The locus of fixation in strabismic amblyopia changes with increasing effort of recognition as assessed by scanning laser ophthalmoscope

Kirsten Siepmann,[1] Jens Reinhard[2] and Volker Herzau[2]

[1]Department of Diseases of the Anterior and Posterior Segment, University Eye Hospital, Tübingen, Germany
[2]Department of Pathophysiology of Vision and Neuroophthalmology, University Eye Hospital, Tübingen, Germany

ABSTRACT.
Purpose: **We performed a qualitative assessment of fixation behaviour in relation to the fovea in patients with strabismic amblyopia.**
Methods: **The fixation of 25 patients with strabismic amblyopia was examined using a scanning laser ophthalmoscope (SLO). A digital frame grabber board was programmed to scan onto the patient's retina single solid black discs of 5, 10 and 15 degrees in diameter and Landolt Cs in different orientations and corresponding to a visual acuity (VA) of 0.01–0.2 in European decimals. The relative position of the fovea was video-recorded. Fifty video fields per second were plotted as x/y (fixational positions in relation to the fovea) and x/t (motion over time) graphs.**
Results: **Three main groups of patients were seen. Group 1 (n = 6), with a VA of < 0.1, showed a grossly eccentric and unstable locus of fixation independent of size/type of test stimulus used. Group 2 (n = 15), with VA of 0.1–0.8, initially used an eccentric retinal area for fixation that, however, shifted to the fovea with decreasing size and increasing detail of the target for fixation. Group 3 (n = 4), with VA of 0.3–0.8, had stable central fixation throughout.**
Conclusions: **We speculate that the reduced VA associated with strabismic amblyopia is due to a defective motor control of fixation that can be modulated by recognitional effort.**

Key words: strabismus – strabismic amblyopia – fixation – scanning laser ophthalmoscope (SLO)

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Introduction

Strabismic amblyopia is always unilateral and is caused by active inhibition within the cortical pathways of visual input originating from the deviating eye. It is thought to be due to an abnormal binocular experience during early childhood and has long been deemed a deficit in visual resolving capacity alone. Psychophysical investigations have contributed greatly to a better understanding of the amblyopic process as an abnormal binocular experience early in life. The light sense of amblyopic eyes is normal (Schor 1983). However, the reduction in visual acuity (VA) with decreasing luminance is less than that of normal individuals and much less than that of individuals with reduced VA due to morphological changes (Herzau et al. 1989, 1993). Strabismic amblyopes exhibit a distortion of space perception in the deviated eye (Oppel 1962; Hess et al. 1978), as well as impaired localization of objects in space (Bedell & Flom 1981; Bedell et al. 1985). Marked spatial uncertainty and distortion occur in the deviated eye of squinters with both normal and reduced VA (Levi & Klein 1983) but cannot be found in normal eyes in which VA has been artificially reduced (Stigmar 1971; Williams et al. 1984), suggesting that uncertainty in strabismic amblyopic eyes does not result from reduced acuity. It has also long been known that the locus of fixation (normally the foveola) in around 50% of all amblyopic patients is shifted to an eccentric retinal area, without the sensation of eccentric viewing (Mimura et al. 1984). Von Noorden

(1966) therefore suggested that eccentric fixation may be caused by an abnormal fixation reflex due to a shift of retinal co-ordinates. We studied the fixation behaviour in strabismic amblyopes using a scanning laser ophthalmoscope (SLO) with the aim of analysing whether fixational control was in any way modulated by recognitional effort.

Materials and Methods

Patients

Twenty-five patients (12 females, 13 males) with strabismic amblyopia (Table 1) were examined according to the tenets of the Declaration of Helsinki. Their ages ranged from 7 to 64 years (mean 28.44 years). Seventeen patients suffered from congenital esotropia, six from exotropia and two from consecutive exotropia. Of the latter two patients, one had suffered from congenital esotropia in childhood and had turned spontaneously exotropic in her early teens, while the other had undergone strabismus surgery abroad as a child. The details of the operation, however, could not be retrieved. Each patient underwent a full orthoptic and ophthalmic examination including assessment of best corrected VA prior to the SLO investigation. Nine patients had a VA ≤ 0.1, whereas 16 had VA of 0.2 -0.8 in their amblyopic eye (Table 1). All patients presented to our department with the intention of undergoing squint surgery. Patients exhibiting a strong latent nystagmus were excluded.

