 'seeing', and says that he is aware of something happening in his defective hemifield, but that this experience is not 'seeing' (see for instance Morland *et al.*, 1999; Weiskrantz *et al.*, 1999). A possible interpretation is that his residual capacity is too much altered quantitatively and/or qualitatively for him to want to call it 'vision'. In this case, it would still be phenomenal vision, but of an unusual, probably low-level kind. Alternatively, GY's early lesion and long-term experience with tests of residual visual functions in his hemianopic field could have created a situation that allows him to consciously access the visual information from the impaired field, and thus know whether or not something is happening, but not to have a phenomenal sensation. The latter alternative reflects a differentiation of phenomenal ('P') and access ('A') consciousness (Block, 1995; 1996; Nelkin, 1996).

To learn whether GY's residual vision constitutes an example of conscious access to visual information which is not phenomenally represented, we attempted to image-process a stimulus *s* which was detectable in the impaired field, so that when shown in the transformed version *T(s)* in GY's normal hemifield it would evoke a similar sensation[1]. The rationale was that if any such stimulus could be found this would imply that GY's residual vision was phenomenal because normal veridical conscious vision always is P-conscious. In contrast, if GY had no phenomenal vision in his defective field but instead has gained conscious access to visual information not phenomenally represented (A without P), no

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[1] Note that such a match is not sufficient for the transformation T to be identified as an operation implemented somewhere in GY's brain.

transformed visual stimulus ought to produce a response similar to that from the defective field.

Methods

Patient and Visual Field Perimetry

GY, born in 1956, was involved in a traffic accident at the age of 8 years. A lesion destroying the left occipital cortex followed upon a severe craniocerebral trauma. MRI scans show that it affects the striate cortex as well as surrounding extrastriate cortex. The homonymous hemianopia to the right with a 3-4° macular sparing is shown in Fig.1a and b. The plots represent the results of static perimetry with a 116', 200ms, 320 cd/m2 white stimulus which would appear at closely spaced positions (centre to centre distance 1°) along the 90, 105, 130, 145, 160, 175 and 180° meridians. Each presentation was indicated by a click. In independent test series the subject was asked to press a button when he 'saw' the target (Fig.1a) or when he 'was aware' of the target (Fig.1b). Only the instruction - 'press when you see something', and 'press when you are aware of something' differed between the series. Nevertheless, the difference between the resultant plots (Fig. 1 a, b) is striking. While that in Fig.1a is largely similar to the one published by Barbur *et al.* (1980), the 'field of awareness' extends well into the impaired hemifield. The difference illustrates the problem we here address, whether GY has a phenomenal sensation when he indicates that he is aware of the target but does not see it.

Please insert Figure 1 about here

Stimuli and Procedure:

1. Perceptual Matching

Three series of tests were conducted. In the first, we used a flashed bar (s_f) as stimulus for the impaired field. In the later series, it was replaced by a moving bar (s_m). Throughout, the subject fixated a fixation spot that was displaced horizontally to the left or to the right of the monitor's centre where all stimuli were presented. Viewing distance was 57 cm in the first and 25 cm in the later tests. Ambient-light intensity was 0.3-0.4 cd/m^2. The right eye with the defect in the temporal field was used; the left eye was covered with a patch. Only one stimulus was presented per trial; presentation was repeated upon the subject's request. His task was to maintain fixation, and to decide whether the stimulus *T(s)* shown in his good hemifield was similar the stimulus *s* shown in the bad hemifield. No formal rating procedure was used to assess perceptual similarity. Instead, GY was asked to comment on the sensations and describe in what way they differed between the fields so that we could attempt to change the transformed stimulus accordingly.

1st Series

An early series of experiments was conducted on a SGI workstation at the Institute of Medical Psychology in Munich in 10/1996. The stimulus s_f that was presented in the bad hemifield was a rectangular bar tilted by 45° to the left or right. It subtended 5 x 2.5°, and was either darker or brighter than the uniform gray background. The maximum contrast was 1.2 log (see Fig.3 b). It appeared for 200ms at 10° eccentricity on the horizontal meridian. The corner closest to the normal hemifield, in the upper or lower quadrant, depending on the direction of tilt, was approximately 7° from the line of fixation.

