Temporal and spatial distortions in adult amblyopia

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To Thomas and Coralie

Table of Contents

Abstract

Amblyopia is a developmental disorder of the visual system that leads to reduced vision in one or both eyes. People suffering from amblyopia show different perceptual deficits like reduced contrast sensitivity, reduced or no stereopsis, spatial uncertainty, and spatial and temporal distortions when viewing with the amblyopic eye. In the following thesis, different psychophysical methods are used to investigate anomalous perception of amblyopic participants in detail with the main focus on the perception of temporal instability. In the qualitative experimental paradigms it is shown that temporal instability is mainly perceived by strabismic and strabismic-anisometropic amblyopes. The temporal deficits occur only at spatial frequencies higher than 1.6 c/deg, and are perceived in addition to the spatial distortions. Illusory colours sometimes accompany the temporal distortions. There seems to be a relationship between crossed hand and eye dominance and the perception of temporal instability. In the quantitative experiments it is shown that temporal instability in amblyopic perception has a negative impact on the performance in psychophysical tasks. Amblyopes perceiving temporal instability show enhanced spatial uncertainty and spatial distortions for different types of stimulus presentation (auditive vs. visual) when compared to amblyopes without temporal instability. This might be due to deficits in auditive-visual mapping. These deficits in auditory-to-visual mapping suggest an impairment of the dorsal “where” pathway. Thus, it might be that amblyopes with temporal distortions have deficits in the dorsal pathway that come up in addition to the known deficits of the ventral “what” pathway and are related to the perception of temporal instability. The different results of the experiments found in this thesis seem to confirm this hypothesis. Studies using functional imaging techniques might be appropriate for a further investigation of amblyopic deficits involving the dorsal pathway.

1. Introduction

There are five senses humans are endowed with: vision, audition, smell, taste and touch. Vision is the one most finely tuned sense, which is also capable of obtaining information from distant elements. The visual system is our major source of obtaining information about the environment. In order to retrieve information, we analyze the environmental object. We localize and recognize objects and use different kinds of information like wavelength, shape and texture. However, our visual system is not fully developed at birth and needs time to mature. Especially in the early period of visual development i.e. the first year of life, the visual system is very sensitive to influences that distract the critical developmental steps. Everyone knows about the sight of small children wearing a patch over one of their eyes, for example. These children are in orthoptic therapy in order to prevent or reverse amblyopia. Amblyopia is one of the most widespread visual disorders that can occur in early childhood, due to an undesirable early development of the eyes' visual perception. Amblyopia carries many implications for the perception of an amblyopic person and furthermore, there are several functional aspects of vision which are changed due to amblyopia.

One way to investigate the visual perception of humans and, more specifically, the perception of amblyopic people, is to observe the phenomenon when it occurs naturally. However, as the subjective visual perception is impossible to study by direct observation, it is examined by indirect observation, e.g. in an interview (Atkinson, Atkinson, Smith, Bem & Nolen-Hoeksema, 1996), or by qualitative descriptions of one's perceptual experiences. Often additional data to the subjective descriptions are provided by an anamnesis of the medical history and the actual visual status of the individual. This method of qualitative investigation has a very old tradition in psychophysical research and, besides the experimental approach, is one of the two main research methods used in psychophysical experiments. The experimental approach uses a different type of investigation, gathering quantitative data about the nature of the investigated object or variable, respectively, and the relations it has with other variables. In the case of visual perception, this concerns the relation of visual perception to relevant internal and external stimuli, and, especially, the influence of these stimuli on perception.

This thesis is about the anomalous visual perception of people suffering from amblyopia, investigated with both qualitative and quantitative research methods. First, an introduction on the anatomy and function of the visual system of normally sighted people is given. Second, the development of the visual disorder “amblyopia” is explained and visual deficits caused by amblyopia are presented. After that, four experiments are reported to answer the question of how a special visual phenomenon, the temporal instability in amblyopic vision, is actually experienced by amblyopic people and which implications this instable perception has on other spheres of action. Temporal instabilities are investigated as well as their relationship with the spatial distortions, which occur in amblyopic perception. Due to the paucity of qualitative and quantitative data about temporal instabilities in amblyopic vision, experiments 1 and 2 center upon the issue of how the perception of temporal instability is subjectively experienced by amblyopic people. Descriptive data about the amblyopic perception of different geometrical patterns with low and high spatial frequencies have been collected and qualitative descriptions of the temporal distortions acquired. In addition, experiments 3 and 4 investigate the implication of a temporally instable perception on the performance of psychophysical tasks. Indeed, amblyopes perceiving temporal instability show deficits in auditory-to-visual mapping. In sum, it is shown that strabismus, in addition to amblyopia, is needed to elicit significant spatial and temporal distortions. The results of the qualitative as well as the quantitative experiments suggest an impairment of the dorsal pathway in amblyopes with temporal instability in addition to the known deficits in the ventral pathway.

2. The nature of vision

This chapter gives a short overview over the visual system with its anatomical and functional aspects - starting from the entrance of light into the eyeball to the processing of an image in higher visual areas. Detailed information on pathological aspects will be given where it is relevant for the further understanding of the amblyopic vision described in chapter 3.

2.1 Anatomy and function of the eye

For moving the eyes towards different objects of interest within a wide field of vision, six muscles are attached to each eye: four rectus muscles and two oblique ones (Kandel, Schwartz & Jessell, 2000). These extraocular muscles rotate each eye in its orbit and have a functional complement in the other orbit. By that, the eyes can rotate in the same plane, but in opposite directions, e.g. both eyes rotate to the left, one eye away from the nose, and the other nasally. The proportion of 1) horizontal, 2) vertical and 3) torsional rotation performed by each muscle depends on the horizontal position of the eye in the orbit. It is critical for the brain that the muscles function together to interpret the images from each eye as a single one. An improper functioning of these muscles can cause strabismus, a misalignment of the two eyes. Result of this misalignment is double vision, also called diplopia, as the image of the object of interest is no longer located on the same retinal position in each eye. The six extraocular muscles are innervated by three groups of motor neurons: the abducens nerve, the trochlear nerve and the oculomotor nerve. All have specialized functions and if injured, each shows a characteristic syndrome, e.g. damage to the oculomotor nerve results in a nearly complete droping of the eyelid, a so-called ptosis.

The cornea is the outermost layer of the eye through which light passes and - with about 43 diopters - the principal refractive structure of the eye (figure

1). Its shape is convex, it has a horizontal diameter of about 11,6 mm and is surrounded by the sclera, a white, non-transparent tissue. The sclera together with the cornea forms the outer layer of the eye and is continuous with the dura mater covering the optic nerve and the brain. The inner space between the cornea and the lens is called the anterior chamber and is filled with the aqueous humor, a fairly homogeneous clear liquid. Within this anterior chamber lies the iris, which surrounds the pupil and is the structure giving "color" to the eye. The pupil is a hole in the middle of the iris, which bundles the light going into the eye. The pupil changes its size in response to different light levels: e.g. due to the muscle sphinctor pupillae the pupil becomes small (minimum about 2 mm), while its agonist dilatator pupillae causes the pupil to become larger (max. 6-8 mm). Both muscles are associated with each other forming a systematic alliance.

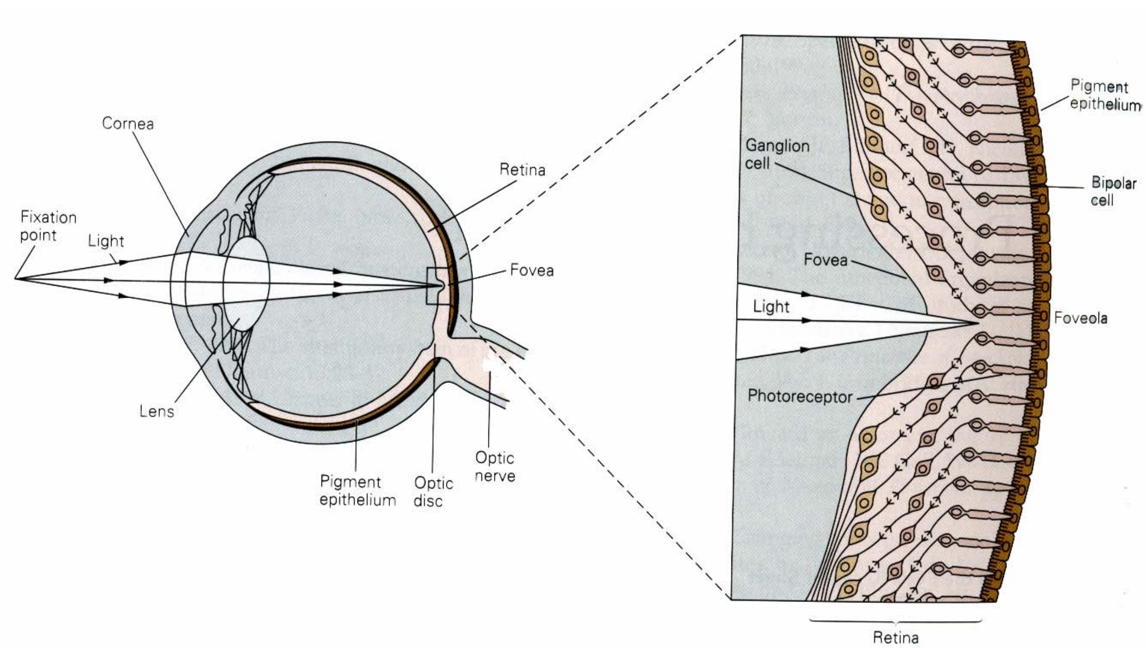


Figure 1. Anatomy of the eye (from Kandel et al., 2000).

With about 15 diopters, the lens is the second refracting element of the eye (Dodt, 1975) - the other elements, the humor and vitreous body are only of marginal influence. To a small amount, the lens is differently curved on the back in comparison to the front side and is attached via zonular fibers to the ciliary muscle which can change the shape of the lens. The ciliary muscle is formed like a ring - when it contracts, the diameter of the muscle ring is reduced, thereby relaxing the tension of the zonular fibers and making the lens more spherical. The main function of the lens is focusing on objects on different distances. For focusing on nearby objects the ciliary muscle contracts to unease the curvature of the lens, for focusing on far objects the ciliary muscle relaxes – rendering the lens more flat. This process of changing the shape of the lens is called accommodation.

One’s ability to clearly focus on an object depends on two factors: the dimension of the eyeball and the shape of the lens and cornea. At the age of 6-8 years, the eye should reach its optimal length of about 24 mm. If the eye is too long, the image is not focused on the retina, but between the lens and the retina. This is called myopia, near sighted vision. For hyperopia or farsighted vision respectively, the opposite is true. The eyeball is too short, and therefore the image is focused beyond the retina. In some cases the cornea or the lens does not have an optimal shape; they are not spherical yet rather cylindrically shaped - the so-called astigmatism. This causes the light to focus on more than one point on the retina and results in blurred vision. Astigmatism often is accompanied by myopia or hyperopia.

To conclude, incoming light is focused by the pupil and refracted by the cornea and the lens, then passing the vitreous humor, a clear liquid between lens, retina and the vitreous body, and reaching the photoreceptors, which are located in the retina at the back of the eye.

2.2 The visual system

2.2.1 The retina

Talking about the visual system in the brain means starting to talk about the retina, as the retina is already part of the central nervous system. It is formed embryologically from the optic vesicle that evaginates from the diencephalon. The photoreceptors can be considered as the "entrance gate" for the light to the retinal cells (Birbaumer & Schmidt, 1999), while the ganglion cells are the only cells with axons that leave the eye, forming together the optic nerve (Held, 1988). Between the photoreceptors and the ganglion cells three other types of cells are imbedded: the horizontal cells, the bipolar cells and the amacrine cells, forming together the bipolar layer. All the different retinal cells are arranged in an inverse way: the photoreceptors are turned away from light and towards the pigment epithelium at the outermost surface of the eye. The photoreceptor layer is at the back of the retina, while the ganglion cells form the inner cell layer. This inverse system prevents light from being reflected off the back of the eye to the retina again (Kandel et al., 2000) and provides a very high efficiency of the cells supporting the photoreceptors with oxygenated blood for the essential photopigment regeneration. Thus, retinal cells with the highest metabolism are close to the chorio capillaris. In animals eyes other than mammals, where a lower efficiency of the photosensitivity is needed, the receptors are arranged in an everse way (e.g. in the eyes of cephalopods).

The two types of photoreceptors are: cones (about 120 millions) and rods (about 6 millions). Cones are most prevalent in the central retina, and provide colour vision and a very good acuity. In the central retina, the fovea centralis – with the central spot of the foveola - is the area of finest vision. Here, cell bodies arranged in front of the photoreceptors are shifted away to get highest photosensitivity (Kandel et al., 2000). The light-sensitive cones are the only photoreceptors prevalent in the foveloa. They are most sensitive to moderate up to high wavelengths of light (380-760 nm) and mediate information about hue. Three different types of cones contain each one of the three different visual pigments whose abs0000orbencies are maximal for blue, green and red lights (Held, 1988). Rods are more prevalent in the periphery of the retina. In contrast to cones, rods are sensitive to light of low luminance and process basically monochromatic information (Carlson, 2001).

For the transduction of the visual information, initiated by a complex chain reaction, photopigments are involved in the first step. Photopigments decay by the exposition to light and due to this process the permeability of the sensors and the membrane potential is changed: with the breakdown of visual pigments hyperpolarization to -70 mV of the cones and rods follows (Held, 1988). This hyperpolarization reduces the release of neurotransmitters and causes the membrane of the bipolar cell to depolarize. In turn, the depolarization causes the bipolar cells to release more neurotransmitters. This process depolarizes the membrane of the ganglion cell at the inner cell layer, causing it to increase its rates of firing (Carlson, 2001). Taken together, light shining on the photoreceptors triggers a cascade of events leading to the excitation of the ganglion cell.

Functionally the receptive fields of the ganglion cells consist of two parts: the receptive field center and the surround. Retinal ganglion cells can be subdivided into different classes in terms of their size, shape and functional properties. For excitation of the cell, e.g. on-center ganglion cells are excited when light falls on the center of the receptive field, while they are inhibited when light is directed to the surround. Off-center ganglion cells have a reverse mechanism. On-center and off-center ganglion cells are present in more or less equal numbers and thus provide two parallel pathways for the processing of visual information (Kandel et al., 2000). This organization of the receptive fields is very important as it provides best transduction of the visual information. Receptive fields "respond best when light intensities in the center and surround are quite different" (Kandel et al., 2000, p 519), e.g. to stimuli with high-contrast properties like black-and-white patterns. In this context, the firing rate of a ganglion cell is a fine measure for the difference in intensity of light illuminating the center and surround. In addition to measuring contrast and illumination, ganglion cells analyze several other aspects of the visual image, such as color. Most ganglion cells fall into two functional classes: M (magno) cells and P (parvo) cells. M cells respond optimally to large objects and rapid changes in the stimulus, while P cells respond optimally to small, slowly moving objects and to color. This distinct functionality leads to parallel processing with parallel networks of ganglion cells.

At the layer of the optic nerve fibers, axons from ganglion cells are traversing the retina to leave the eyeball at the optic disk and carry visual information into the brain. The optic disk produces a blind spot since no receptors are located in that area. On the primary retinal-geniculo-cortical pathway, the axons of the retinal ganglion cells form the optic nerve pass the chiasma opticum, reach the lateral geniculate nucleus, and then proceed through the optic radiations to the primary visual cortex.

2.2.2 Optic nerve and chiasma opticum

The axons of the optic nerves of both eyes intermingle at the basis of the brain in the chiasma opticum, and then are sorted into the two optic tracts. Here the optic nerves are divided into temporal and nasal parts. Respectively, axons from ganglion cells on the nasal sides of the retinae cross the hemispheres through the chiasma opticum, while axons from cells on the temporal sides remain at the same side of the brain (figure 2). Thus the left part of the visual field of each eye is projected to the right hemisphere, while the right hemifield of vision is projected to the left hemisphere. Therefore, in analogy to the somatosensory system, each hemisphere receives information from the contralateral half of the outer world.