Scanning laser ophthalmoscopy

An SLO (Model 101; Rodenstock, Munich, Germany) was used to image the fundus (He-Ne laser) and to present stimuli simultaneously using an acousto-optic modulator. A frame grabber board was programmed to present black stimuli that were generated on a bright red background of $3.6 * 10^4$ trolands (contrast 0.986). For fixation targets three solid discs of 15, 10 and 5 degrees and Landolt Cs in decreasing order of size ranging from a linear VA of 0.01–0.2 in European decimals were used (Fig. 1.). This not only allows for exact determination of the position of the fovea in relation to the fixation target and stimulus over time, but also for the measurement of eye movements without calibration. Although the SLO per se allows presentation of smaller stimuli, for the purpose of analysis, the gap of the smallest Landolt C could not be smaller than two video lines corresponding to approximately 5 minutes of arc, equalling a VA of 0.2. The temporal resolution is 50 video fields per second, and the spatial resolution at least 12 minutes of arc.

Procedure

Each patient was asked to fixate on the centre of each of the black discs as if trying to aim at the centre of a target. Then Landolt Cs in decreasing size were presented (Fig. 2.) and the patient was asked to identify the clock orientation of the gap and then to fixate exactly on the gap itself. When the subjective limit of detection (i.e. the gap of the Landolt C could no longer be located correctly) was reached, the examination was terminated. All examinations were performed in both the amblyopic and the sound eye.

Data analysis

A video-recording of each examination was made on S-VHS tape. The fixation was tracked using a semiautomatic program using fundus images that were digitized and transferred to a PC. Fixational eye movements were measured by marking a high contrast landmark (e.g. vessel branching) in every video field of a continuous sequence of at least 4 seconds (200 fields) for each stimulus. The program calculated the landmark's change of position (i.e. its vertical and horizontal co-ordinates) field by field. By referring all values to the anatomical fovea by simple vector calculation (Fig. 1), a continuous trace of fixation plotted as x/y (fixational positions in relation to the fovea) and x/t (motion over time) could be drawn.

Table 1. Summary of main patient data.

Sex	Form of strabismus	Amblyopic eye	Visual acuity (OD/OS)	Fixation (Visuscope)	Fixation SLO	Foveal fixation possible?
F	Esotropia	OD	0.1/1.0	ND	Nasal/superior	Yes
M	Exotropia	OD	CF/0.8	ND	Nasal/superior	No
F	Exotropia (consecutive)	OS	1.3/0.05	ND	Temporal	No
M	Esotropia	OS	1.3/0.05	Nasal	Nasal	No
M	Esotropia	OS	1.0/0.2	ND	Temporal	Yes
M	Esotropia	OD	0.3/1.3	ND	Nasal	Yes
M	Esotropia	OD	0.7/1.3	Central	Central	N/A
F	Esotropia	OD	0.05/1.0	ND	Nasal/inferior	No
F	Esotropia	OD	0.5/0.3	ND	Nasal	Yes
F	Esotropia	OS	0.6/1.3	Central	Central	N/A
M	Esotropia	OD	0.6/1.0	ND	Nasal	Yes
M	Esotropia	OS	1.0/CF	ND	Nasal/inferior	No
M	Esotropia	OS	1.3/0.3	ND	Nasal	Yes
M	Exotropia (consecutive)	OD	0.3/1.0	Central	Central	N/A
F	Esotropia	OS	1.3/0.1	Foveal (wandering)	Nasal	Yes
F	Exotropia	OD	0.5/1.0	Central	Central	N/A
F	Exotropia	OD	0.8/1.0	Central	Temporal/superior	Yes
M	Exotropia	OD	0.6/1.3	ND	Temporal	Yes
F	Esotropia	OS	1.0/0.2	ND	Nasal	Yes
M	Esotropia	OD	0.2/1.0	Central	Nasal	Yes
M	Esotropia	OS	0.1/1.0	ND	Nasal/superior	No
F	Esotropia	OD	0.2/1.0	ND	Nasal	Yes
M	Exotropia	OD	0.4/1.3	Foveal (wandering)	Temporal	Yes
F	Esotropia	OD	0.1/1.0	ND	Nasal	Yes
F	Exotropia	OS	0.8/0.2	ND	Temporal	Yes

N/A = not applicable; ND = not done.
Visual acuity provided in European decimals.