Please insert Figure 2 about here

In our attempts to find a perceptually matching stimulus for the normal hemifield, we used a predefined set of transformations of the stimulus s_f : The first was reduction of stimulus contrast, i.e. multiplication by a constant *c*. The second was spatio-temporal low-pass filtering where the parameters f_s and f_t controlled the amount of spatial and temporal smear respectively. The third was the addition of random blobs to the stimulus, so that variable amounts of randomly chosen groups of stimulus pixels were subjected to increases or decreases of intensity. An example of the combined effect of the third type of transformation and of low-pass filtering is illustrated in Fig. 3a. Lastly, polarity was reversed for $T(s_f)$, so that the transformed stimulus would appear below background luminance while the original presented in the impaired field was above. For better visualization of the effects of these transformations, a selection of examples is shown on our www site (www.ebarth.de/demos/gy).

Please insert Figure 3 about here

2nd series

The second series of tests was conducted on an Apple Macintosh at the Institute of Experimental Psychology in Düsseldorf in 8/1997. Having failed in the first series to find a stimulus $T(s_f)$ that the subject said matched his awareness of the flashed bar (s_f) shown in his impaired field, we now used a different stimulus for the bad field. Prompted by reports indicating that in his impaired hemifield, GY is especially sensitive to moving stimuli (Barbur *et al.*, 1980; Benson & Blakemore, 1998; Blythe *et al.*, 1987; Finlay *et al.*, 1994), and less sensitive to orientation (Morland *et al*., 1996), we combined both features for stimulus s_m , using tilted moving bars throughout series 2 and 3. This stimulus s_m was a narrower bar of 5 x 1° with spatially blurred contours (see Fig.4b). Its luminance was 55 cd/m^2 on a homogenous gray background of 3.8 cd/m^2 (corresponding to a log contrast of $log_{10}(55)-log_{10}(3.8)=1.16)$. Again, the bar was tilted by 45° to the left or right. In contrast to s_f, which was flashed for 200 ms at its retinal position, stimulus s_m moved at 15.2°/s within a virtual window subtending 12 x 12°. The window was displaced from the line of fixation so that its centre, again on the horizontal meridian, was either 10° or 27° eccentric (see Fig.2). The amplitude of the horizontal motion was 5.5° across the centre of the screen (-/+ 2.25° off centre). The centre of the bar therefore moved between 7.75 and 12.25, and 24.75 and 29.25°, respectively, off fixation on the horizontal meridian. The motion was represented by 24 frames with a total duration of 360 ms. The frame rate of the VDU was 66.5 frames/s.

In the normal hemifield, only the 27° eccentric position was used. The public-domain ray-tracing tool POV-Ray (POV-Team(tm) 1997) was chosen as programming environment in which stimulus s_m was generated and transformed. This tool allows for defining a virtual environment with various objects, light sources, cameras, etc. In particular, scenes can be defined in which all objects and backgrounds have the same colour and texture and, without motion, the objects do not segregate from the background. This set-up allows the generation of 'motion-only' stimuli as well as an intuitive search for the best-matching stimulus $T(s_m)$; (in addition, once one had found the matching types of textures, one could attempt to simulate a whole V1-less world). For the transformations stimulus s_m was defined as an object in POV-Ray and both the rectangle and the background of its virtual window were given the same texture, for details see Appendix. This stimulus was displayed at a low light intensity that varied between 0.03 and 4.7 cd/m^2 on the overall background of 3.8cd/m^2. The final values of the parameters were derived by adjustment based on GY's judgements. In addition, an apparent-motion stimulus was used in several trials. It was represented by 12 frames, the bar moved the same distance with 30.4°/s, but frames 4 to 9 only showed the background. A single frame of the stimulus movie is shown in Figure 3a. Note that the bar is not visible in the single frame. However, a motion detector senses the moving rectangle as illustrated by arrows in Figure 4. Like the apparent-motion stimulus, this movie can be viewed at www.ebarth.de/demos/gy.