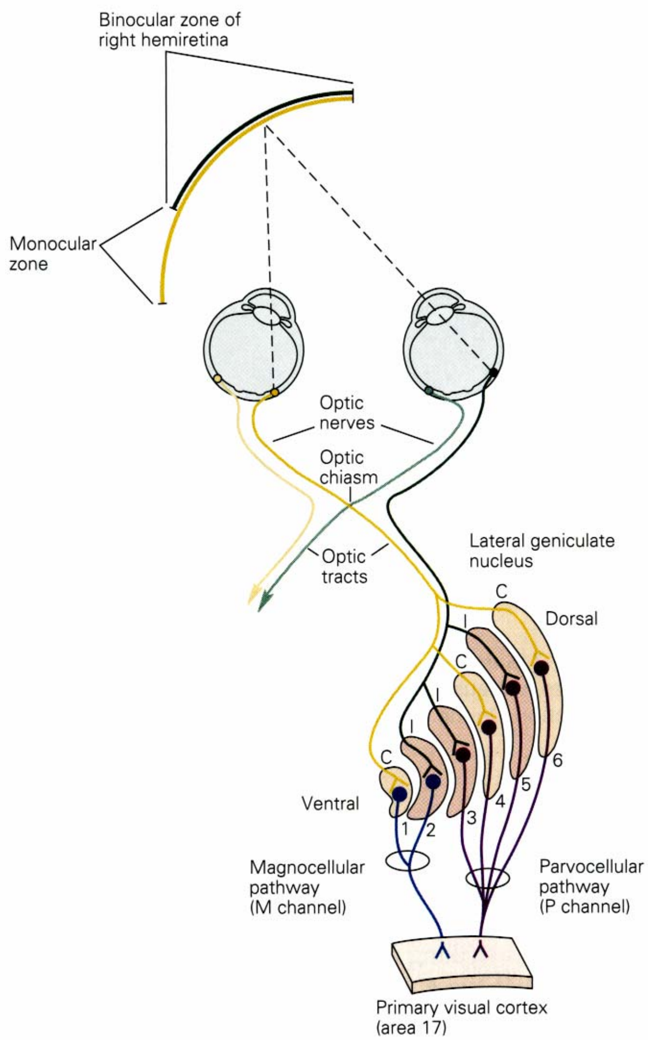


Figure 2. Course of the optic nerves, chiasma opticum and the tracti optici (from Kandel et al., 2000).

Beyond the chiasma, the axons of the ganglion cells continue through the optic tracts to reach several visual relay nuclei in the brain (Held, 1988) and each of the axonal projections is precisely organized. The distribution of fibers from one optic nerve into the two optic tracts relates to the amount of binocular vision, however at this time the two visual impressions of both eyes still remain separate. The partial crossing of retinal fibers in the chiasma opticum is necessary for stereoscopic vision, since it is necessary for later fusion of corresponding retinal images from the two eyes in higher cortical brain areas - that is, inputs from the two hemiretinae which view the same part of the visual field form two maps that are exactly aligned with each other (Held, 1988). The optic tract projects onto three subcortical targets: the lateral geniculate nucleus, the pretectal area of the midbrain and the superior colliculus. Of these three subcortical regions only the lateral geniculate nucleus processes visual information that ultimately results in visual perception (Kandel et al., 2000).

2.2.3 The lateral geniculate nucleus

The lateral geniculate nucleus (LGN) of the thalamus is the first station on the way to further visual processing. The axons of the retinal ganglion cells ascend through the optic nerves and reach the synapses of the LGN (Carlson, 2001). This is the only relay between retina and cortex. This nucleus contains six layers of neurons; the inner two ventral layers (laminae 1 and 2) are called magnocellular layers. They receive input from M-ganglion cells. The outer four dorsal layers are called parvocellular layers (laminae 3 to 6), receiving input from P-ganglion cells (see figure 2). The neurons in the two magnocellular layers contain cell bodies which are much larger than those of the parvocellular layers. There are striking differences between both cell types: P cells are critical for color vision and vision that requires high spatial and low temporal resolution vision, while M cells are most important for low spatial and high temporal resolution vision (Kandel et al., 2000). A third type of neurons can be seen in the koniocellular sublayers, which are positioned ventrally to the magno- and parvocellular layers. All those three types of layers - the magnocellular layer, the parvocellular layer and the koniocellular layer - belong to three different systems, each of which analyses different types of visual information.

The LGN is the site of termination of most optic tract fibers (Held, 1988). Each of its six layers receives input from only one eye, however the areas of the retina are not represented equally: the fovea - area of finest vision - has a relatively larger representation than does the periphery of the retina. The neuron layers are alternatingly allocated to the ipsi- and the contralateral eye. Inputs from the ipsilateral and contralateral eye remain segregated in laminae 2, 3 and 5 and 1, 4 and 6, respectively. Only few interactions between the ipsi- and contralateral layers occur, therefore no binocular processing of the visual signals is found in this stage. Going further, the neurons in the LGN send their axons through the optic radiations to the primary visual cortex (V1).

2.2.4 The striate visual cortex

Visual processing goes through different stages: from low level feature extraction in primary areas to complex processing of visual information in higher cortical areas. The visual cortex is organized in a hierarchical way, with the primary visual cortex at the bottom of such a hierarchy. V1, also called the striate cortex due to the “stria of Gennari”, which is visible with the naked eye, has six different layers and gets his main input from the lateral geniculate nucleus via the optic radiations. From the striate cortex several segregated pathways feed into extrastriate areas: the most important ones are the dorsal, magnocellular, “where” pathway and the ventral, parvocellular, “what” pathway (figure 3).

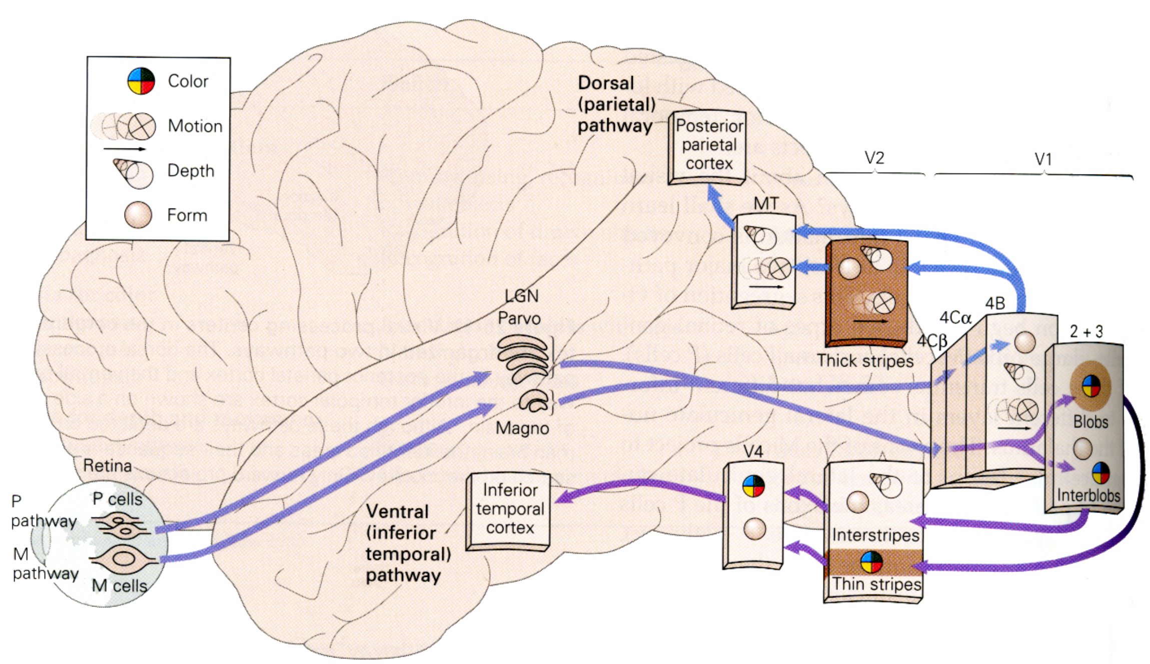


Figure 3. The visual cortex (from Kandel et al., 2000).

The primary visual cortex is a horizontal fissure surrounding the calcarine fissure and is located in the medial and posterior occipital lobe (Carlson, 2001). It processes the information of the retinal ganglion cells more precisely and then transmits it to the visual association cortex. The striate cortex has a retinotopic organization with the fovea having the largest area of representation. Input from the optic radiations leads mostly to layer IV of the primary visual cortex. Exactly speaking, from the LGN both magnocellular and parvocellular layers project to the primary visual cortex to layer 4C - the magnocellular layer to 4Cα and the parvocellular layer to 4Cβ. Continuing from this point both M and P pathways remain partially separated from each other through V2 (Kandel et al., 2000).

It is thought that the primary visual cortex is organized into different functional modules. There are three systems crossing the layers of the primary visual cortex: a) orientations columns, b) blobs, and c) ocular dominance columns (Kandel et al., 2000). These vertically oriented systems transfer information to each other by major horizontally oriented connections. Orientation columns contain neurons that are selectively sensitive to specific axes of orientation, while the blob regions (structures about 0.2 mm in diameter, revealed by a stain for cytochrome oxidase) are sensitive to colour and to low spatial frequencies. These blob regions are part of the parvocellular system. From the blob regions of V1, the P pathway continues to the thin stripes of V2 forming the ventral pathway, which reaches the inferior temporal cortex. In contrast to that, the M pathway projects from the stripes of V1 to the thick stripes of V2 forming the dorsal pathway (figure 3).

As pointed out above, neurons in the primary visual cortex are grouped in functional vertical columns. Each of these columns processes visual information from a specific region of the visual field (Kandel et al., 2000). They are commonly referred to as ocular dominance columns, as the left or the right eye dominates them. Input from the eyes has been found to enter layer IV in alternating patches, however in between are binocular areas as well that are activated from both, the left and the right eye. This combines the input from the two eyes, a step that is necessary for the perception of depth (Kandel et al., 2000).

Perception of depth

For the perception of depth two types of clues are necessary: monocular cues for depth and stereoscopic cues for binocular disparity (Kandel et al., 2000). The six monocular cues are the following: familiarity of size, occlusion of objects, linear perspective, and size perspective, distribution of shadows and illumination, and motion parallax. For large distances, perception relies on monocular cues, as the retinal images seen by the two eyes are almost identical. The slight difference in an object’s position between the two retinal images is very important for stereoscopic vision - this difference in position is called binocular disparity. Stereoscopic vision cannot arise until the disparity information of the two eyes gets together in the visual cortex. In V1 certain neurons are sensitive to horizontal disparity. Also cells in the extrastriate areas V2 and V3 respond best to retinal disparity, and some cells in area MST fire in response to the combination of disparity and direction of motion (Kandel et al., 2000). Two types of cells can be found in the striate cortex, simple and complex cells. Simple cells receive only monocular input and respond best to a bar of light with a specific orientation and position within the receptive field (Kandel et al., 2000), whereas complex cells have much larger receptive fields than simple cells and are stimulated by both eyes – most of them are binocular cells. There seems to be a hierarchy between the cells: each simple cell surveys the activity of a group of geniculate cells, and each complex cell surveys the activity of a group of simple cells (Kandel et al., 2000). Differences can be recognized even in the anatomy of V1: simple cells are found mostly in layer IV, complex cells more in layers above or beneath layer IV. To conclude, the only clue necessary for stereoscopic vision is retinal disparity. Complex cells do respond best to retinal disparity and thus are likely to play a role in depth perception.

2.2.5 The extrastriate visual cortex

The areas of the extrastriate visual cortex are located in two general regions: in the prestriate cortex and in the inferotemporal cortex (see Pinel, 2003). The prestriate cortex is a band of tissue in the occipital lobe that surrounds V1. The inferotemporal cortex is the cortex of the inferior temporal lobe. The secondary extrastriate visual areas (V2, V3, and V4) have still a retinotopic organization. Signals coming from neurons of area V1 are passed to V2, V3 or V4 depending on their functional aspect, that is, the neurons in each functional area respond most vigorously to different aspects of visual stimuli (e.g. color, movement, or shape). To be more specific, e.g. in area V5, commonly referred to as area MT (middle temporal area), neurons respond mainly to small, moving objects, whereas neurons of area MST respond to wide moving visual stimuli or global motion, respectively.

Although connections between areas of the extrastriate and the association cortex are reciprocal, the flow of information is up the hierarchy, from more simple to more complex areas. That means the higher in the visual hierarchy, the larger receptive fields the neurons represent and the more specific and complex are the stimuli to which the neurons respond. In addition, higher cortical areas have also feedback connections lower cortical areas. The pathways that conduct information from V1 through extrastriate and association cortex are parts of two major streams: the dorsal stream and the ventral stream. The dorsal stream flows from the primary visual cortex via the dorsal prestriate cortex to the posterior parietal cortex - including the middle temporal area -, the ventral stream flows from the primary visual cortex via the ventral prestriate cortex to the inferotemporal cortex - including area V4 (figure 4). The dorsal stream is involved in the perception of where objects are, while the ventral stream is involved in the perception of what objects are.

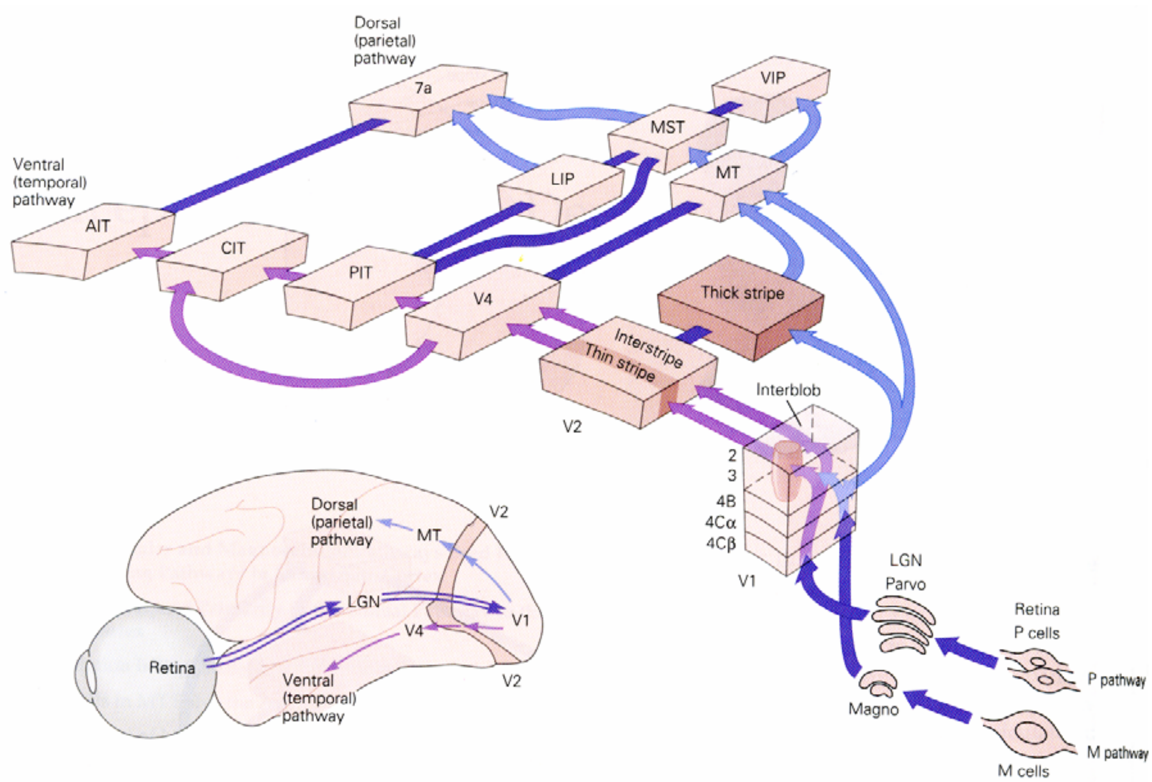


Figure 4. The visual pathways (from Kandel et al., 2000).

To put it in a nutshell, "the parietal cortex is specialized for spatial representation, whereas the temporal cortex is specialized for object recognition" (Kandel et al., 2000, p 498).

3. Amblyopia

Amblyopia is a developmental disorder of the visual system that leads to losses in spatial vision. The medical term "amblyopia" is derived from the Greek words αμβλυ-ωπός and means dull vision. Amblyopia is medically defined as the reduction of visual acuity in one or both eyes in absence of ocular disorders - it is the weak-sightedness of an eye and therefore often referred to as "lazy eye". The weak-sightedness happens despite good retinal image quality, does not involve any retinal defects or ocular deficits, the rod and cone receptors are oriented normally and the foveal pigment density is without pathological findings (Levi & Carkeet, 1993). Since spectacles cannot rectify the symptoms of the acuity loss, amblyopia is presumed to have a neurological source. Reason for the development of amblyopia is most probably abnormal neuronal processing of the visual information in the visual cortex. A detailed description of the development of strabismic and anisometropic amblyopia and the impairment of visual functions due to amblyopia is given in the following subsections.