Results

When analysing fixation strategy two very distinct patterns were evident: One group of patients (patients 2, 3, 4, 8, 12, 21) fixated eccentrally far away from the fovea. Although all patients in

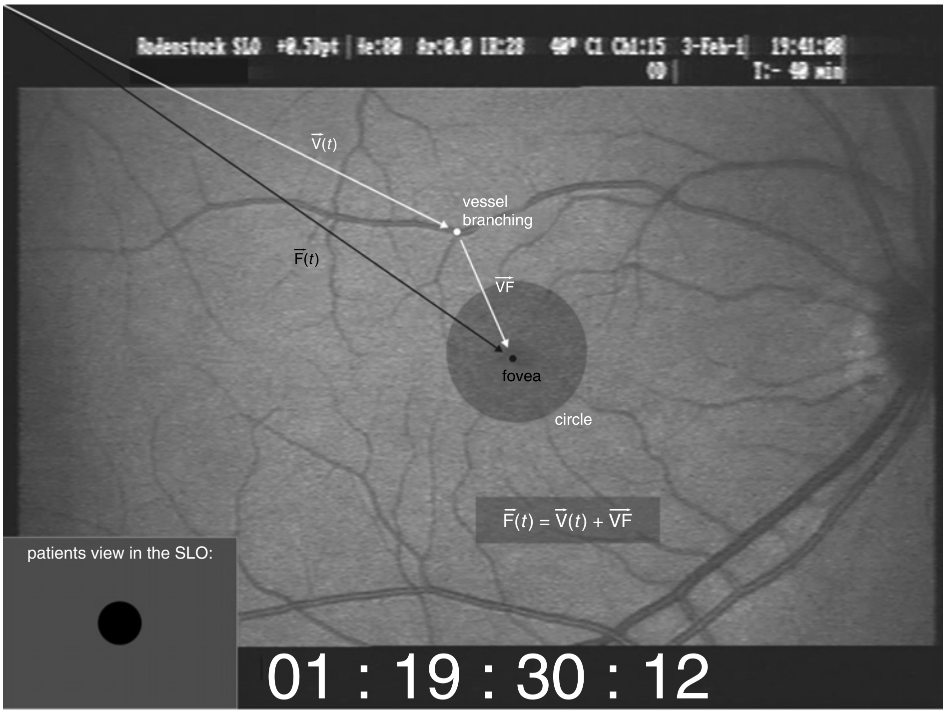

Fig. 1. Snapshot of an SLO video sequence. The patient sees a black disc in the middle of a bright red field in the SLO (see inset). The retina and the stimuli are simultaneously observed by the investigator. For offline analysis, the video sequences were digitized and the position of the vessel branching was marked in every video field (50 fields per second). For technical reasons the origin of the co-ordinate system is set at the top left hand corner of the video image. The program calculated the position of the fovea and its change over time.

this group correctly identified the gap orientation of the Landolt C (the smallest Landolt C recognized defined the highest individual recognitional effort), the locus of fixation did not change to any large extent and remained eccentric throughout the examination (see Figs 3B and 4C, D for examples of fixation strategy and pattern). Four patients in this group had VAs of either 0.05 (patients 3, 4, 8) or 0.1 (patient 21). Two patients in this group at routine VA testing were able to count fingers (CF) only. However when examined with the SLO there was a slight discrepancy (possibly due to the high contrast of the SLO stimuli on the bright red background). Both were able to see the 0.02 or 0.03 Landolt ring, respectively, and thus qualified for analysis. None of the patients when questioned had the impression of 'indirect viewing' and all confirmed that the stimulus was 'straight ahead'.