Please insert Figure 4 about here

Given the huge number of possibilities (even for our smallest and shortest stimuli of 64x64x12 pixels the number of possible stimuli is 6.5×10^{118369}) it was impossible to test all variations. Within a class of stimuli, those where objects and backgrounds have the same texture and objects segregate from the background only due to motion, we experimented with different texture types and different degrees of blurring, and varied background intensity and pattern contrast. In some cases we added a temporal or a spatial mask to stimulus $T(s_m)$. The temporal mask consisted in a full dark square of 12 x 12° that was drawn onto the screen before the first and after the last frame of the movie. The spatial mask was a 0.1° wide and 12x12° large dark and stationary frame around the moving rectangle. The pattern, a tilted rectangle, was kept constant throughout, as was the speed of motion in all trials except those in which apparent motion was used.

3rd series

To learn whether the results of the 2nd series were replicable, a 3rd series of tests was done in June 2000. The same stimuli as in series 2 were used (s_m, $T(s_m)$) and displayed on a Macintosh in Düsseldorf.

2. Discrimination

It was only stimulus s_m and the transformed stimulus $T(s_m)$ described above that the subject found to satisfactorily match the impressions he got from his two hemifields. To learn whether the perceptually matched stimuli would yield comparable discrimination performance in the two hemifields, we measured orientation and motion direction discrimination. Stimulus s_m was presented at the 27° eccentric position in the impaired hemifield. The symmetric retinal position was used in the normal hemifield where several of the transformed 'motion-only' stimuli $T(s_m)$ were used. In either field, to measure orientation discrimination, either the left- or rightward tilted bar moved only leftwards; for motion direction discrimination, only the leftward tilted bar moved either leftwards or rightwards (see Fig.2b). The subject was to press one of two keys on the keyboard, to indicate rightward or leftward tilt in the orientation discrimination, and right- or leftward motion direction in the motion discrimination task. 200 presentations were given per run. Note that all stimuli were visible to the subject.

Like the perceptual matching task, these psychophysical tests of discrimination were repeated in the last (3rd) series of experiments.

Results and Discussion

Perceptual matching

The goal of the experiment was to learn whether image processing of a stimulus that GY was aware of in his hemianopic field would yield a stimulus, which when presented in his normal hemifield would evoke a feeling or perception similar to that evoked by the original stimulus in the hemianopic field. In the 1st series of tests, we used a large tilted bar flashed for 200ms as stimulus s_f. The transformations we used in our attempts to find a perceptually equivalent stimulus $T(s_f)$ for the normal hemifield included (1) contrast reduction, (2) spatial and temporal smearing, (3) addition of random blobs, and (4) reversal of polarity. In line with GY's description of his experiences in the impaired hemifield, contrast reduction seemed to be the most straightforward way to make the stimulus less visual. Temporal and spatial smearing was motivated by the fact that GY's vision in the hemianopic field is low-level and ought to be lacking at least in spatial and possibly also in temporal resolution. The rationale for the addition of random blobs was that sensitivity in the impaired field is spatially heterogeneous (see Kentridge *et al.*, 1997, and Fig.1) which may yield a sensation of spatial scatter. Lastly, polarity reversal was prompted by the report of a different patient (DH) who described bright stimuli in his field of relative cortical blindness as darkish (P.S., unpublished). All four stimulus manipulations could be combined. In addition, although stimulus s_f was only shown at 10° eccentricity in the impaired field, the resultant stimuli $T(s_f)$ were shown in the normal hemifield at several more eccentric positions, all the way out to 50°, in addition to the symmetric 10° eccentric one. The reason was that both psychophysical (see Weiskrantz, 1972) and anatomical (Cowey, 1974; Cowey et al, 1989) data indicate that, following a V1 lesion and its degenerative consequences, the affected central retina bears more similarity to the normal peripheral than to the normal central one.