3.1 Development of amblyopia

Amblyopia is a developmental disorder of spatial vision - it occurs quite early in life and with up to 2-5 % is "the most common cause of visual loss in childhood" (Sireteanu, 2000 a, p. 63). Amblyopia results from an abnormal visual stimulation early in life, and there are different types of amblyopia, which are defined according to their etiology. The main factors for abnormal postnatal visual development, which are associated with an enhanced risk for amblyopia, are an early misalignment of one eye, unequal refraction in both eyes, a cataract or a ptosis. If these disorders occur late in life, amblyopia does not develop and therefore a critical period in the development of amblyopia has to be assumed. There is some evidence that the onset of amblyopia may not begin prior to 3-4 months of age or at least not before the onset of the normal development of binocular interaction in the visual cortex, yet also that the onset of amblyopia is highly dependent on the type of amblyopia (Levi & Carkeet, 1993). Depending on these factors for the abnormal visual development, there are two main types of amblyopia: strabismic amblyopia, and deprivation amblyopia which also includes anisometropic amblyopia.

3.1.1 Strabismic amblyopia

The onset of eye alignment, and of binocularity, respectively, occurs for most infants sometime between 2 and 6 months after birth (Tychsen, 1993). In strabismic amblyopia an early misalignment of the eyes is mostly due to a squint - the two visual axes differ from each other. Due to miscoordination between both eyes, the visual axes do not meet at the fixated object. In one eye the fixation point lies on the fovea, but on another retinal area in the other eye: the signals from the two eyes are not correlated to each other and diplopia (double images) occurs. To prevent these double images, the perception of one eye is being suppressed. By this, the squinting eye is being excluded from vision and the functionally stronger eye becomes the dominant eye, resulting in a reduction of visual acuity in the squinting eye after a period of time (Sireteanu & Fronius, 1981). Only 35-50 % of the strabismic children also develop amblyopia (Levi & Carkeet, 1993). It seems that several factors are important for the development of strabismic amblyopia, like the age of onset (the earlier the worse) or the type of strabismus. E.g. strabismic amblyopia is more prevalent among esotropes (strabismus convergens - inward deviated eye) than among exotropes (strabismus divergens - outward deviated eye) (Howard, 2002).

3.1.2 Deprivation amblyopia

Deprivation amblyopia can occur due to a cataract or a ptosis. These conditions lead to the deprivation of visual stimuli or to inadequate visual stimulation respectively and consequently to the loss of form vision in the affected eye. Anisometropic amblyopia is considered to be a mild form of deprivation amblyopia - due to unequal refraction in the two eyes, probably caused by an unequal eye growth. Both eyes have a different focus of image, so that one eye gets a clear visual image, while the other perceives a blurred one. Due to the bilateral reflex for accommodation there is only a limited possibility to independently accommodate both eyes monocularly. In most cases the dominant eye gets the clear visual image, while the non-dominant eye - like in strabismic amblyopia - is being suppressed in order to avoid confusion. Although little is known about the development of anisometropia, it is discussed that "anisometropic amblyopia may have its onset considerably later than amblyopia associated with strabismus" (Levi and Carkeet, 1993, p. 402). Continuous blur has to persist for a longer period to develop anisometropic amblyopia (Daw, 1998). Consequently, anisometropic amblyopes show quite different (more similar to normal) results in psychophysical and imaging experiments than do strabismic amblyopes (Sireteanu, Tonhausen, Muckli, Lanfermann, Zanella, Singer & Goebel, 1998).

In general, any condition which provides no adequate visual stimulation and therefore causes a constant suppression of one eye early in childhood, is a potential source of amblyopia. However, due to the fact that only about 1/3 of the strabismic or anisometropic children are developing amblyopia, strabismus, anisometropia or other derivational factors are a necessary, still not sufficient condition for the development of amblyopia. Additionally, in all cases it is valid that the earlier the visual disorders occur and the greater the degree of the misalignment, the anisometropia or the stimulus deprivation, the greater the depth of amblyopia.

3.2 Mechanisms of adaptation

3.2.1 Interocular suppression

As pointed out above, interocular suppression is an adaptation mechanism due to strabismic or anisometropic amblyopia. The unequal refraction or the squint in one eye would cause double or blurred images, respectively, and in order to avoid diplopia, the brain of the young child suppresses the visual input of the most affected eye. There are two ways of suppression: first, only one eye is suppressed all the time. Due to the suppression, this eye may develop a reduction of visual acuity – amblyopia -, which cannot be corrected by spectacles. When the two eyes are suppressed alternatingly (strabismus alternans) the visual acuity remains normal in both eyes: due to the alternating fixation each eye contributes to the regions in which it is best (Sireteanu, 1982). People with alternating suppression do not belong to the group of amblyopes, as they have no reduction of visual acuity in one eye. While alternating fixation may only occur in strabismic people, suppression of always the same eye occurs in strabismics as well as in anisometropes. The area of the visual field affected by suppression is a different one in strabismic amblyopia and in deprivation amblyopia. Strabismic amblyopes have an asymmetric distribution of suppression. The suppressed areas of the deviated eye involve mainly the central and nasal retina (Sireteanu & Fronius, 1981; Abdolvahab-Emminger & Sireteanu, 1993; Sireteanu, 2000b). Contrary to this, anisometropes do not have an asymmetric interocular suppression (Sireteanu & Fronius, 1981). Sireteanu and Fronius (1981) found that in anisometropic amblyopes the acuity loss as well as the suppression of the nasal and temporal fields is symmetrical in the central as well as in the peripheral areas of the amblyopic eye.

Further, as a consequence of interocular suppression, humans with early strabismus or anisometropia suffer partial or complete loss of binocular vision and stereopsis (Sireteanu, Fronius & Singer, 1981). Most people who develop an interocular suppression (or alternating fixation, respectively) have monocular vision and therefore lost stereopsis. However, probably due to the limitation of the suppression to the central and nasal retinal areas, in some amblyopes, the peripheral non-suppressed regions of the amblyopic eye are still involved in binocular vision (Sireteanu, Fronius & Singer, 1981; Sireteanu, 1982). A reason for the most evident loss of binocularity in the foveal region may be that "with its high resolution and small receptive fields, binocular function is more likely to be disrupted than in the peripheral field, were the resolution is relatively low and the receptive fields relatively large" (Sireteanu, 2000b, p.40). Consequently, there is a loss of binocular neurons visible on the neuronal level of V1 (Hubel & Wiesel, 1977). Instead of binocular neurons, neurons that are activated monocularly were found in the striate cortex of monkeys and cats. However, the total number of neurons was not reduced (Sireteanu, 1991).

3.2.2 Anomalous retinal correspondence

Dependent on the gathered experiences, the developmental selection process optimizes and adapts neuronal connections in the visual cortex. One important function of this process is to make sure that binocular neurons form precisely aligned receptive fields in both eyes. This exact correspondence of the receptive fields can not only be defined via genetic information, as it also depends on individual characteristics, e.g. the distance between the eyes. So, by definition, those retinal regions are correspondent to each other, which get identical visual stimulation during binocular fixation (Singer, 1984). In a squinting eye exact alignment of the receptive fields can no longer be developed, so the brain evolves an adaptation mechanism. That is, in anomalous retinal correspondence (arc) the retinal coordinates are shifted in relation to the angle of squint: in harmonic anomalous retinal correspondence (h-arc) the objective angle of squint matches the subjective localization. This complete adaptation of subjective localization to the angle of squint is only possible in small and constant angles, as in so-called microstrabismus. In non-harmonious anomalous retinal correspondence (nh-arc), objective and subjective localization of the angle of squint do not match exactly.

The fact that strabismic amblyopes preserve binocularity in the periphery of the visual field suggests that in this region retinal coordinates are shifted due to anomalous retinal correspondence. In the central field, with its small receptive fields, any correspondence is hard to maintain with the deviated eye, and thus suppression is most evident in that region. However, in the periphery with larger receptive fields, anomalous retinal correspondence can be prevalent and no suppression is needed (Sireteanu & Fronius, 1989). There is evidence (Sireteanu, 1991; Sireteanu & Best, 1992) that mostly extrastriate areas are involved in this developmental process of anomalous retinal correspondence. The higher visual areas are more tolerant for deviations due to the squinting eye due to their bigger receptive fields. In V1, with its small receptive fields, no such compensation would be possible. So, on the neuronal level a process similar to that in the fovea and the periphery is assumed.

3.3 Visual deficits

3.3.1 Contrast sensitivity

Visual acuity represents the smallest high contrast stimulus that can be resolved. Still this is only one limit of visual capacity. In fact, most objects in daily life are large stimuli with low contrast. That is, every visual object can be analyzed by a combination of some basic visual patterns, so called sine-wave gratings. The threshold of contrast is the smallest difference in intensity between these dark and bright stripes one is able to detect. The contrast sensitivity is defined in relation to this threshold as the 1/contrast threshold ratio. The measurement for contrast sensitivity with sine-wave gratings is much more exact (about 4 - 5 times) than for instance with letters, and gives a quite good impression for the visual sensibility for objects. In addition to visual acuity, contrast sensitivity function is used for diagnostics in pathological changes of the visual system.

The reduced ability for strabismic amblyopes to detect low contrast objects is well known in literature (Asper, Crewther & Crewther, 2000a) - especially the higher frequencies (6 - 18 c/deg) are affected due to amblyopia. There is no significant contrast threshold difference between the eyes of normal observers, so amblyopes can be considered as their own control by comparing their amblyopic and their dominant and unaffected eye, respectively. Hess and Howell (1977) argued for two categories of reduced contrast sensitivity in strabismic and anisometropic amblyopes: either only the higher frequencies are affected (type I amblyopia), or both, high and low frequencies (type II amblyopia). They considered the type I amblyopia to be similar to simple dioptric blurring of moderate degree, however not the type II amblyopia. In the latter "the effect of defocus on low frequencies is slight ... when the high frequency degradation is equivalent to the amblyope's high frequency loss" (Hess & Howell, 1977, p. 1053). Note that only the amblyopic eye shows marked losses in contrast sensitivity, while the dominant eye is mostly unaffected. Secondly, the high frequency loss tends to be more severe in the high-and-low-frequency-abnormality class than for the high-frequency-only-abnormality class. Although the loss of contrast sensitivity at high spatial frequencies increases with the severity of amblyopia (Levi, 1991), still a small reduction in acuity is reflected by a large loss in contrast sensitivity. Strabismic amblyopes seem to lose contrast sensitivity especially in the central part of the retina, anisometropic amblyopes in the central and the peripheral part (Hess & Pointer, 1985). Most importantly, the reduced contrast sensitivity of the amblyopic eye is a result of a neural loss in foveal function (Hess, Bradley & Piotrowski, 1983). It does not result from optical factors, eccentric fixation or unsteady fixational eye movements (Levi, 1991).

3.3.2 Perceptual distortions

Perceptual distortions in adult amblyopia have been reported as early as in the late 1950ies (Pugh, 1958). In Pugh's study, participants reported pattern distortions of letters; the outline of a circle "became "jagged", "dragged", "smudged", or "rubbed", the blackness faded, and the circle appeared to be flattened" (p. 453). The distortions did not show any symmetry, however in all cases a consistency of the pattern distortion was observable.

Later the interest for perceptual distortions in strabismic and non-strabismic amblyopes increased in connection with several different topics e.g. concerning the deficit in spatial localization and intrinsic positional uncertainty in the amblyopic visual system. Quantitative and qualitative approaches have been used to investigate these amblyopic distortions.

In the qualitative way, investigators asked participants to describe their perception with the amblyopic eye. This was done mainly with gratings of different spatial frequencies shown to the amblyopic participants. Hess, Campbell & Greenhalgh (1978) discussed the effect of spatial frequency on pattern distortion. They showed participants gratings at a range of different spatial frequencies and asked them to compare their appearance as seen by the amblyopic eye with the appearance seen by the fellow normal eye. The vision by the amblyopic eye gets progressively distorted the higher the spatial frequency, while the vision of the dominant eye remains normal. Repeatedly, on a number of different sessions low spatial frequency gratings appeared fairly undistorted, however at higher spatial frequency gratings spatial distortions increased. The gratings were perceived as fragmented and jumbled.

Quantitative measurements of spatial errors and uncertainty were specified in studies from Bedell & Flom (1981; 1983). They described monocular spatial distortions, defined as the relative overestimations and underestimations in space in the nasal and temporal fields (Bedell & Flom, 1981), and directionalisation errors, as well as spatial imprecision. Spatial imprecision may also be labeled as spatial uncertainty and is defined by the variability of a participant's judgment regardless of its accuracy (Bedell & Flom, 1983). Bedell and Flom (1983) showed that considerable distortions and imprecision of spatial judgements characterize the amblyopic eye of strabismic but not of anisometropic amblyopes. Especially for the strabismic amblyopic eye, reduced acuity or unsteady fixation cannot account for the errors of relative directionalisation and imprecision of the spatial judgments.

On the other hand, the uncertainty and the magnitude of the errors in a vertical alignment task of Fronius & Sireteanu (1989) were quite closely related to the participant's visual acuity. They found a larger area of the visual field of the deviated eye to be more or less involved in abnormal space perception. The participant had to align several test stimuli between two vertical reference points. Instead of building up a straight vertical line with the two reference points as endpoints of the line, the amblyopic person constructed a curved line. That is, in the center of the visual field the differences between the amblyopic eye and the non-amblyopic eye are most pronounced. A map of the two-dimensional space perception (vertical and horizontal) of amblyopic participants showed spatial distortions especially in the amblyopic eye of strabismics with a large angle of squint (Lagrèze & Sireteanu, 1991). Hereby, each participant exhibited his or her individual distortion pattern for the amblyopic eye. It seems that showing a reference point during the perception task influences the direction of the distortions with regard to the position of the reference point. There was no significant difference between the non-amblyopic eye and the monocular two-dimensional map of normal observers.

Sireteanu et al. (1993) showed that amblyopic participants perceived distortions at higher frequency gratings using their amblyopic eye. The gratings of low spatial frequency seemed to be quite irregular and not exactly straight; the lines seemed to be bended to the outward. The high spatial frequency gratings were even more blurred with some participants showing a deep scotoma in some part of the gratings. Sireteanu et al. (1993) compared these individual subjective distortions by assigning results based on a quantitative psychophysical experiment (Lagrèze & Sireteanu, 1991; Sireteanu et al., 1993) to the grating stimuli. Results revealed that these reconstructed patterns only partially reflected the distortion perceived with the amblyopic eye. The spatial distortion of the percept through the amblyopic eye was often reported to be less than expected. The authors argued that this may be due to the different nature of the tasks that are likely to affect two different mechanisms in the brain.

Recently, Barrett, Pacey, Bradley, Thibos & Morrill (2003) categorized individual distortion patterns of amblyopic participants. They used the same procedure as Hess et al. (1978) and Sireteanu et al. (1993) with gratings of various spatial frequencies and orientations. One third (10 out of 30) of their participants showed no perceptual distortions, two third reported nonveridical perception with the amblyopic eye. Barrett et al. (2003) divided the anomalous spatial perceptions into five distinct classes of distortions: (1) wavy appearance of straight gratings; (2) the "jagged" type with abrupt positional shifts orthogonal to the grating orientation; (3) errors in perceived orientation; (4) fragmented perception in which the gratings appeared broken; (5) and scotomatous distortions showing large gaps in the gratings. Interestingly, for most of the participants the type of the perceptual distortion was not constant across different spatial frequencies or orientations.

In addition to these constant perceptual errors, amblyopic participants often describe their pattern perception as being temporally unstable on a short time scale (Barrett et al., 2003). In fact, this phenomenon of temporal instability in pattern perception has been briefly mentioned in some studies concerning amblyopia (e.g. Hess et al., 1978; Sireteanu, 2000 a). Amblyopic participants describe this phenomenon of temporal instability as if images are permanently changing, as if "seen through hot air" (c. f. Sireteanu, 2000 a, p. 71). However, there are no systematic studies aimed at describing this phenomenon in detail - no researcher has made the effort to describe this perceptual phenomenon or to investigate it psychophysically.

On the other hand, several studies have addressed the temporal aspects of amblyopic perception, especially dealing with motion (c.f. Simmers, Ledgeway, Hess & McGraw, 2003). Ellemberg, Lewis, Maurer & Brent (2000) found deficits in amblyopic temporal vision caused by visual deprivation, yet only at low temporal frequencies and with less severity than deficits in spatial vision. Ellemberg et al. (2000) concluded that mostly the slower developing aspects of spatial and temporal vision are affected and therefore the longer the deprivation of the amblyopic eye lasts, the higher temporal frequencies will be affected. Further, a deficit in perception of flickering stimuli was found to be highly dependent on the spatial properties of the stimulus and the individual amblyopic deficit (Bradley & Freeman, 1985). For large stimuli covering also peripheral parts of the retina or consisting of low spatial frequencies, no temporal deficits were found. In a temporal integration task, Altmann & Singer (1986) found a positive correlation between severity of amblyopia and impaired performance. In their study, there was a pronounced deficit of the amblyopic system to integrate temporally separate stimuli, and the interocular differences between the amblyopic and the dominant eye were getting bigger the longer the interval of the stimuli. Altmann & Singer (1986) proposed a disturbance of channels dealing with processing of temporal aspects and high spatial resolution. They suggested that neuronal responses on the amblyopic pathway might be less sustained in processing than those of the pathway of the fellow eye.