The larger group of patients ($n = 15$), which was also the cohort with better VA (0.2–0.8), showed very clear and consistent fixational strategies (Figs 3A and 4A, B). Initially, fixation remained eccentric when looking at the black discs and the larger Landolt rings. However, it was able to switch to the fovea as soon as recognitional effort was required. Although all the patients were able to keep their fixation foveal as long as they were looking at the required

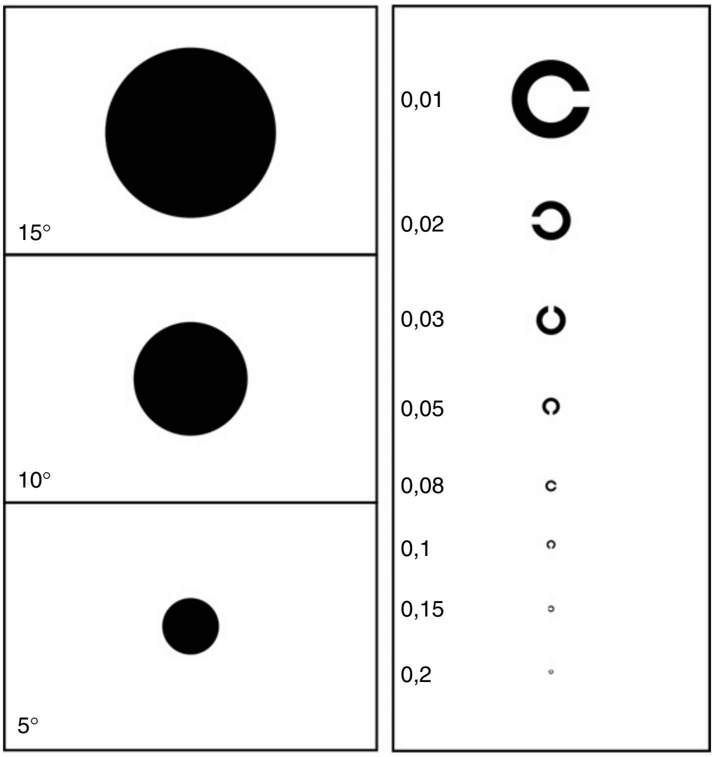

Fig. 2. Diagram of the stimuli that were presented at each examination. Patients were asked to exactly fixate the centre of each disc or the gap in the Landolt C. All target stimuli were perceived as in the subjective 'straight ahead' position.