Nevertheless, all these efforts failed to produce a stimulus $T(s_f)$ that when presented in the normal field appeared to the subject like stimulus s_f presented in the impaired field. Although low-level vision is often characterised by an apparent reduction in brightness, size, and spatial resolution, and the presence of islands of vision has been reported (Fendrich *et al.*, 1992) and could reflect heterogeneous coverage from transneuronal degeneration of retina ganglion cells (Cowey *et al.*, 1989), none of the transformations we tried were successful: Whenever the contrast was high enough for anything at all to be visible, GY pronounced stimulus $T(s_f)$ as simply 'visual' and thus as ‚no match at all‘ for what he was aware of in the impaired field.

Instead of attempting further types of image processing on stimulus s_f, we used a moving rather than a flashed bar in the second series of tests. This was prompted by GY's relatively preserved sensitivity to motion in the impaired field. For the moving stimulus s_m we did indeed find a 'motion-only' stimulus $T(s_m)$ (described above, see Figure 4a) which according to GY matched the percept of stimulus s_m in the impaired field (Figure 4b). An improvement of the perceptual match was achieved by using the apparent-motion stimulus, raising the question whether GY does indeed sense the motion or rather the motion on- and offsets in his impaired field. Regarding the variations of blur and contrast, we found that the stronger the blur of the textures the better the match, provided the blurring operation did not affect too much the pattern itself, indicating that the particular texture is relevant only in the sense that we need to have some variation relative to the size of the rectangle. The optimum contrast was at the lowest level permitting effortless perception of motion.

Psychophysical performance

To see whether discriminability in both fields was similar for the acceptably matched stimuli, 200 presentations were given, using the moving low-contrast texture in the normal, and the moving luminance-defined bar in the impaired hemifield. Discrimination of motion direction (left- or rightward) was assessed first, followed by orientation discrimination (tilted left or right, always moving rightward). The accumulated values of percent correct classification are shown in Fig.5 as a function of trial number. Fig.5a shows data collected in the second series of tests; 5b data from the third series. Results agree in that for both fields and series, motion direction discrimination is much the easier task, yielding a mean percentage correct of 97,5 and 94.5% in the the second, and 77 and 71% for the good and bad field, respectively, in the third series. Orientation discriminability is much worse, with 55% in the good field in the second and 54% correct in the third series, and 65% and 56% in the impaired hemifield. In this task, in the third series, a trend toward better discriminability over time is seen in the slight upward slope of both curves, indicating that even a learning effect may be quite similar. The drop in performance between series is more pronounced for motion discrimination, affects both fields similarly, and may be due to the less extensive testing carried out in the later session; as is often the case in perceptual learning, a long interval decreases discriminability which can then be relearned.

When the spatially or temporally masked stimuli were used, in both hemifields discriminability both of the direction of motion and the orientation fell to chance level, indicating that discrimination of s_m and $T(s_m)$ is susceptible to the same operations.

Please insert Figure 5 about here

Visual experience

The results, both in the form of GY's judgements of similarity between his two fields and the psychophysical orientation and motion direction discriminability, show that an acceptable match could be achieved for the moving stimulus s_m and the moving texture $T(s_m)$. Both results could be replicated in the third series of tests, and fit well with GY's descriptions of his visual experience: He is aware of 'something moving' but it appears as 'black on black', like a mouse under a blanket (persl. comm.), or 'similar to that of a normally sighted man who, with his eyes shut against sunlight, can perceive the direction of motion of a hand waved in front of him' (Beckers & Zeki, 1995, p.56). His vision appears characterised by a presence of positional information and in-plane translation in space, while brightness and contours appear to be absent or grossly reduced. Of course this cannot describe his residual vision in full, as other aspects of phenomenal vision have not been tested here; in other experiments he has for instance stressed an absence of colour sensation as well. A V1-less visual world may thus feature very little spatial detail, and little if any brightness and colour. Indeed, it may also lack the normal conscious sensation of motion since the fact that the apparent-motion stimulus was rated as an acceptable if not better match indicates that instead of motion *per se*, only the on- and offsets of a moving object may be sensed, which would suffice to discriminate motion direction in numerous tasks including ours (see also Azzopardi and Cowey, 2000).

Regarding our failure to find a match for the flashed stimulus s_f, we should like to stress that it only indicates that the set of transformations we used was inadequate, and does not imply that this type of stimulus cannot be matched.