To summarize, perceptual distortions occur in adult amblyopia in addition to other perceptual deficits like loss in contrast sensitivity in the amblyopic eye (c.f. Hess & Howell, 1977), deficits in spatial localization (Bedell & Flom, 1981; Levi & Klein, 1983; Fronius & Sireteanu, 1989; Lagreze & Sireteanu, 1991;

Sireteanu, Lagrèze & Constantinescu, 1993) and spatial uncertainty in the amblyopic visual system (Bedell & Flom, 1981, 1983; Fronius & Sireteanu, 1989; Demanins & Hess, 1996; Wang, Levi & Klein, 1998; for a recent review see Asper et al., 2000a). The perceptual distortions can be separated in spatial and temporal ones. Strabismic amblyopic participants report their vision to be blurred, spatially distorted and temporally instable (Sireteanu, 2000 a; Sireteanu, 2000 b). Spatial misperception is absent or not so obvious at very low spatial frequencies, but increases for higher spatial frequencies. In amblyopes, vision for high spatial frequencies and low temporal frequencies is evidently impaired, and probably higher-level cortical processes are abnormal in amblyopia (Asper et al., 2000a; Sharma, Levi & Klein, 2000; Simmers et al., 2003; Sireteanu, 1991; Sireteanu et al., 1998).

4. Part I: Qualitative methods

The qualitative part I of this thesis consists of two studies, which attempt to get step by step as close to a description of the amblyopic perception as possible. In study 1, participants were shown different geometrical patterns of low and high spatial frequency and asked for their subjective amblyopic experience: a descriptive base of spatial and temporal distortions was assessed in this study. In study 2 an evaluation of the perceptual distortions encountered in study 1 was performed by the use of a matching paradigm.

4.1 Study 1: Drawing experiment

The purpose of the first study was to investigate the temporal instability and spatial distortions in amblyopic perception and thus to understand the nature of the amblyopic vision more fully. Due to the lack of previous research on temporal distortions, the main interest was in collecting descriptive data on the amblyopic perception of different geometrical patterns with low and high spatial frequencies. In addition, it was investigated if there were any systematic relations between the occurrence of spatial and temporal distortions and other characteristics of the amblyopic vision.

4.1.1 Method

Participants

Fourteen amblyopes participated in the study: seven strabismic amblyopes, four anisometropic amblyopes without strabismus and three anisometropic-strabismic amblyopes. Selection criteria for the amblyopic participants were: corrected visual acuity in the deviated eye of at most 0.5 Snellen acuity, measured with the Landolt C test for single optotypes and an interocular difference between the dominant and the amblyopic eye of at least 0.3 Snellen acuity. To be classified as anisometropic, amblyopes were required to have a minimum difference in refraction of 1.5 dpt between the eyes. All participants were 18 - 65 years old, had no red-green deficiencies, and no neurological or psychiatric ailments. They participated in the experiment for course credits or for a payment of 10,- € per hour. Informed consent was obtained from all participants after the nature and purpose of the study has been fully explained. The experiments were performed in accordance with the Declaration of Helsinki. The study was approved by the Ethical Committee of the Johann Wolfgang Goethe-University Frankfurt.

Orthoptic examination

All participants underwent full refraction and orthoptic assessment before testing. The orthoptic measurements included an anamnesis of the patients' medical history. The subjective refractive error of the eyes was assessed with the aid of Fronhäuser refraction lenses. Corrected visual acuity for far vision was measured with the Snellen acuity chart at 5 m distance, for near vision with the Landolt-C test at 40 cm distance. Angle of squint was assessed with simultaneous and alternate cover and prism test for far and near fixation. The visuscope test was used for the determination of fixation. Stereopsis was assessed with the TNO-, Randot-, Titmus- and Lang-Tests. For the evaluation of the retinal correspondence, the participants were tested with the Maddox cross in connection with dark and light red filters and with Bagolini striated glasses for far and near vision. The orthoptic examinations were performed by a professional orthoptist. Table 1 provides an overview of the clinical data of all participants.

Contrast sensitivity

As loss of contrast sensitivity is a major deficit in spatial amblyopic vision (see also chapter 3.3), prior to psychophysical testing, the participants' contrast sensitivity was tested for far (3.0 m) and near (0.4 m) vision. Monocular and binocular foveal contrast sensitivity function (CSF) was measured using the VIS -

Table 1. Orthoptic data of amblyopic participants.

Partici-pant	Gender, Age	Eye	Refraction	Visus c.c. (near vision)	Fixation	Strabismus (sim. Cover test)	Stereopsis	Correspondence	History
Strabismic amblyopes									
R.S.	male,	RE	+ 6.00 -1.25/171°	0.60	foveolar	far +2½°+ VD	negative,	h arc	Occlusion at 1 yr
	58 yr	LE*	+ 6.75 -1.50/5°	0.10	1.5°-2° nasal	near +3° + VD	excl. LE		
L.P.	female,	RE	+ 0.50 sph	1.00	foveolar	far -12½°+ VD 1°	negative,	nrc	Onset and occlusion at 4 yr, glasses until 15 yr
	33 yr	LE*	+ 0.75 sph	0.25	temporal	near ~± 0°	excl. LE		
M.K.	male,	RE*	+ 5.50 -4.00 / 145°	0.10	temporal	far +1½° + VD½°	negative,	h arc	Strabismus from early childhood, occlusion at 5
	29 yr	LE	+ 5.00 -4.75 / 5°	1.00	foveolar	near +1½° + VD¾°	excl. RE		yr
S.B.	female,	RE*	-10.0 sph	0.30	temporal	far +12° + VD	negative,	nh arc	Family history, strabismus from early childhood,
	25 yr	LE	- 9.0 sph	0.60	foveolar	near +12° + VD 7°	excl. RE		glasses at 5 yr
D.S.	male,	RE*	+ 5.25 -2.50 / 100°	0.25	fov. margin	far ± 0°	negative,	nh arc	Onset and glasses at 6 yr
	51 yr	LE	+ 4.50 -2.25 / 95°	1.00	foveolar	near +4° - VD	excl. RE		
A.F.	female,	RE	- 1.25 -2.00 / 85°	1.00	foveolar	far +3° - VD 1°	negative,	h arc	Strabismus from early childhood, glasses and
	22 yr	LE*	- 1.25 -1.75 / 105°	0.32	temp. margin	near +4½°- VD 1°	excl. LE		occlusion at 5 yr for one year
G.P.	female,	RE*	+ 1.25 sph	0.50	1° nasal	far +1°	negative	nrc	Occlusion at 6 yr, glasses at 7 yr
	27 yr	LE	+ 1.25 sph	1.00	foveolar	near +1°	excl. RE		
Strabismic and anisometropic amblyopes									
B.B.	female,	RE*	- 0.75 sph	0.08	temp. margin	far + ½° + VD 3°	negative,	nh arc	Strabismus from early childhood, glasses at 3 yr,
	29 yr	LE	- 1.50 +2.0 / 175°	0.90	foveolar	near - 2½° + VD 2°	excl. RE		occlusion 3-6 yr, surgery at 20 months
M.H.	female,	RE	+ 5.00 -0.75 / 142°	1.00	foveolar	far + 1½° ± VD	negative,	h arc	Family history, strabismus from early childhood,
	31 yr	LE*	+ 1.50 -0.50 / 0°	0.08	nasal	near + 4°	excl. LE		glasses at 3 yr, occlusion 4–5 yr, surgery at 5 yr
C.L.	male,	RE	- 3.50 -1.50 / 20°	1.00	foveolar	far +15° +VD 1°	negative,	nh arc	Strabismus from early childhood, occlusion in
	28 yr	LE*	+ 1.00 -1.25 / 0°	0.50	nasal - fovea	near +15° +VD 2°	excl. LE		kindergarten for 3 yr, surgery at 4 yr
Anisometropic amblyopes									
H.L.	male,	RE	plano	1.40	foveolar	± 0°	negative	nrc	Occlusion at 11 yr, glasses at 18 yr
	27 yr	LE*	+ 6.25 sph	0.25	foveolar				
T.S.	male,	RE	+ 1.25 sph	1.00	foveolar	± 0°	negative,	nrc	Occlusion and glasses at 6 yr
	30 yr	LE*	+ 2.75 -3.75/135°	0.40	nasal margin		excl. LE		
J.B.	male,	RE	- 2.25 sph	1.00	foveolar	± 0°	Positive	nrc	Occlusion and glasses at 6 yr
	26 yr	LE*	- 0.75 -2.00 / 15°	0.50	temporal				
M.B.	male,	RE	- 0.50 -0.50 / 45°	1.00	foveolar	± 0°	Positive	nrc	Glasses at 17 yr
	34 yr	LE*	- 3.00 -3.25 / 2°	0.50	foveolar				

Abbrevations: nrc = normal retinal correspondence, nh arc = non-harmonius anomalous retinal correspondence, h arc = harmonius anomalous retinal correspondence, VD = vertical deviation, + = esotropia, – = exotropia, * = amblyopic eye.

TECH CSF test charts (VCTS 6500 charts, VISTECH Consultants, Dayton, Ohio) consisting of 40 circular targets with gratings of different contrasts and spatial frequencies, arranged in five rows of eight targets each. The gratings were vertical or tilted 15 deg clockwise or counter clockwise from vertical and were arranged randomly in one of the three orientations. The spatial frequency of the gratings increased from 1.5 c/deg in the top row to 18.0 c/deg in the bottom row when viewed at 3.0 m distance. The spatial frequencies in the intermediate rows were 3.0, 6.0 and 12.0 c/deg.

Apparatus and stimuli

The stimuli for study 1 were geometrical black-and-white patterns: two gratings of spatial frequencies of 0.4 c/deg and 1.6 c/deg, one checkerboard with a spatial frequency of 0.4 c/deg and a rectangular grid with a line spacing corresponding to 3.2 c/deg (figure 5 a-d). The patterns were computer-generated, high-contrast and printed on white paper. They were presented to the participants in a distance of 57 cm.

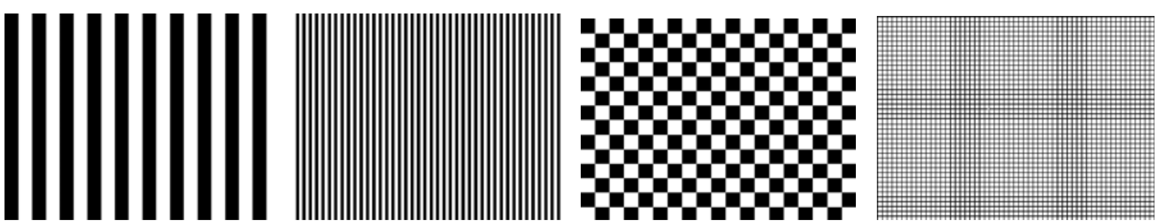


Figure 5 a-d. Grating stimulus of 0.4 c/deg. b. Grating stimulus of 1.6 c/deg. c. Checkerboard stimulus of 0.4 c/deg. d. Grid stimulus of 3.2 c/deg.

Procedure

A three-alternative forced-choice method was used for CSF measurements. The participants were asked to report the orientation of each of the eight gratings row by row. If the participants reported that the circular patch appeared blank, they were required to guess. Then, the number of the correct choices was recorded.

For the assessment of spatial distortions, the participants were asked to look at the different patterns with their amblyopic eye and to memorize their perception. The non-amblyopic eye was covered during this time. After memorizing, the participants were asked to draw the gratings, the checkerboard and the grid from memory, as they had perceived them with the amblyopic eye. They used the non-amblyopic eye for drawing the percept of the original patterns. There was no time limit to fulfill this task. The participants were allowed to look at the pattern with the amblyopic eye as often as they needed to refresh their memory. For testing the temporal distortions, the procedure was as described for the spatial ones. The participants were asked to describe verbally whether the spatial distortions captured in their drawings were stable or changed over time. They had to tell in which way they perceived the instability, whether temporal distortions appeared in addition to spatial ones, if there was a special "type" of instability occurring in the stimuli and for how long the temporal instability was perceivable. Based on the descriptions and drawings of the participants, images of the perception of each pattern and each amblyope were generated.

4.1.2 Results

Results of the orthoptic examination

Out of the seven strabismic amblyopes, three (LP, AF and GP) had either no noteworthy or relatively low refractive errors in either eye and could thus be classified as primarily strabismic amblyopes. Two other participants (MK and DS) had a high ametropia in both eyes (hyperopia combined with astigmatism) and thus can be classified as accommodative strabismic amblyopes. The remaining two participants (RS and SB) had reduced acuity in both eyes, probably due to an early, uncorrected high refractive error in both eyes and a consecutive microtropia. RS had a high bilateral hyperopia with astigmatism, SB a severe bilateral myopia. In the following, these participants shall be classified as “refractive strabismic amblyopes”. With the exception of LP and SB, all strabismic participants were microtropic. None of them underwent surgery, however RS, LP, AF, GP and CL were occluded at various ages. All of them were stereoblind and showed an exclusion of the most affected eye. Fixation was eccentric in all cases, correspondence ranged from normal (LP and GP) to differing degrees of anomality (harmonious in RS, MK and AF, non-harmonious in SB and DS).

The three anisometropic-strabismic amblyopes (BB, MH and CL) showed differing degrees of refractive errors, usually in combination with astigmatism. All had been occluded and underwent surgery quite early in life. None of them showed any residual stereopsis, all showed an exclusion of the amblyopic eye. Participants BB and MH were microstrabismic, participant CL had a large-angle consecutive esotropia.

The four anisometropic participants (HL, TS, JB and MB) showed differing degrees of refractive errors, no squint, normal correspondence and central fixation in both eyes. Not all of them showed an exclusion of the amblyopic eye. Participants JB and MB showed some residual stereopsis. All had received their first treatment after 6 years of age. Participant MB did not undergo occlusion therapy and even got his first glasses at 17 years of age.

Relationship between spatial and temporal misperception and the orthoptic characteristics of the participants

Of the 14 participants included in this study, two did not report any distortions, six perceived spatial distortions but no temporal instability and another six perceived temporal instability either in addition or in the absence of spatial distortions. Out of the six participants presenting spatial distortions only, one participant was purely strabismic (LP), two were strabismic with a severe bilateral refraction error (RS and SB) and 3 were purely anisometropic (JB, HL and MB). Of the temporal-instability group, 3 were strabismic (MK, DS and GP), 2 strabismic-anisometropic (BB and CL), and one purely anisometropic (TS). Of the two participants experiencing no distortions at all, one was strabismic (AF), and one strabismic-anisometropic (MH). As these data suggest, temporal instability is perceived mostly in amblyopes with a history of strabismus (table 2).

	Type of amblyopia			
	Strabismic	Strabismic & refraction	Strabismic & anisometropic	Anisometropic
No distortion (n = 2)	1	-	1	-
Spatial distortion only (n = 6)	1	2	-	3
Temporal instability (n = 6)	3	-	2	1

Table 2. Type of amblyopia and type of perceptual distortion.

For the purpose of analysis, acuity loss was divided in three categories: very deep (visus of the amblyopic eye was 0.08-0.19), moderate-to-deep (0.2-0.39), and moderate (0.4-0.5). The visual acuities of the amblyopic eyes of the participants not experiencing any perceptual distortions were 0.32 for the strabismic participant AF and 0.08 for the strabismic-anisometropic participant MH. Thus, it appeared that even strabismic participants with a very deep amblyopia do not necessarily experience distorted vision. This finding is quite surprising, as it seems that neither the aetiology nor the severity of amblyopia are a requirement for the presence of spatial distortions in amblyopic participants (see also Barrett et al., 2003). The acuity loss of the participants showing spatial-distortions-only ranged from moderate to deep (visus of the amblyopic eye was 0.50 for MB and JB, 0.30 for SB, 0.25 for LP and HL, and 0.10 for RS). The same was true for the group experiencing temporal distortions (visus was 0.50 for GP and CL, 0.40 for TS, 0.25 for DS, 0.10 for MK and 0.08 for BB, see figure 6). There was no significant difference in visual acuity between the three distortion groups ($F(2,11) = .36$, $p = .71$). Means for the no-distortion-group, the spatial-distortion-group and the temporal-distortion-groups were $M = .20$, $M = .32$, and $M = .31$, respectively.