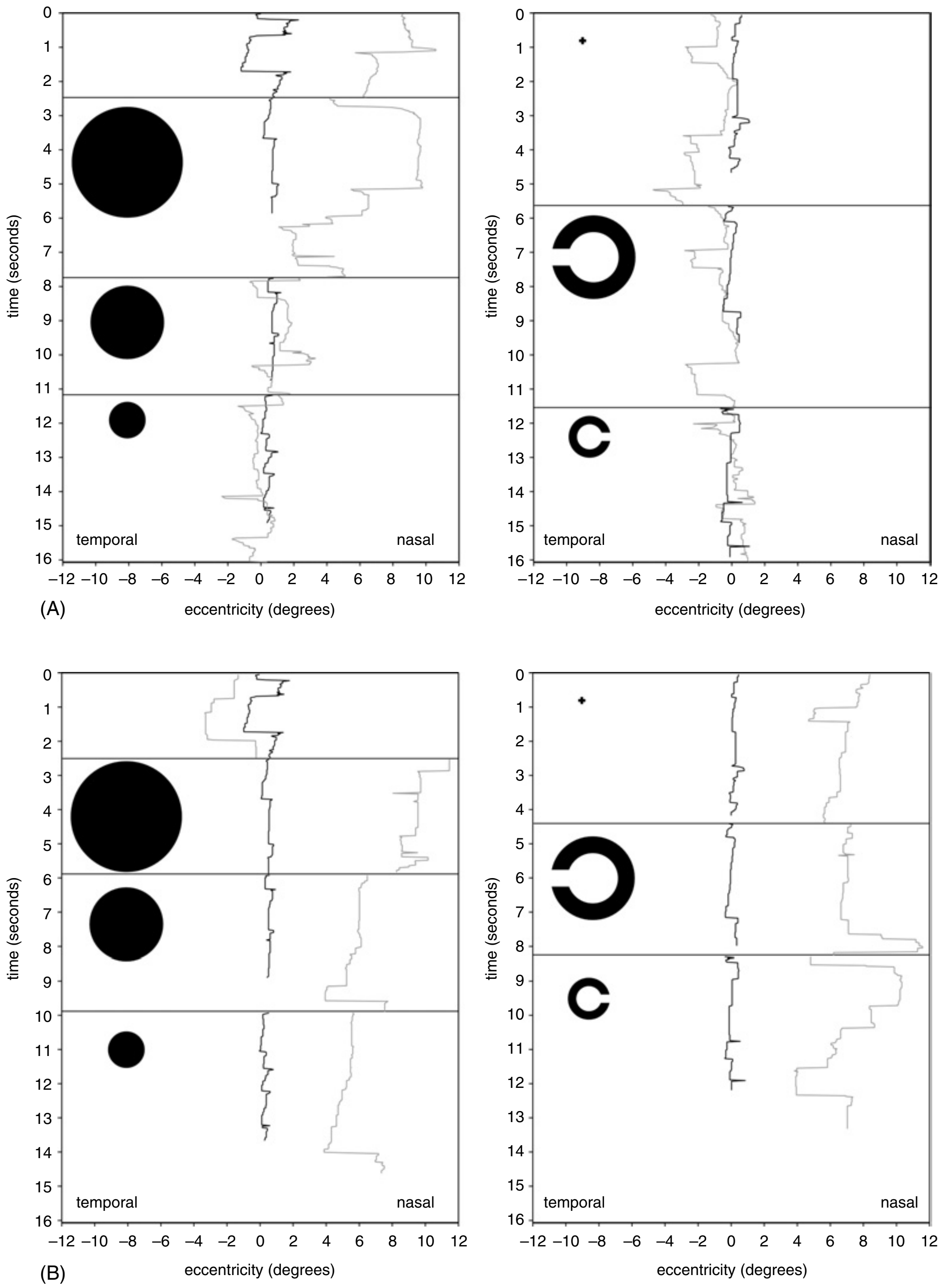

Fig. 3. (A) Fixation strategy of patient 20 (exemplary of group 2). The black line shows the sound eye, the grey line the amblyopic eye, respectively, when fixating the target stimulus. '0 eccentricity' describes the fovea. (B) Fixation strategy of patient 4 (exemplary of group 1).

stimulus, some very small nystagmic jerks through the fovea (Fig. 3A) could be detected in almost all cases.

The third group of patients ($n = 4$) fixated centrally throughout the examination.

Discussion

Strabismic amblyopes show distorted space perception in their deviated eye (Pugh 1958; Hess et al. 1978), as well as an impaired localization of objects in space (Bedell 1981; Bedell et al. 1985). It has been shown that amblyopes make large errors in partitioning horizontal lines (Bedell 1981) as well as in vertical alignment when compared to strabismics without amblyopia (Bedell 1981; Bedell et al. 1985; Fronius & Sireteanu 1989). Bedell et al. (1985) speculated that reduced VA and abnormal eye movements are not the causes but, rather, the consequences of distortions and uncertainty originating at a central level, possibly 'at the visual cortex'. Strabismics with normal or nearly normal acuity frequently exhibit oculomotor abnormalities such as unsteady and eccentric fixation (Flom & Weymouth 1961; Ciuffreda et al. 1979) and inaccurate pursuit tracking (van Hof-van Duin & Mohn 1982). These strabismics are often uncertain in making visual discriminations and in