Perceptual versus forced-choice matching

Our conclusions as well as our approach differ from those recently reported by Morland et al. (1999) who 'forced' GY to match stimuli between his hemifields: Stimuli were presented simultaneously, one in each field, and the subject had to try and adjust the speed, colour, or intensity of the variable one in one field to the fixed one in the other field. They found reasonably normal matches for colour and motion, but not for brightness, and concluded that that it is brightness in particular that depends on V1 (see also Pollen, 1999). Although GY's refusal of all stimuli $T(s_f)$ as 'simply visual' would agree with this conclusion, we still think it may be misleading, because (1) GY has often claimed not to see any colours in his impaired field, (2) a forced choice need not be based on a perceptually acceptable match, and (3) only one stimulus dimension could be adjusted in each task, preventing capture of possible additional differences, for instance in spatial resolution. In contrast, in order to find a true perceptual match, we discarded every stimulus that GY found unsuitable, and adjusted a variety of parameters (e.g. contrast, smear, on- and off-set) according to his comments. While we failed in succeeding with the flashed stimulus s_f, perceptually adequate stimuli were found for the moving stimulus s_m, in the form of moving or apparently moving low-contrast textures. From this we conclude 1. that vision in the impaired field is enormously reduced in phenomenal content, although what qualia are present are visual (GY has no doubt that it is through his eyes that he comes by the sensation, and that they are not of another sensory modality), and 2. that the presence of an acceptable perceptual match indicates that his type of residual vision is not A-conscious without being P-conscious as well.

P- and A-conscious vision

Phenomenal and access consciousness have been distinguished, for instance by Block (1995; 1996) and also by Nelkin (1996) who defined the phenomenal ones as 'mental states that have a certain kind of experiential 'feel' to them' (p.15). Neuronal encoding of sensory information can produce adaptive behaviour without causing any kind of 'feel'. This is known for instance from visual reflexes that can be elicited in unconscious subjects, and from the non-reflexive visual functions (localisation, detection, and discrimination) demonstrated in fields of absolute cortical blindness and known as 'Blindsight' (Stoerig & Cowey, 1997; Stoerig, 1999; Weiskrantz *et al.*, 1974). Blindsight is characterised by an absence of visual qualia expressed in the Blindsight patients' denial of any visual impression, as well as by an absence of conscious access to the neuronally encoded information expressed in affirmations of their being just guessing. GY's residual vision that we studied here is not blindsight, not only because he is aware of at least some visual events, but also because it must be at least minimally phenomenal; otherwise no perceptual equivalent of the sensation in the hemianopic field could have been found in the normal field. It is thus both A- and P-conscious, and does not constitute an instance of conscious access without a (concurrent or preceding) phenomenal representation[2]. The plastic changes in the visual system that are enhanced if not brought about by long-term training of residual visual functions and that

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[2] Whether anything can be A-conscious without being or having been P-conscious is a matter of debate (Block, 1995; Stoerig, 1996).

involve extrastriate visual cortical areas (see Kleiser et al., in prep.) have produced an unusual type of phenomenal vision in this extensively studied subject. They have not provided an example of conscious access in the absence of any kind of 'feel'.

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Appendix: Stimulus computation

Procedure

In the first set of experiments test images were created and displayed on a SGI workstation. The parameters we manipulated were contrast, degree of spatial blur, amount of noise, polarity, and retinal eccentricity. For better visualization, we have provided a small program in MATLAB than can be used to generate a similar range of stimuli. It is available on our www site.

In the second set of experiments the image sequences were created by using POV-Ray on a SGI workstation. The resulting images were converted to a three-dimensional IPRS image structure and filtered by using IPRS routines (Caelli, Dillon et al. 1997), to be transferred to a Macintosh computer. The experiments on discrimination were performed by using *SuperLab* (Cedrus, 1989-1997, version 1.7.).

In the third set of experiments the same stimuli as in the second set where used, but the experiments where performed by using *ShowTime* (see http://vision.arc.nasa.gov/showtime for information and download).