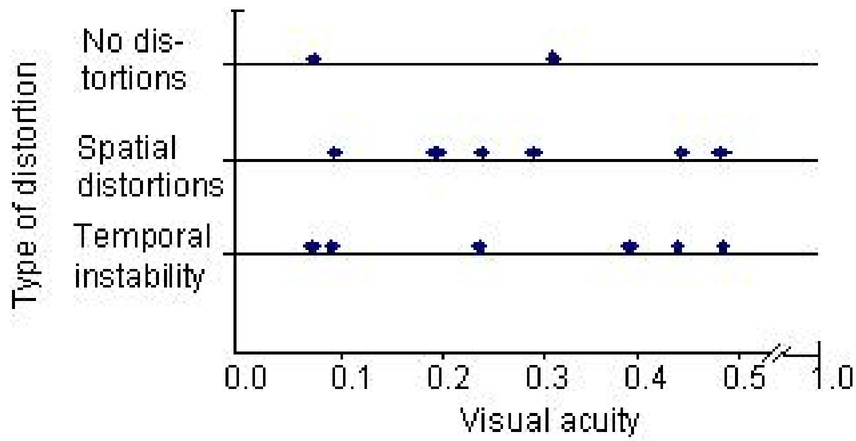


Figure 6. Type of distortions in comparison with visual acuity of the amblyopic eye.

There were no significant correlations between the type of distortion (spatial, temporal or none) and any of the clinical orthoptic data like angle of squint, eccentric fixation, residual stereopsis, type of correspondence etc. However there was an intriguing positive trend between the side of the amblyopic eye and the type of distortion, meaning that when the right eye is the amblyopic eye, temporal distortions are more likely to occur: 67% (4 out of 6) of the participants with a left amblyopic eye perceived temporal instability, while in 83% (5 out of 6) of the amblyopes with a right amblyopic eye only spatial distortions occurred. In addition, most of the participants perceiving temporal instability with the amblyopic right eye (4 out of 6) were right-handed.

Anomalous perception in amblyopic vision

12 out of 14 amblyopes examined in this study (86%) reported anomalous spatial perception. Two cases of strabismus (participants MH and AF) did not report visual misperceptions or differences in their perception between the eyes for any of the four patterns. Both participants without anomalous perception had a microstrabismus and an exclusion of the left, amblyopic eye. Of the twelve participants who reported anomalous perception, six perceived spatial distortions but no temporal instability (the microstrabismic participant LP, the purely anisometropic participants MB, JB and HL, and the two refractive-strabismic participants RS and SB). The remaining six participants perceived temporal

instability of the original patterns, either in addition (the microstrabismic participant GP, the anisometropic participant TS and the strabismic–anisometropic participants CL and BB), or in the absence of spatial distortions (the microstrabismic participants DS and MK).

In the following, a detailed qualitative description of the subjective experience of the anomalous perception in the amblyopic participants is given.

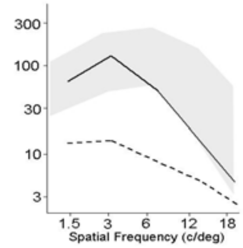
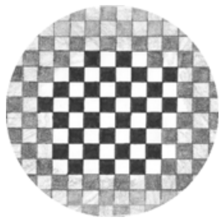
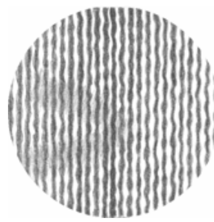
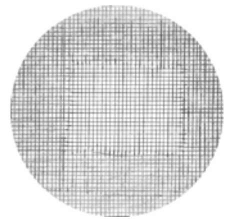
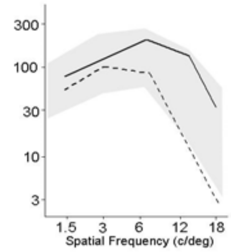
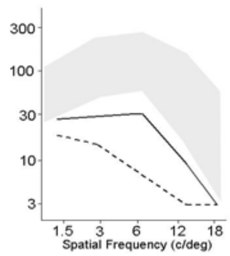
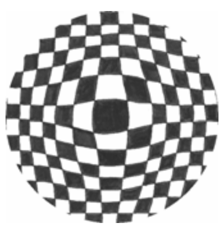
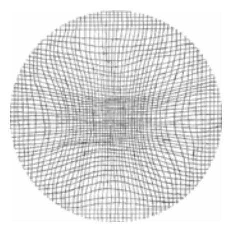
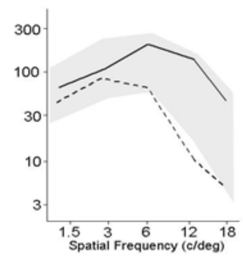
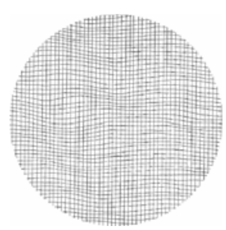
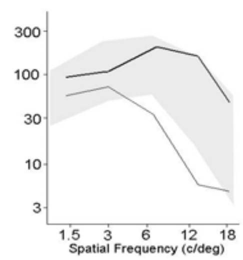
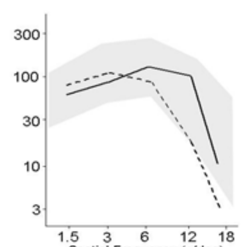
a) Spatial distortions

Participants RS, LP, SB, JB, HL and MB reported distorted perception for the amblyopic eye. All experienced constant spatial distortions, yet no temporal instabilities at any spatial frequency. The results of these participants are shown in table 3.

We could find in our sample the five different distortions categories proposed by Barrett et al. (2003). The wavy appearance of vertical lines only emerged in grating patterns, either in low and high spatial frequency (participant LP) or only at low spatial frequency (participant SB). This wavy perception or bending of vertical lines showed up solely in the group of strabismic amblyopes. Additionally, one participant (participant HL) reported perception of wavy horizontal lines for the high frequency grid. However the incidence of these horizontal waves was extremely low, and the wave-like distortions were hardly observable.

The "jagged type of perceived positional modulation" (Barrett et al., 2003, p. 1558) was clearly visible in participant MB. In both, high and low frequency gratings the jags appeared as a quite regular pattern. The jags were all of similar size and orientation; however, the repetition rate of the jags was much higher for the high spatial frequency grating. In comparison with the waves perceived by some participants, the jags seemed to be generally higher in repetition.

Table 3. Spatial misperception and contrast sensitivity for amblyopic participants with stable vision in the amblyopic eye.

Participant	Grating 0.4 c/deg	Checkerboard 0.4 c/deg	Grating 1.6 c/deg	Grid 3.2 c/deg	Contrast Sensitivity (in c/deg)
RS	Blurred perception	Blurred perception		Blurred perception	
LP					
SB					
JB			No distortions		
HL		Blurred perception			
MB		No distortions		No distortions	

Most of the participants reported misperceptions referring to a third category, the so-called "errors in perceived orientation" (Barrett et al., 2003, p.1558). These orientation errors were observed by 4 out of 6 amblyopes (67 %: participants LP, SB, JB and HL). However there seemed to be two subtypes within this category, at variance from the subtypes proposed by Barrett et al. (2003). One of them was only appearing in the checkerboard and the grid. Lines were here bended to the left (participant SB – checkerboard 0.4 c/deg) or bended inwards or outwards (participant JB – checkerboard 0.4 c/deg and grid 3.2 c/deg). In the second subtype, superimposed lines or contours distorted the high frequency patterns. Participant LP perceived a shadow-like inward positioned arrowhead on the left side of the pattern, in addition to the wavy perception of the lines of the grating. Participants RS and SB reported no perceptual errors of the high spatial frequency grating or the grid, except that the patterns were broken by blurred lines of a different orientation, which intersected the patterns. This error in orientation was observable in all strabismic participants for higher spatial frequencies.

Finally, three out of six participants (50 %) reported to perceive blurred images of the patterns. Two of them (participants RS and HL) had a blurred perception of the whole pattern, while for participant LP either the surround in the low frequency checkerboard or the left side in the high spatial frequency grating appeared blurred. Even if in the amblyopic perception of participants RS and HL the blurring of the pattern was not as unsettling as the spatial distortions, blurred vision might represent a significant factor in the spatial misperception in amblyopia.

It is hereby noticeable that in all except two participants (JB and MB), when distortions were perceived at low spatial frequency grating or checkerboard, there were also distortions perceived at the high spatial frequency grating and grid, respectively. There was a strong relationship between the spatial frequency and the appearance and severity of the spatial misperception:

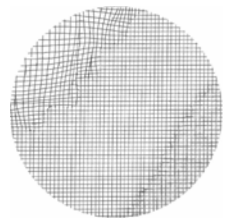
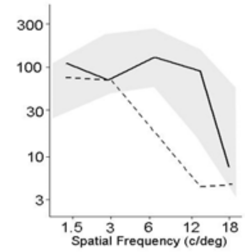
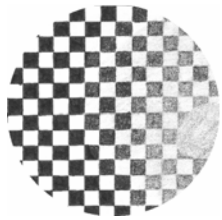
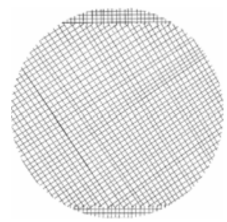
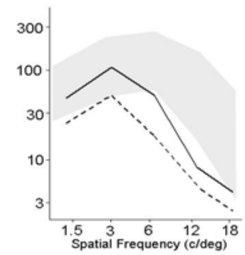
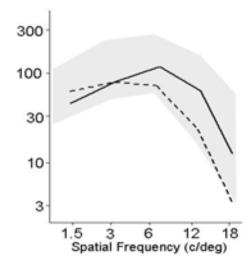
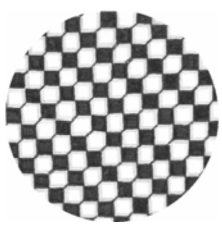
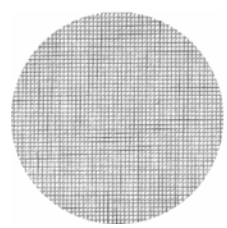
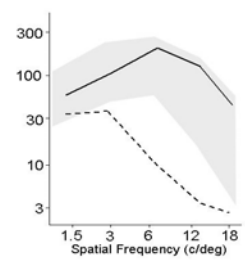
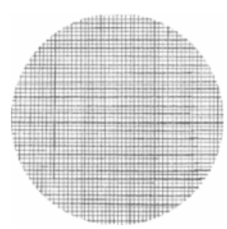
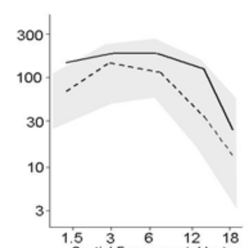
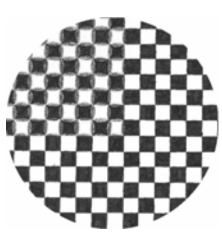
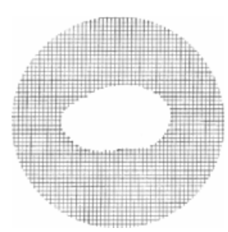
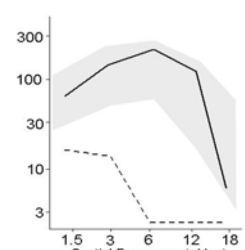
for the higher spatial frequencies (1.6 and 3.2 c/deg), the spatial distortions were more pronounced than for the lower spatial frequency patterns. In participants RS and especially SB, lines intersected the grating or grid and distorted the appearance of the pattern even more extremely.

b) Temporal instability

The remaining six amblyopes (43% - MK, DS, GP, TS, CL and BB) perceived temporal instability, either in addition or in absence of spatial distortions. The spatial distortions experienced by these participants were comparable to those of the previous group and shall not be discussed in detail here. There was a high correlation between the amount of spatial frequency and the prevalence of pattern instability: Temporal instability was only perceived at the higher spatial frequency grating and grid, no instability appeared in the 0.4 c/deg spatial frequency patterns (see table 4). Temporal instability was perceived without any nystagmus evident in the amblyopic or both eyes, respectively.

As described above, the participants perceived the spatial distortions to be unstable on a short time scale. These temporal instabilities fall into two categories. In the first one, the whole pattern was perceived as moving or flickering, while in the second, moving lines pervaded the pattern. Examples for the first category - the "whole pattern flicker" - were most common (4 out of 6 participants). Participants GP and BB perceived in the higher spatial frequency grating all stripes as vibrating, participant CL as moving from one side to the other. In the first two participants the stripes flickered on a short time scale, while in participant CL movement of the whole grating was experienced. CL also perceived a movement of the whole pattern in the grid, yet to the opposite direction than in the grating. Participant DS perceived a movement of the grid as well, in his case all stripes were moving in the upward direction. All of these participants were strabismic (participants DS and GP were microstrabismic, participants CL and BB strabismic-anisometropic amblyopes).

Table 4. Spatial misperception and contrast sensitivity for amblyopic participants perceiving temporal instability.

Participant	Grating 0.4 c/deg	Checkerboard 0.4 c/deg	Grating 1.6 c/deg	Grid 3.2 c/deg	Contrast Sensitivity (in c/deg)
MK		No distortions	 Lines moving		
DS			 Lines moving	 Lines moving up	
GP			 Stripes vibrating		
TS			 Moving inside to out		
CL		No distortions	 Moving from left - right	 Moving jerkily to left	
BB			 Lines vibrating		

Participants in the second category - the "line moving only" – were the two accommodative strabismic amblyopes MK and DS. They reported lines crossing the high spatial frequency grating and moving constantly on a small spatial range. In both participants, the lines distorted the pattern on the horizontal axis, they moved from the left to the right. Unlike in perception of patterns in the whole-pattern-flicker category, here the grating itself remained undistorted. There were no spatial distortions in addition to the temporally instable lines.

The temporal misperception of the anisometropic participant TS was difficult to allocate to one of the proposed instability categories. TS perceived squares propagating from the inside to the outside of the grating field. After focussing on the high frequency pattern, the participant saw an unstable, small diameter area in the center of the grating. This area of temporal instability was getting bigger in diameter as it propagated to the periphery of the grating field. The stripes of the high spatial frequency grating itself remained undistorted.

Generally, it can be said that in the whole-pattern-instability category, spatial distortions were perceived in addition to the temporal ones, while in the line-moving-only category no spatial distortions were perceived. Here, temporal misperception occurred solely.

c) Colour illusions

Four participants (MK, DS, CL and BB) reported, in addition to temporal instability, perception of colour-like contours in the high spatial frequency patterns. These 4 participants (67%) were strabismic (MK and DS) or strabismic-anisometropic (CL and BB) amblyopes. Participants MK and DS perceived the moving lines pervading the grating in rainbow-like or red-and-green colours, respectively. In participant’s CL vision, the stripes in the high spatial frequency grating appeared also in prism colours - similar to participant MK -, while the cubicles in the grid pattern were perceived in greenish colour. Participant BB had a perception of vibrating lines, appearing in red and yellow.

In sum, there seem to be two types of colour misperceptions accompanying the perception of temporal instability: on the one hand all kinds of colours in the prism or rainbow spectrum are appearing. On the other hand, only one or two colours (green, red or yellow) are perceived. There is no relationship between the appearance of colour misperception and the category or type of temporal misperception.

Relationship between perceptual errors and contrast sensitivity

The findings of different types of contrast sensitivity loss in amblyopia were replicated in this study (for a short overview to loss in contrast sensitivity in amblyopic vision see chapter 3.3.1). In the following, the two types of contrast sensitivity loss in amblyopic participants described by Hess & Howell (1977) shall be called “high spatial frequency loss” and “high and low spatial frequency loss”, respectively. Examples for the first type are the participants MH, LP, JB, HL, MK and TS, for the second participants RS and BB. A third type of contrast sensitivity loss where participants experience no or only a mild contrast sensitivity loss (Weiß, Rentschler & Caelli, 1985) or a bilateral contrast sensitivity loss shall be called “mild contrast sensitivity loss”: This category comprises participants in which contrast sensitivity was either in the normal range for both eyes (participants AF, MB, GP and CL), or below the normal range in both eyes (participants SB and DS).

Of the participants with undistorted perception, participant AF showed a mild contrast sensitivity loss (both eyes were in the normal range), while MH showed a much deeper loss for higher spatial frequencies for the amblyopic eye (the non-amblyopic eye was in the normal range). Thus, contrast sensitivity loss does not seem to be related to the occurrence of perceptual distortions.