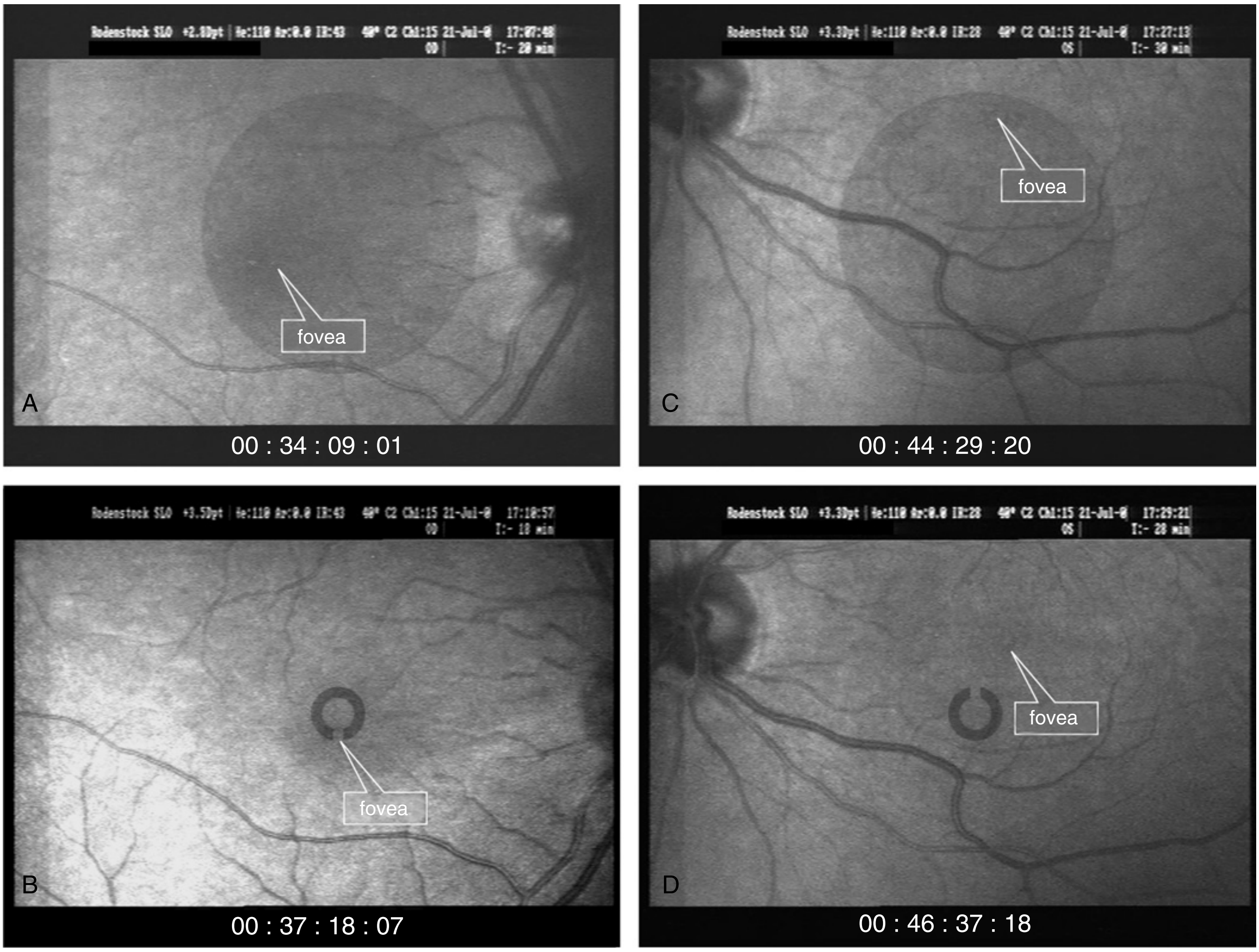

Fig. 4. Fundus images of patient 20 while fixating (A) the centre of the 15-degree disc (nasally eccentric) and (B) the gap in the Landolt C. Fundus images of patient 21 while fixating (C) the centre of the 15-degree disc (nasosuperiorly eccentric) and (D) the gap in the Landolt C.