Texture and filter parameters

The textured stimulus $T(s_m)$ was of type granite with a turbulence value of 0.6 and it was scaled by 0.5 (POV-Team(tm), 1997). The camera was of type orthographic and placed 10 units away from the background, which was offset 0.0001 units from the rectangle. The motion was sampled with 32 frames of size 64 by 64 pixels. It was then filtered with the IPRS routine 3Dgausslp with $f_s=f_t=0.5$, i.e., the cut-off frequency of the Gaussian low-pass filter was half of the maximum frequency in both space and time directions. The length of the movie was reduced to 24 frames by cutting off the first and last 4 frames. In case of the apparent motion stimulus, the granite texture had a turbulence of 0.3. The background was scaled by 0.05 and the rectangle texture by 0.2. The motion was sampled with 16 frames and the length of the movie was reduced to 12 frames after the filtering. The filter parameters were $f_s=0.35$ and $f_t=0.8$. The experiments were prepared by generating a set of movies with different textures and filter parameters.

Figure Captions

Figure 1. Static visual field perimetry: a) The visual field plot for the right eye that was used for testing shows a hemianopia to the right, with a macular sparing of about 3°. The subject was asked to indicate whether he saw the 116', 320cd/m^2 white stimulus appeared for 200ms on a white background of 10cd/m^2. b) The plot resulting from the same procedure but with the subject asked to indicate whether he was aware of the same stimulus. In both sets of measurements, GY pressed a button for a positive response. Each presentation was indicated by a sound from the shutter; catch trials (sound only) were low at <10%. The marked difference between a) and b) illustrates the field where GY is aware of the stimuli although he does not 'see' them. Note that the extent of this field depends on the precise conditions used for testing. (empty symbols: positive responses; filled symbols: negative responses).

Figure 2. The stimulus arrangements used for the testing in the 2nd and 3rd series. The dashed lines indicate the range of motion, which was not present in the 1st series in which the bar was flashed at a 10° eccentric position in the impaired field. The distances indicated in (a) refer to centre-to-centre distance. b) The two discrimination tasks, with the arrow indicating the direction of motion (series 2 and 3).

Figure 3. One of the transformed stimuli $T(s_f)$ shown in the normal field of view (a) and the original 200ms flashed stimulus s_f shown in the hemianopic field (b) in the first set of experiments. Note the effects of adding random blobs and low-pass filtering. The contrast was variable but much lower than shown here. These types of transformations did not lead to a perceptual match.

Figure 4. One frame of the texture-defined moving stimulus $T(s_m)$ (a) and the luminance-defined moving stimulus s_m (b) used in the second set of experiments (the stimuli can be viewed at www.ebarth.de/demos/gy). Estimated motion vectors are shown as overlaid arrows. Note that the algorithm for motion estimation mimics the perceptual match and that although the rectangle is not visible on the left it is detected by the algorithm. The algorithm is based on a general framework for visual processing and has been developed to

model the perceived direction of motion, and to compute a motion sketch from image sequences (Barth, 2000).

Figure 5. Results for orientation and direction discrimination. The percentage of correct responses is evaluated at each trial by using all responses available up to that trial, i.e. cumulated percent correct classification is shown as a function of trial number. Performance with texture-defined motion stimuli $T(s_m)$ in the normal field is indicated by diamonds for direction and squares for orientation discrimination. Results for the luminance defined stimuli s_m in the hemianopic field are displayed with asterisks for direction and 'x' for orientation. Results obtained in 1997 are shown in a), those obtained in 2000 in b). Percentage correct for direction discrimination in the bad field was 94.5±1.6%, χ^2= 158, p≤0.0001 (1997) and 71±3.2%, χ^2=36, p≤0.0001 (2000). In the normal field, the corresponding values are 97.5±1.1% (χ^2=180, p≤0.0001; 1997) and 77±3 % (χ^2=58, p≤0.0001). For orientation discrimination, percentage correct in the impaired field was 65±3.4% (χ^2=18, p≤0.001, 1997) and 56±3.5% (ns, 2000), as compared to 55±3.5% (ns, 1997) and 54±3.5% (ns, 2000) in the normal field. In both fields and at both times GY performed well with direction discrimination and much poorer with orientation discrimination.