Out of the group of participants showing spatial distortions only, the participants LP, JB and HL had a deep contrast sensitivity loss in the amblyopic eye, affecting mainly the higher spatial frequencies (6 c/deg or above; see table

3). These participants showed clear perceptual distortions for the higher spatial frequencies of the patterns. The mildly amblyopic anisometrope MB showed only moderately reduced contrast sensitivity in the amblyopic eye (both eyes were in the normal range). He did not experience distortions in the higher, but only in the lower spatial frequency range, for which his contrast sensitivity was not affected (0.4 or 1.6 c/deg). For the two refraction-strabismic amblyopes SB and RS, contrast sensitivity of both eyes was in the lower or below the normal range. Both participants showed clear distortions, especially for the higher spatial frequency grating.

Of the participants with temporal instabilities, those showing the deepest contrast sensitivity losses (the deeply amblyopic microstrabismic participant MK, the moderately amblyopic anisometropic participant TS and the very deep amblyopic strabismic-anisometropic participant BB) also showed spectacular perceptual distortions. The spatial and temporal distortions in the microstrabismic participant GP and the strabismic-anisometropic participant CL, both moderately amblyopic, do not seem to be related to their modest pattern of contrast sensitivity loss. Also, the spectacular pattern of distortions of the microstrabismic participant DS is difficult to reconcile with his bilateral contrast sensitivity loss.

In sum, participants experiencing constant spatial distortions and participants with temporal instability nearly fall into the same contrast sensitivity loss categories (see table 5). Qualitatively, it might seem that participants with the deepest contrast sensitivity losses (LP, JB, HL, TS and BB) tend to show the most pronounced perceptual distortions. Nevertheless, as illustrated in table 5, there was no quantitative relationship between contrast sensitivity losses and the type or severity of distortions.

	Type of contrast sensitivity loss		
	Low & High	High only	Mild loss
No distortion (n = 2)	-	1	1
Spatial distortion only (n = 6)	1	3	2
Temporal instability (n = 6)	1	2	3

Table 5. Type of contrast sensitivity loss and type of perceptual distortion.

Results of the contrast sensitivity test for both eyes for the two groups of amblyopic participants experiencing spatial or temporal distortions, respectively, are shown in figure 7. Both, for participants with constant spatial misperceptions in the amblyopic eye and for participants with temporally unstable misperceptions, the deficit in contrast sensitivity for the amblyopic eye became clear at a spatial frequency of 3 c/deg and increased for frequencies of 12 and 18 c/deg. Contrast sensitivity of the amblyopic eye is similar for amblyopes with and without temporal instability for all spatial frequencies (all $F(1,10) > .025$, all $p > .35$).

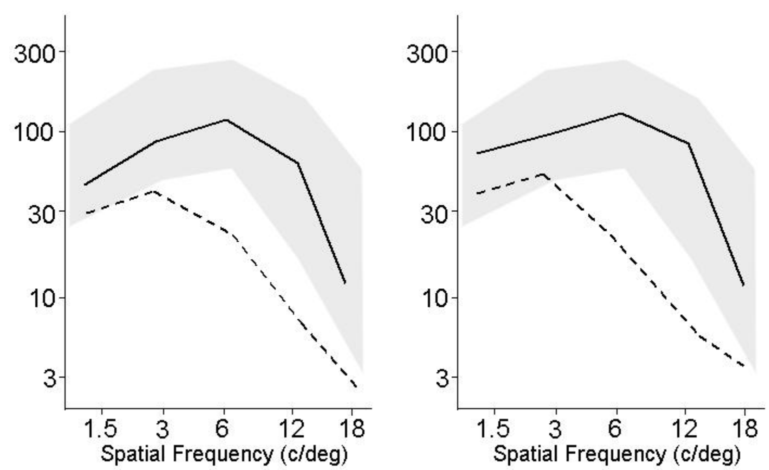


Figure 7. Contrast sensitivity functions for the amblyopic eye (dashed lines) and fellow (solid lines) eye of participants experiencing constant spatial distortions (left) and temporal instability (right).

4.1.3 Discussion

In this study, different types of distortions became apparent in the drawings of the amblyopic participants: a) blurring of patterns, b) wavy and jagged appearance of horizontal and vertical lines, c) distortions due to superimposed lines or contours, and d) errors in orientation. These different types of distortions correspond to the five distortion categories proposed by Barrett et al. (2003).

Concerning the temporal instability, almost half (6 out of 14) of the investigated amblyopes experienced temporal distortions, either in addition (4 cases) or in absence (2 cases) of spatial misperception. Temporal instability occured only at high spatial frequency, spatial distortions for low spatial frequency had a stable character. In total, there were two types of categories concerning temporal instability: a) the whole pattern is perceived as jittering, and b) single lines or parts in the pattern are perceived as moving. The temporal instability patterns were superimposed to the spatial distortions and emerged in addition to them.

The role of aetiology

As this sample of amblyopic participants reflects, there might be a preponderance of strabismic participants in the temporal-instability group - temporal instability phenomena seem to occur mainly for strabismic and strabismic-anisometropic amblyopes: three out of four strabismics and two out of three stabismic-anisometropic amblyopes, but only one out of three anisometropic amblyopes sensed temporal instability. One of the unexpected findings of this study is that the subjective experience of spatial distortions, with or without temporal instability, can occur in purely anisometropic participants. This is at variance from previous reports (e.g. Lagrèze & Sireteanu, 1991) and indicates that an early ocular misalignment is not a necessary condition for spatial misperceptions. Neither is absence of stereopsis or total exclusion of the amblyopic eye from binocular vision a prerequisite for the occurrence of spatial or temporal distortions: all four anisometropic amblyopes showed some degree of spatial or temporal distortion, albeit two of them (JB and MB) had some residual stereopsis.

There is also no secure relationship between pattern of distortions and angle of strabismus, presence of eccentric fixation, type of correspondence, therapy or known early history. However, the positive relationship between the side of the amblyopic eye (left or right eye is amblyopic) and the type of distortion might be an important result for understanding the temporal distortions more deeply. It seems that the eye dominance is a crucial factor for the development of a temporally instable perception in amblyopic vision in addition to spatial distortions. 4 out of 6 amblyopes perceiving temporal instability had a right amblyopic eye and in addition were right-handed. These results show that it is not only the side of the amblyopic eye by itself, but probably the interaction between opposite sides of hand and eye dominance.

The role of visual acuity loss

Of the six participants with spatial distortions only, one had a very deep (RS), 3 a moderate-to-deep (LP, SB and HL) and 2 a moderate amblyopia (JB and MB). In the temporal-distortions group, 2 participants suffered a very deep (MK and BB), one a moderate-to-deep (DS) and 3 a moderate amblyopia (GP, TS, and CL). From the two participants without distortions, one had a very deep (MH) and one a moderate-to-deep amblyopia (AF).

Thus, very deep amblyopia seems not to be a good predictor of either spatial or temporal distortions. Moderate-to-deep acuity loss is more often associated with spatial distortions, while temporal distortions occur more often in moderate amblyopes. It seems indeed that neither the severity of amblyopia nor any other factors of the orthoptic status of an amblyopic person are good predictors whether spatial or temporal distortions are going to occur.

The role of contrast sensitivity loss

Hess & Howell (1977) described two types of amblyopic deficit, which could be replicated in this study: a type affecting both, higher and lower spatial frequencies and the other show only a loss of higher spatial frequencies. In addition, a “mild” loss was defined in which both eyes remain either in the normal contrast sensitivity range or slightly below it. For most participants, higher spatial frequencies were progressively more affected in the amblyopic eye. With very few exceptions (participants RS and BB), all patterns used for examining distortions had spatial frequencies as low as to be seen equally well through both eyes of the amblyopic participants. Thus, the experienced distortions could not have been due to reduced contrast sensitivity.

The „spatial-distortions-only“ group contains one participant with a high and a low spatial frequency deficit (RS), 3 participants in which only the higher spatial frequencies were affected (LP, JB and HL), and 2 mild cases (SB and MB). In the „temporal-distortions” group, one participant presented a deficit for both higher and lower spatial frequencies (BB), 2 participants had a deficit for the higher spatial frequencies alone (TS and MK) and 3 participants could be classified in the „mild loss” type (DS, GP and CL). The two participants not experiencing any distortions belong to the higher-frequency-only (MH) and the mild type (AF), respectively.

Thus, the contrast sensitivity losses do not predict accurately the occurrence and severity of distortions. A deep loss, affecting both high and low spatial frequencies, is certainly associated with a distorted vision, however it does not necessarily predict whether a purely spatial or a combination of spatial and temporal distortions is going to occur. Participants with mild losses often do not report distortions, still sometimes they do, especially in cases of severe ametropia, like in participants SB, MB, DS or CL. Spatial distortions without temporal instability occur more often in participants with a selective loss of higher spatial frequency. Temporal instabilities are most often associated with a mild contrast sensitivity loss.

4.2 Study 2: Matching experiment

To provide an objective measurement of amblyopic distortions, study 2 operationalises the spatial distortions, reported by the amblyopic participants in study 1. In a previous study, Sireteanu et al. (1993) transferred experimental data that mirrored the spatial distortions into computer-generated geometrical patterns. Their participants were asked to compare the constructed patterns with their own perception observed through the amblyopic eye. As they found, vision seems to be more distorted at the higher and more complex patterns, however the results also indicate that the transformed patterns do not always reflected the actual perception of the amblyopic eyes (Sireteanu et al., 1993). The aim of the following study is to go one step further and come as close to the amblyopic perception as possible. This is done by using transformed patterns that are based on the amblyopic vision acquired in study 1 and that are computer-generated stimuli that show the perceived spatial distortions of the original patterns. The results of this psychophysical study are also used as stimuli for a following study using functional MRI to investigate the neuronal sites of activation deficits in strabismic and anisometropic amblyopes (Sireteanu, Bäumer, Sârbu, Tsujimura & Muckli, in preparation).

4.2.1 Method

Participants

Participants for a pretest of the experiment were eight persons with normal or corrected-to-normal vision (age 26 to 48, three of them male, all right-handed). Participants for the main experiment were the same as in study 1 (see table 1).

All participants participated for course credits or for a payment of 10,- € per hour. The refractive errors were fully corrected in all participants.

Apparatus and stimuli

In study 2, using the drawings from the first part, computer-generated stimuli were created by the experimenter, which showed the perceived spatial distortions of the original patterns. Criterion for the computer-generated stimuli were the individual distortions, and by that individual stimuli were constructed for all of the four different patterns for each participant. For each distorted pattern, four experimental stimuli were prepared. These four stimuli differed in amount of distortion: the first stimulus was the original undistorted pattern, the third stimulus corresponded to the reported amblyopic perception, mapped from the drawings of study 1, and the second and fourth were stimuli with smaller and more exaggerated distortions, respectively. The second and the fourth stimuli were either more or less distorted than the reported distortions. This was done in order to appraise the precise spatial distortions in the participants' amblyopic vision. In total, there were four test stimuli of differing distortion amount for each pattern: the first stimulus was not distorted at all, while the fourth stimulus was the most distorted one.

The stimuli we used were presented on a 19'' Iiyama colour monitor with a frame rate of 85 Hz. Size of the stimuli was 12.5 degrees. For monocular stimulation during the experiment, participants wore red-green goggles. Stimuli were presented in corresponding colours: red stimuli (RGB = 242, 0, 0) were shown to the dominant eye, green stimuli (RGB = 0, 249, 177) to the amblyopic eye. Depending on the colour of the stimulus (either red or green), the eye seeing through the complementary filter of the goggles is thereby excluded from perception. The perceived colour of the stimulus at the screen was hereby black and white. The wavelengths of the red and green stimuli and the goggles had been matched. For exact matching, luminance of the stimuli was measured with a photometer (LiteMate II, Kollmorgen Co., Burbank, USA) and the colour of the stimuli was adjusted accordingly. All stimuli were presented against a grey background. The advantage of this presentation procedure was that manipulation or cover of one eye was not necessary for monocular stimulation.

Procedure

The participants were seated in front of the monitor screen in an otherwise darkened room and wore the red-green goggles. To control for head position, the participants' head rested on a chin-rest to maintain an eye-to-monitor distance of 57 cm. It was ensured that the participants understood their task before the experiment started. The procedure for one trial was the following: an undistorted reference stimulus (e.g. the low spatial frequency checkerboard) was shown to the amblyopic eye for five seconds. Then, two test stimuli were presented on the screen of which the participants had to chose the one which fitted best their perception of the reference stimulus; that is of the amblyopic perception, respectively. After that another trial followed. Showing all pairs of the stimuli (4 x 3 pairs) and having five repetitions per pair, the participants had to make 60 comparisons in total. There was no time limit to fulfil the task.

At the beginning, each participant accomplished a test trial with the dominant eye. For best comparison between the amblyopic and non-amblyopic perception, the whole experiment was repeated twice. At the end of the second session, participants were debriefed and the purpose of the experiment was explained.

4.2.2 Results

Pretest

Prior to the main experiment of study 2, a pretest was conducted in order to investigate if the matching task is a proper tool, capable of identifying the target reference stimulus from different test stimuli, as well as to test the reliability of the task. For statistical analyses, the number of hits for each matching were computed. Due to the dichotomous type of each matching variable, data were analysed first with descriptive statistics, a further analysis of probabilities for each stimulus was submitted to a paired-samples t-test and an ANOVA with a repeated measurement design. Here and in all subsequent analyses, the α level was set to .05.

The pretest showed that all participants (N = 8) had a clear preference for test stimulus 3, which was the test stimulus that matched 100 % with the reference stimulus. Means of frequencies for test stimuli 1 through 4 were M_1 = 1.5, M_2 = 13.25, M_3 = 28.63, and M_4 = 16.63, respectively. Standard deviation was lowest for test stimulus 3 (SD = 1.19), and highest for the two test stimuli 2 and 4 (SD_2 = 5.06, SD_4 = 6.46). The main effect for “test stimulus” was significant, $F(3, 5) = 1670.82$, $p = .00$, and more specifically, a two-tailed t-test for pair wise comparison revealed a significant difference between the test stimuli 1, 2 and 4 in comparison with test stimulus 3 (ts (7) > 6.28, ps < .00).

A 2-tailed paired-samples t-test was done to calculate the influence on the stimuli comparisons for showing a test stimulus either on the left or the right side of the monitor screen. None of the pairs for stimuli 1 through 4 showed a significant difference between the placed sides - left versus right stimulus side (ts (7) < 2.05, ps > .08).

For testing the reliability of the task, the experiment was repeated twice. First and second sessions were submitted to a repeated measurement ANOVA. Again, as expected, the main effect “test stimulus” was significant, $F(3, 2)$ = 4132.17, $p = .00$, however the interaction between test stimulus and repetition did not reach a significant level, $F(3, 2) = 1.068$, $p = .52$. Mean and standard deviation of the two test sessions were exactly the same, Ms = 25, SDs = .00.

The significant effect for test stimulus 3 in difference to the other three test stimuli, and additionally the low standard deviation for making the decision for this stimulus, indicates that the participants did not have any problem in choosing the test stimulus that corresponds to the reference stimulus. This also fits the high standard deviations of test stimuli 2 and 4, which are most similar to stimulus 3 and therefore most difficult to distinguish from test stimulus 3. The lack of significance for a side effect as well as for a difference in repetition accounts for the robustness of this paradigm and shows that it is an appropriate tool for matching stimuli with each other with regard to a reference stimulus.

Main experiment

Amblyopic participants had first to pass a test trial to be sure that they understood the task. This test trial was the same as in the pretest done by normally sighted participants, but here it was done by amblyopic participants with the non-amblyopic eye. All amblyopic participants passed the test trial (frequencies for test stimulus 3 were fs > 26, minimum differences from test stimulus 3 to other test stimuli were fs > 4) except participant SB, who chose test stimulus 4 instead of test stimulus 3. The data of this participant were excluded from further analysis, as it was not sure if SB was either not willing or able to follow the instructions properly. SB had a bilateral refractive strabismic amblyopia and probably the low vision of the non-amblyopic eye influenced the results of the matching task. Vision of the amblyopic eye could therefore not be tested in the desired way.

First run. One basic assumption was that the distortion results of the drawings in study 1 should also emerge in study 2. It was thus expected that the third test stimulus - which was made exactly like the distortion drawing in study 1 - would be the test stimulus to be chosen by the participants. Results show that this was only true for participant HL for matching the low frequency grating. For all other trials or stimuli, respectively, participants chose either the first, or second, or the fourth test stimulus (see table 6 a-d).

For the low spatial frequency grating (table 6 a), participant HL chose test stimulus 3 with a probability of p = .48 (f = 29), all other test stimuli showed a probability of p < .30 (f < 18). Participants JB and MB chose test stimulus 2 with probabilities of p_{JB} = .40 (f = 24) and p_{MB} = .48 (f = 29), probabilities and frequencies for both participants for all other test stimuli in the low frequency grating were ps < .35 and fs < 21. Participant LP was the only one to choose the undistorted test stimulus 1 in the low frequency grating. Success probability of test stimulus 1 was p = .48 (f = 29), probabilities (with frequencies in parentheses) of test stimuli 2 through 4 were .35 (21), .16 (10) and .00 (0). Overall, the difference between the chosen test stimulus which matched best with the reference stimulus, and all other test stimuli had a range from p_{min} = .50 (f = 3) to p_{max} = .18 (f = 11). Participant RS was the only one to report veridical perception in this grating of .4 c/deg.