performing visually guided tasks with the deviated eye (Pugh 1958; May et al. 1983). Quantitatively more severe oculomotor and sensory abnormalities occur in strabismic amblyopic eyes (Flom & Weymouth 1961; Ciuffreda et al. 1979; Schor 1983), suggesting that these abnormalities exist as a manifestation of the same phenomenon and may be related roughly to the acuity level. It is indeed important to consider the relation between the fixation pattern and VA. The normal decrease in VA is a function of the distance of the object image from the fovea. However, this does not hold true for the amblyopic eye, where factors other than eccentricity of fixation alone determine the degree of visual acuity (von Noorden & Helveston 1970), although eyes with low VA tend to have greater eccentricity of their fixation pattern (von Noorden & Mackensen 1962; Mackensen et al. 1967; von Noorden 1969; von Noorden & Helveston 1970). Some amblyopic eyes can be induced to assume spontaneous central fixation relatively easily. Such eyes do not, however, necessarily attain normal vision, although it is also true that unless foveolar fixation is achieved, the physiological basis for a normal VA is absent. There are basically two opposing theories with regard to the pathogenesis of non-foveolar fixation. The Cüppers Theory, often referred to as the 'Correspondence Theory', states that the 'straight-ahead' sensation is no longer transmitted by the fovea but rather by some eccentric retinal area and due to this shift the patient no longer fixates with the fovea (Cüppers 1956). Cüppers equated loss of the straight-ahead sensation by the fovea with loss of the principal visual direction in anomalous correspondence (Cüppers 1956, 1961, 1966), as he never found normal correspondence in patients with eccentric fixation. As a consequence of this theory the degree of eccentricity of fixation should be identical to the angle of anomaly, which according to Cüppers is true for 50% of cases. A great deal of work has gone into verifying Cüppers' claim and the results obtained were equivocal (von Noorden & Mackensen 1962; von Noorden 1969). The other, even older, theory is the 'Scotoma Theory', according to which the amblyopic eye fixates with that retinal area adjacent to the scotoma that has the highest resolving power (Böhme 1955; Oppel 1962; Aggarwal & Verma 1980). This theory has also failed to achieve unanimous support (Mackensen 1957; Aulhorn 1967; Aulhorn & Lichtenberg 1972; Hess 1977; Avetisov 1979; Mimura et al. 1984). An alternative explanation for the eccentric fixation in strabismic amblyopes was given by von Noorden (1969), who suggested that eccentric fixation may be caused by an abnormal fixation reflex. A visual object falling on the peripheral retina of a normal eye elicits a fixation reflex that will cause the eye to move so that the image is shifted from the periphery to the fovea. In contrast to acquired maculopathy, where patients fixate eccentrically but still have the sensation of 'indirect viewing', in strabismic amblyopes the situation is quite different. Due to suppression early in life when abnormal conditions produce abnormal visual behaviour, the decreased foveal VA leads the fixation reflex to become associated with the eccentric fixation area. This motor adaptation will position the image of an object of interest directly onto the eccentric fixation area without placing it first on the fovea. In that sense the fovea has lost its 'zero retinomotor value', which may now be found at the eccentric fixation area. So far it is unclear, however, whether this adaptation is absolute and complete in all cases or whether the abnormal fixation reflex can be overcome by increased recognitional effort. The scanning laser ophthalmoscope provides a unique way of carrying out real-time examination of strabismic amblyopes. It offers the advantage to the observer of being able to visualize and simultaneously place an image onto the patient's retina. In our studies we found that patients with a VA of < 0.1 showed a stable area of fixation in a location outside the fovea. In amblyopes with better VA, fixation became more and more 'foveolized' as the recognitional effort increased.

Our observations provide further evidence that eccentric fixation in strabismic amblyopes is indeed part of a spectrum of sensory and motor adaptations of visual functions in patients with strabismus. Some amblyopes (with better acuity) may fixate randomly at the margin of a central suppression scotoma to obtain better vision when the non-amblyopic eye is covered. In others (with severely reduced VA) the adaptation is more complete and the motor component of the fixation reflex becomes more stably associated with the new (eccentric) centre of retinomotor orientation for fixational eye movements. Further experiments under different viewing conditions are needed to characterize the nature of this retinomotor adaptation.

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Correspondence:
Kirsten Siepmann MD, PhD or
Professor Volker Herzau MD
University Eye Hospital
Schleichstrasse 12–16
72076 Tübingen
Germany
Tel: + 49 7071 298 4761
Fax: + 49 7071 294 763
Email: kirsten.siepmann@web.de