Table 6 a. Probabilities (and frequencies) for matching of grating .4 c/deg (matched test stimuli are put in bold letters).

Participant	Test stimulus 1	Test stimulus 2	Test stimulus 3	Test stimulus 4
HL	.11 (7)	.30 (18)	**.48 (29)**	.10 (6)
JB	.35 (21)	**.40(24)**	.20 (12)	.50 (3)
LP	**.48 (29)**	.35 (21)	.16 (10)	.00 (0)
MB	.33 (20)	**.48 (29)**	.18 (11)	.00 (0)
RS	No distortions	No distortions	No distortions	No distortions

For the high spatial frequency grating, differences between the test stimuli were similar to those of grating .4 c/deg (table 6 b). Differences between the test stimulus matched with the reference stimulus, and all other test stimuli ranged from p_{min} = .08 (f = 5) to p_{max} = .16 (f = 10). With the highest possible score, participant MB chose test stimulus 2 (p = .50, f = 30) over the other stimuli (ps < .33, fs < 20). Participants HL and LP chose either the most exaggerated test stimulus 4 or the undistorted test stimulus 1, respectively, with probabilities of p_{HL}

= .38 (*f* = 23) and p_{LP} = .46 (*f* = 28), probabilities and frequencies for both participants for all other test stimuli in the grating were *p*s < .36 and *f*s < 22. As well as participant LP, participant RS matched the undistorted test stimulus 1 with the reference stimulus (*p* = .50, *f* = 30), probabilities and frequencies for the other test stimuli 2 through 4 were *p*s < .33 and *f*s < 20. Participant JB did not report any spatial misperceptions.

Table 6 b. Probabilities (and frequencies) for matching of grating 1.6 c/deg

Participant	Test stimulus 1	Test stimulus 2	Test stimulus 3	Test stimulus 4
HL	.06 (4)	.25 (15)	.30 (18)	**.38 (23)**
JB	No distortions	No distortions	No distortions	No distortions
LP	**.46 (28)**	.36 (22)	.16 (10)	.00 (0)
MB	.33 (20)	**.50 (30)**	.16 (10)	.00 (0)
RS	**.50 (30)**	.33 (20)	.16 (10)	.00 (0)-

Participants JB and LP perceived spatial distortions in the low spatial frequency checkerboard, while participants HL, MB and RS reported normal perception of the pattern (table 6 c). Somehow corresponding to the undistorted perception of participants HL, MB and RS, both, participant JB as well as participant LP chose the undistorted test stimulus 1 with a very high frequency, *f* = 29 and *f* = 30, respectively. Success probability of test stimulus 1 was *p* = .48 for participant JB and *p* = .50 for participant LP.

Table 6 c. Probabilities (and frequencies) for matching of checkerboard .4 c/deg

Participant	Test stimulus 1	Test stimulus 2	Test stimulus 3	Test stimulus 4
HL	No distortions	No distortions	No distortions	No distortions
JB	**.48 (29)**	.35 (21)	.16 (10)	.00 (0)
LP	**.50 (30)**	.33 (20)	.16 (10)	.00 (0)
MB	No distortions	No distortions	No distortions	No distortions
RS	No distortions	No distortions	No distortions	No distortions

Again, in the high spatial frequency grid (3.2 c/deg), participants chose either test stimulus 1 or 2 (table 6 d). Success probability was very high for the chosen test stimulus 1 in participants HL and JB, p = .50 (f = 30) and p = .48 (f = 29), respectively. Differences between test stimulus 1 and all other test stimuli were quite big, ps > .13, fs > 8. Participant LP preferred test stimulus 2 over all other test stimuli (p = .46, f = 28), and the differences in success probabilties were even higher (ps > .20, fs > 12).

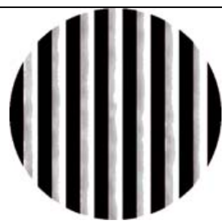
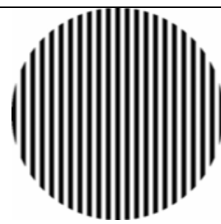
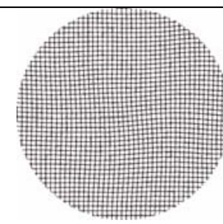
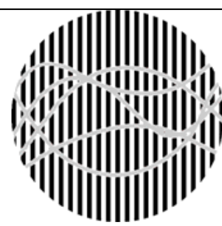
Table 6 d. Probabilities (and frequencies) for matching of grid 3.2 c/deg

Participant	Test stimulus 1	Test stimulus 2	Test stimulus 3	Test stimulus 4
HL	**.50 (30)**	.33 (20)	.16 (10)	.00 (0)-
JB	**.48 (29)**	.35 (21)	.13 (8)	.03 (2)
LP	.23 (14)	**.46 (28)**	.26 (16)	.03 (2)
MB	No distortions	No distortions	No distortions	No distortions
RS	No distortions	No distortions	No distortions	No distortions

Overall, participant LP was the one who had spatial misperceptions throughout all of the four patterns. However, in most of the cases (7 out of 12), participants chose either the first test stimulus or the last one. In these cases it is not clear if the distortion perceived is even more exaggerated (when choosing test stimulus 4) or much less pronounced (when choosing test stimulus 1). For this reason, the experiment was repeated twice.

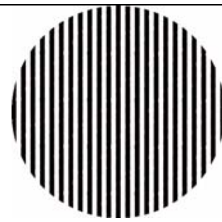
Second run. In the second run of the experiment, test stimuli were provided in a way that the test stimulus which was matched in the first run with the reference stimulus still was the third test stimulus in the second run. Depending on the perceived distortion of this matched test stimulus, the remaining test stimuli were made with much finer more or less exaggerated distortions to get more precise matching results. Results are now listed not by the patterns but by each participant for a more individual description of the matched spatial distortions; data are only provided for the final results after two sessions in the experiment. Participants HL and RS did not take part in the second run of this experiment. Results of the spatial distortions matched in the first run of the experiment are provided in table 7 for both participants HL and RS.

Table 7. Results of the matching experiment for participants HL and RS for gratins 0.4 c/deg and 1.6 c/deg, checkerboard 0.4 c/deg, and grid 3.2 c/deg.

Participant	Grating (0.4 c/deg)	Grating (1.6 c/deg)	Checkerboard (0.4 c/deg)	Grid (3.2 c/deg)
HL			No distortion	
RS	No distortion		No distortion	No distortion

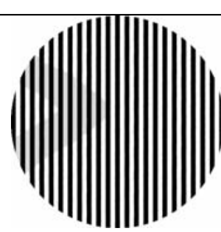
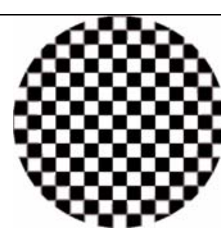
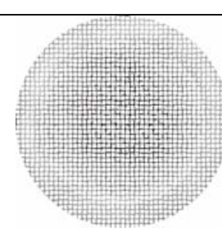
Participant MB reported spatial misperception only for the grating patterns of .4 c/deg and 1.6 c/deg (see table 8). Due to the finer gradation, there was no undistorted test stimulus 1, but one with very small spatial distortions. Participant MB chose in both, the low spatial frequency grating and the high spatial frequency grating, test stimulus 1. Probabilities and frequencies for this stimulus were p = .48, f = 29 and p = .50, f = 30, respectively. Differences between test stimulus 1 and all other stimuli were ps > .13 for grating .4 c/deg, and ps > .16 for grating 1.6 c/deg. In sum, the reference stimulus in the second run was matched with a test stimulus much less pronounced than expected from the results of the first run in this study.

Table 8. Results of the matching experiment for participant MB.

Participant	Grating (0.4 c/deg)	Grating (1.6 c/deg)	Checkerboard (0.4 c/deg)	Grid (3.2 c/deg)
MB			No distortion	No distortion

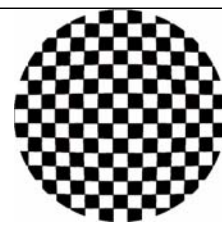
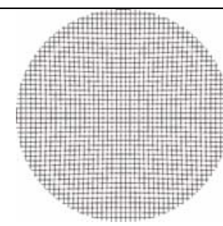
Having spatial misperceptions in all of the four patterns, participant LP chose test stimulus 2 to match the reference stimulus throughout the four patterns. Compared to participant MB, LP had about the same amount of quantity in spatial distortions. MB chose in the first trials test stimuli 2 and in the second trials test stimuli 1, while LP chose in the first trials mostly test stimulus 1 (except for checkerboard 3.2 c/deg) and in the second trials test stimulus 2. Both stimuli treated over the two runs have the same linear gradiations in spatial distortion. For LP, probabilities (with frequencies in parentheses) of test stimuli 2 for grating .4 c/deg, grating 1.6 c/deg, checkerboard .4 c/deg and checkerboard 3.2 c/deg were .45 (27), .45 (27), .41 (25) and .41 (25). Overall, the difference between the chosen test stimulus and all other test stimuli had a range from p_{min} = .06 (f = 4) to p_{max} = .15 (f = 9). The test stimuli which matched best with the reference stimulus and hence with the amblyopic vision can be seen in table 9.

Table 9. Results of the matching experiment for participant LP.

Participant	Grating (0.4 c/deg)	Grating (1.6 c/deg)	Checkerboard (0.4 c/deg)	Grid (3.2 c/deg)
LP				

The second time, participant JB again always chose the undistorted test stimulus 1 over the other test stimuli (table 10). Probabilities and frequencies for the test stimuli 1 were p = .43, f = 26 for the low spatial frequency grating, p = .43, f = 26 for the low spatial frequency checkerboard, and p = .41, f = 25 for the high spatial frequency checkerboard. Differences between test stimulus 1 and all other stimuli were ps > .15 for grating .4 c/deg, ps > .06 for checkerboard .4 c/deg and ps > .02 for checkerboard 3.2 c/deg. As one can see, differences especially between test stimulus 1 and test stimulus 2 in both of the checkerboard patterns are very small.

Table 10. Results of the matching experiment for participant JB.

Participant	Grating (0.4 c/deg)	Grating (1.6 c/deg)	Checkerboard (0.4 c/deg)	Grid (3.2 c/deg)
JB		No distortion		

4.2.3 Discussion

Distortional effects were very similar to those of the previous experiment. In analogy to study 1, refractive strabismic amblyope RS did not report any spatial misperceptions in the low spatial frequency grating and checkerboard and the high spatial frequency grid. The three anisometropic amblyopes JB, HL and MB reported undistorted perception in the low spatial frequency checkerboard (HL), the high spatial frequency grating (JB), and the low spatial frequency checkerboard and the grid (MB). Strabismic amblyope LP was the only participant experiencing spatial distortions in all four patterns.

Relationships first run of the experiment vs. second run

In contrast to study 1, the amblyopic participants perceived much less pronounced spatial distortions than expected from the results of the previous study. In half of the cases (6 out of 12), participants chose the undistorted test stimulus 1, and in 4 out of 12 cases they matched their perception with the least distorted test stimulus 2. These surprising results gave rise to a second run of the experiment, which provided a finer gradation of distortions of the amblyopic vision. Unfortunately, data for a second trial of the experiment were available only for the two anisometropic participants MB and JB and the strabismic amblyope LP. Compared to the first run, distortions were once more less pronounced than expected from the results of the first run. Both anisometropic participants MB and JB chose test stimulus 1, while LP perceived some spatial distortions, and chose test stimulus 2. As the probability differences between the chosen test stimulus and the neighbouring test stimuli were very small, especially in the anisometropic participants, those participants might still perceive spatial distortions, however probably be unsure about their real amount.

The results in this study are similar to the results Sireteanu et al. (1993), and Hess, Pointer, Simmers & Bex (2003) found in their experiments. Hess et al. had veridical matches in an edge-blur task for amblyopes with a history of strabismus as well as for strabismic amblyopes with an associated anisometropia. Hess et al. (2003) concluded that “amblyopes perceive edges as sharp and not blurred even though their acuity and contrast sensitivity is dramatically reduced” (p. 2258). In contrast to that, anisometropic amblyopes without a strabismus did exhibit a mild degree of perceived blur. This is at some variance from the results of the matching experiment in this thesis, as the anisometropic amblyopic participants did not report spatial distortions although the results reflect an increased uncertainty about their matching. A reasonable explanation for the results in study 2 as well as for Hess et al. (2003) experiments might be that contour information is sufficient to recognize an object most of the times (Kandel et al., 2000), especially when the uniform interior does not contain any critical visual information.

Another reason for the small spatial distortions could be that the participants of this sample chose the more undistorted patterns because of the special type of the matching paradigm. By the comparison of two test stimuli, amblyopic participants are more likely to choose the undistorted test stimulus. This may be either because amblyopes who have a distorted perception could identify different spatial frequencies as accurately as those with veridical perception (see also Barrett et al., 2003), and therefore match the distorted perception with the undistorted pattern in any spatial frequency. Or because of their amblyopic vision, which might be influenced by external parameters e.g. such as contour information (Kandel et al., 2000). This would also explain the results of the pretest with normal sighted adults as well as the results of the pretest for each amblyope, conducted with the non-amblyopic eye. In each, they had no problems in matching the distorted stimuli with each other.

In general, the results of the matching task showed distortions that are much less pronounced than expected from the drawings of study 1. This was especially conspicuous in the low frequency patterns. However the structure and complexity of the spatial and temporal distortions remained the same over the two experiments. That is, in the comparison between study 1 and study 2, one can say that the type of distortion was the same for the drawings and the matching task. The spatial distortions did not change in quality for both paradigms, yet in quantity. This is also consistent with previous results from the group of Sireteanu (Sireteanu et al., 1993): quantitative data differ from qualitative descriptions and only partially reflect the amblyopic perception. It seems that amblyopes experience and describe their distortions subjectively more vividly than can be captured accurately in quantitative experiments (see also Hess et al., 2003).

5. Part II: Quantitative methods

5.1 Study 3: Circle experiment (auditory instructions)

As pointed out in the introduction chapter, the aim of the following studies is to quantitatively measure the temporal as well as the spatial distortions in amblyopic vision, and to relate the temporal distortions to the performance of the amblyopic participants in psychophysical tasks. The following experiments are a further development of the work of Lagrèze and Sireteanu (1991), and Sireteanu et al. (1993). These authors could show that spatial distortions and spatial uncertainty are increased in strabismic amblyopia, however did not focus on temporal instability in amblyopic vision. In the following, Lagrèze and Sireteanu's (1991) method was improved and further developed by the additional assessment of temporal instability.

5.1.1 Method

Participants

With the exception of strabismic amblyope GP, amblyopic participants in experiments of part II were the same as in experiment 1. Participants were six strabismic amblyopes, four anisometropic amblyopes, three strabismic and anisometropic amblyopes, and additionally three strabismic alternators and twelve adults with normal vision (see table 11). Selection criteria for the normal participants and the alternators were: corrected visual acuity of ≥ 1.0 Snellen acuity in both eyes, no interocular deviation, and for the normal participants good stereo acuity. The participants with normal vision were matched in gender and age (± 5 years) each with one of the amblyopes or alternators, respectively.

Table 11. Orthoptic data of amblyopic, alternating, and normally sighted participants

Partici-pant	Gender, Age	Eye	Refraction	Visus c.c. (near vision)	Fixation	Strabismus (sim. Cover test)	Stereopsis	Correspondence	History
						Strabismic amblyopes			
R.S.	male, 58 yr	RE LE*	+ 6.00 -1.25/171° + 6.75 -1.50/5°	0.60 0.10	foveolar 1.5°-2° nasal	far +2½°+ VD near +3° + VD	negative, excl. LE	h arc	Occlusion at 1 yr
L.P.	female, 33 yr	RE LE*	+ 0.50 sph + 0.75 sph	1.00 0.25	foveolar temporal	far -12½°+ VD 1° near ~± 0°	negative, excl. LE	nrc	Onset and occlusion at 4 yr, glasses until 15 yr
M.K.	male, 29 yr	RE* LE	+ 5.50 -4.00 / 145° + 5.00 -4.75 / 5°	0.10 1.00	temporal foveolar	far +1½° + VD½° near +1½° + VD¾°	negative, excl. RE	h arc	Strabismus from early childhood, occlusion at 5 yr
S.B.	female, 25 yr	RE* LE	-10.0 sph - 9.0 sph	0.30 0.60	temporal foveolar	far +12° + VD near +12° + VD 7°	negative, excl. RE	nh arc	Family history, strabismus from early childhood, glasses at 5 yr
D.S.	male, 51 yr	RE* LE	+ 5.25 -2.50 / 100° + 4.50 -2.25 / 95°	0.25 1.00	fov. margin foveolar	far ± 0° near +4° - VD	negative, excl. RE	nh arc	Onset and glasses at 6 yr
A.F.	female, 22 yr	RE LE*	- 1.25 -2.00 / 85° - 1.25 -1.75 / 105°	1.00 0.32	foveolar temp. margin	far +3° - VD 1° near +4½°- VD 1°	negative, excl. LE	h arc	Strabismus from early childhood, glasses and occlusion at 5 yr for one year
						Strabismic and anisometropic amblyopes			
B.B.	female, 29 yr	RE* LE	- 0.75 sph - 1.50 +2.0 / 175°	0.08 0.90	temp. margin foveolar	far + ½° + VD 3° near - 2½° + VD 2°	negative, excl. RE	nh arc	Strabismus from early childhood, glasses at 3 yr, occlusion 3-6 yr, surgery at 20 months
M.H.	female, 31 yr	RE LE*	+ 5.00 -0.75 / 142° + 1.50 -0.50 / 0°	1.00 0.08	foveolar nasal	far + 1½° ± VD near + 4°	negative, excl. LE	h arc	Family history, strabismus from early childhood, glasses at 3 yr, occlusion 4–5 yr, surgery at 5 yr
C.L.	male, 28 yr	RE LE*	- 3.50 -1.50 / 20° + 1.00 -1.25 / 0°	1.00 0.50	foveolar nasal - fovea	far +15° +VD 1° near +15° +VD 2°	negative, excl. LE	nh arc	Strabismus from early childhood, occlusion in kindergarten for 3 yr, surgery at 4 yr
						Anisometropic amblyopes			
H.L.	male, 27 yr	RE LE*	plano + 6.25 sph	1.40 0.25	foveolar foveolar	± 0°	negative	nrc	Occlusion at 11 yr, glasses at 18 yr
T.S.	male, 30 yr	RE LE*	+ 1.25 sph + 2.75 -3.75/135°	1.00 0.40	foveolar nasal margin	± 0°	negative, excl. LE	nrc	Occlusion and glasses at 6 yr
J.B.	male, 26 yr	RE LE*	- 2.25 sph - 0.75 -2.00 / 15°	1.00 0.50	foveolar temporal	± 0°	Positive	nrc	Occlusion and glasses at 6 yr
M.B.	male, 34 yr	RE LE*	- 0.50 -0.50 / 45° - 3.00 -3.25 / 2°	1.00 0.50	foveolar foveolar	± 0°	Positive	nrc	Glasses at 17 yr

Abbrevations: nrc = normal retinal correspondence, nh arc = non-harmonius anomalous retinal correspondence, h arc = harmonius anomalous retinal correspondence, VD = vertical deviation, + = esotropia, – = exotropia, * = amblyopic eye.

Partici-pant	Gender, Age	Eye	Refraction	Visus c.c. (near vision)	Fixation	Strabismus (sim. Cover test)	Stereopsis	Correspondence	History
						Alternators			
M.O.	female, 23 yr	RE LE	- 0.50 -1.0 / 163° - 1.00 -1.0 / 27°	1.00 1.00	foveolar foveolar	far + VD 1.5° near - 1.5° + VD5°	negative	nrc	Family history, glasses at 14 yr
R.F.	female, 25 yr	RE LE	plano - 4.00 -1.0 / 15°	1.00 1.00	foveolar foveolar	far - 8° + VD near - 3°	negative	nrc	Strabismus from early childhood, glasses and pleoptic therapy at 2 yr
J.Z.	male, 27 yr	RE LE	- 7.75 sph - 8.50 sph	1.25 1.25	foveolar foveolar	far + 4° - VD near + 4° - VD	negative	arc	Glasses and occlusion at 5 yr
						Normally sighted participants			
A.Fr.	male, 31 yr	RE LE	- 2.75 -0.5 / 160° - 2.25 -1.0 / 20°	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	Glasses at 14 yr
C.E.	female, 25 yr	RE LE	- 0.25 -0.25 / 15° - 0.50	1.25 1.25	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	Glasses at 14 yr
E.B.	female, 21 yr	RE LE	plano - 0.5 / 0°	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	
M.Y.	female, 22 yr	RE LE	+ 0.25 sph + 0.25 sph	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	
R.P.	male, 30 yr	RE LE	plano plano	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	
T.P.	male, 35 yr	RE LE	+ 0.25 sph plano	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	
T.W.	male, 28 yr	RE LE	- 6.50 -0.75 / 50° - 6.50 -0.5 / 170°	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	Glasses at 9 yr
S.H.	male, 31 yr	RE LE	- 0.5 / 95° - 0.75 / 82°	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	
P.G.	female, 40 yr	RE LE	+ 0.25 sph plano	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	
M.N.	female, 30 yr	RE LE	- 5.50 -1.25 / 175° - 3.00 -1.0 / 160°	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	Glasses at 16 yr
E.G.	female, 21 yr	RE LE	- 2.50 -0.25 / 0° - 3.50 -0.5 / 25°	1.00 1.00	foveolar foveolar	far max. - 1.5° near max. - 3°	positive	nrc	Glasses at 10 yr
D.G.	male, 21 yr	RE LE	- 4.25 sph - 2.50 sph	1.00 1.00	foveolar foveolar	far ± 0° near ± 0°	positive	nrc	Glasses at 4 yr

Apparatus and stimuli

The apparatus and the red-green goggles were as described in study 2. The stimuli in study 3 were circles of six different radii of two, four, six, eight, ten and twelve degrees. Corresponding to study 2, stimuli shown to the dominant eye were red, stimuli shown to the amblyopic eye green.

During the experiment participants heard numbers from 1 to 12 by loudspeakers. In a pretest, the numbers were rated to make sure they were understood correctly. Participants (*N* = 15) had to rate the numbers on a scale from 1 (very hard to understand) to 5 (very easy to understand). As table 12 shows, all numbers were understood correctly and means of the ratings were *Ms* > 4.40.

Table 12. Rating of numbers.

Number	Percent of correct understanding	Rating (mean)
1	100 %	4.73
2	100 %	4.47
3	100 %	4.60
4	100 %	4.40
5	100 %	4.73
6	100 %	4.60
7	100 %	4.60
8	100 %	4.40
9	100 %	4.53
10	100 %	4.87
11	100 %	4.53
12	100 %	4.80

Procedure

The participants were seated in front of the monitor screen in an otherwise darkened room and put on the red-green goggles. The participants’ head was rested on a chin-rest to maintain an eye-to-monitor distance of 57 cm. The refractive errors were fully corrected in all participants. There had been twelve test trials to practice the experimental procedure before starting the experiment. The experimenter made sure that the participant understood his/her task entirely before the experiment started.

Participants were asked to fixate a continuously presented cross in the centre of the screen and then memorize the different circles, which were presented in a random sequence. The fixation cross indicated the midpoint of each circle. The circles were presented on the screen for five seconds, only one circle in each trial. One single circle consisted of 12 points, similar to the dial plate of a watch. The circles were presented to the dominant eye, while the amblyopic eye did not receive any stimulus. After the circle disappeared participants heard over loudspeakers a number in the range of 1-12, which was presented randomly.

The participants’ task was to reproduce a circle presented to their dominant eye from memory and reconstruct it by bringing a test point on the imaginary outline of the circle according to the position of the number heard over the loudspeakers before. On a blank screen the test point always appeared in the middle of the fixation cross and could be freely moved on the screen with the aid of the computer mouse. The circle reconstruction had to be done with the non-amblyopic eye as well as with the amblyopic eye and every position on each circle was shown up to five times. Depending on the eye (amblyopic or non-amblyopic) used for the reconstruction, the colour of the test point was either red or green. Each trial took about 10 seconds. After every 84th trial or after about 15 minutes, respectively, there was a break for five minutes. There was no time limit for this task and the participants had the opportunity to cancel the last set position if deemed necessary. Informed consent was obtained from all participants after the nature and the purpose of the study had been explained fully. At the end of the second half of the experiment all participants were debriefed and paid 10,- € per participated session.

5.1.2 Results

Data were submitted to a repeated-measures multivariate analysis of variance (MANOVA) model that included eye, radial position and tangential position of the points as dependent variables, and amount of spatial distortion (difference of the adjusted point to the target point) and amount of spatial uncertainty (standard deviation) as independent variables. The α level was set to .05 for omnibus tests, Wilk's Λ was used as a test statistic. Separate error terms and Bonferroni α adjustments were used for planned comparisons and contrasts. For appraising the spatial distortions and spatial uncertainty in individual amblyopes (strabismic, strabismic-anisometropic and anisometropic), strabismic alternators and normally sighted participants, data of the two eyes were mirrored to each other, to enable comparison of the nasal versus temporal hemifields, respectively.

Normally sighted participants

Figure 8 shows maps of the central visual fields in all normally sighted participants for the radius gradations up to 12 deg. Left and right eyes are displayed separately. The red symbols represent the optimal positions for each adjusted point; the black symbols represent the mean of the individual mean settings for each position.

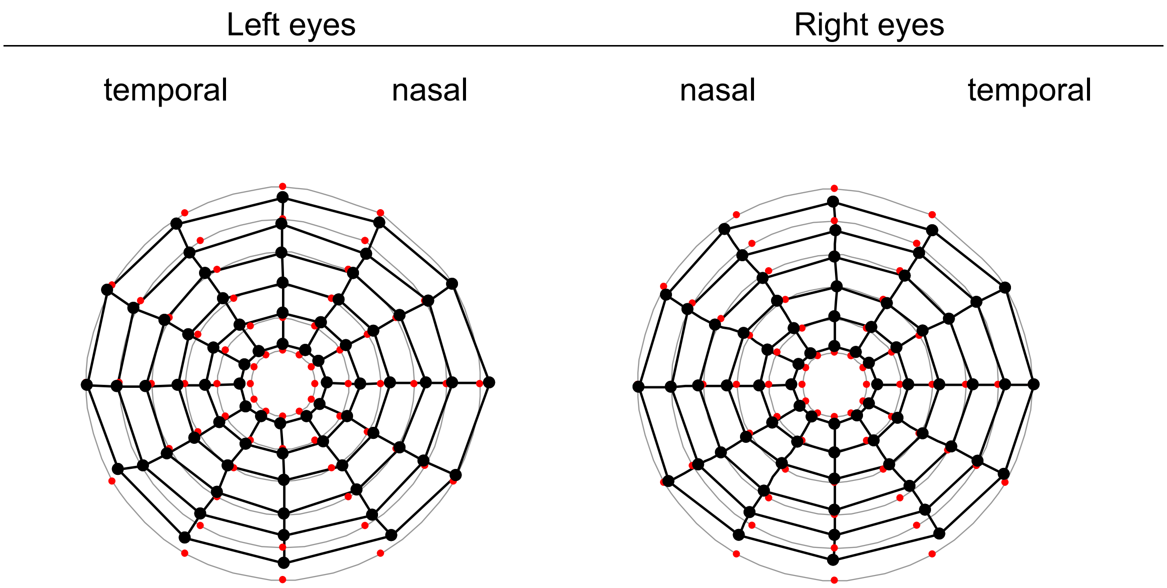


Figure 8. Monocular localisations for all normally sighted participants. Left: settings in the left eye. Right: settings in the right eye. Red symbols: optimal position. Black symbols: mean of individual setting. Radii of the circles are 2, 4, 6, 8, 10 and 12 deg.

Differences in spatial distortions between both eyes were not significant for radial ($F(1,11) = 1.59$, $p = .23$, $\eta^2 = .13$) as well as tangential adjustments ($F(1,11) = .89$, $p = .37$, $\eta^2 = .07$). For spatial uncertainty, radial and tangential standard deviations of the means were quite small with *SD*s ≤ .04 for the left eye and *SD*s = .03 for the right eye. Although very small, there were systematic spatial distortions in the perception of each eye even in normal observers. Positions in the smaller circles with radii of 2 and 4 deg tended to be set larger, indicating an underestimation of the central visual field, while positions in the larger circles (10 and 12 deg), especially in the vertical meridian, tended to be set smaller and were therefore overestimated. In general, spatial distortions ($M_{2\text{ deg}}$ = .26 to $M_{12\text{ deg}}$ = .51) as well as positional uncertainty ($SD_{2\text{ deg}}$ = .04 to $SD_{12\text{ deg}}$ = 0.7) tended to increase significantly with eccentricity of the circle radius ($F(5,7) = 4.71$, $p = .03$, $\eta^2 = .77$), however only for radial adjustments. Positions on the vertical and the horizontal meridian were set more accurately and with a lower spatial uncertainty (*M*s < 1.77, *SD*s < .36) than on the other positions (*M*s > 4.14, *SD*s > .58). There were no significant differences between the patterns for the left and the right eye. On an individual level, the results of the normally sighted participants were very consistent with the group data and showed similar patterns of the adjusted positions in both visual fields.

To put together, since normal observers had no systematic differences between the two eyes and showed small yet consistent spatial distortions and spatial uncertainty, participants with normal binocular vision can be used as control participants for the group of amblyopes and their results can be adopted as a baseline for the amblyopic participants in this study.

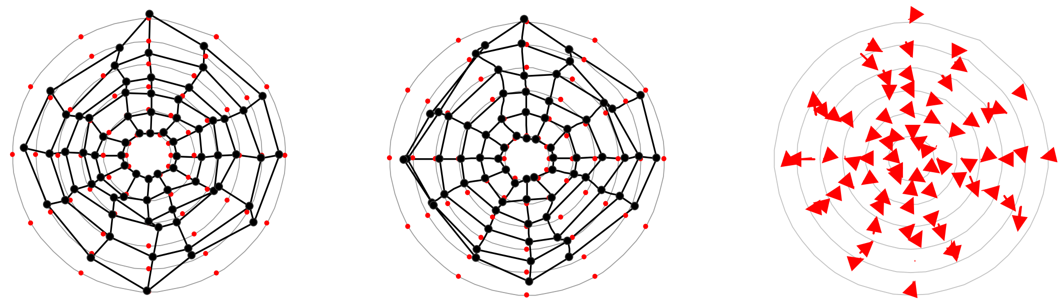
Strabismic amblyopes

Figures 9 to 11 show the individual patterns of spatial distortions and the relative amount of spatial error in the amblyopic eye for strabismic participants RS, LP, MK, SB, DS and AF. The bases of the arrows indicate the mean of the tested positions in the participant's dominant eye, while the tips of the arrows indicate the mean of the tested positions in the amblyopic eye. Thus, the longer the arrow, the more pronounced the spatial distortion in the amblyopic eye in relation to the non-amblyopic eye.

a) Refractive strabismic amblyopes: SB and RS have a reduced visual acuity in both eyes - with the amblyopic eye having an acuity of 0.3 and 0.1, respectively, and the non-amblyopic eye of 0.6. They both showed strong spatial misperceptions and overestimation of nearly all circles in the non-amblyopic and the amblyopic eye (figure 9). The overestimation got higher as the radius of the circle got larger. In the smallest radius with 2 deg, position adjustment was quite precise, as well as was the position adjustment of the vertical and the horizontal axis of the non-amblyopic eyes and the amblyopic eye of participant RS.

Esotropic and refractive strabismic amblyope RS

temporal nasal nasal temporal



Esotropic and refractive strabismic amblyope SB

temporal nasal nasal temporal

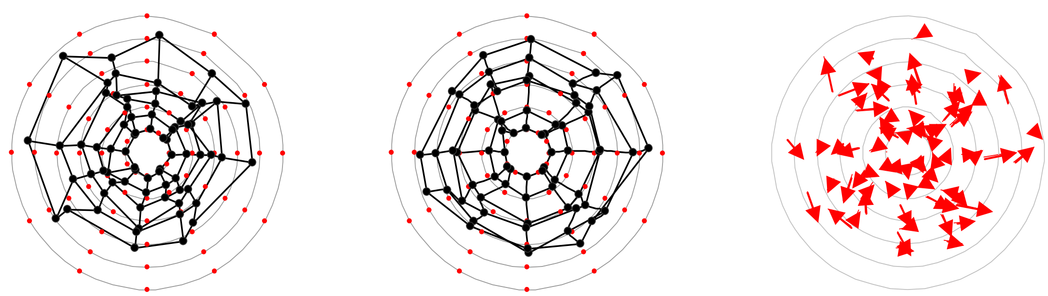


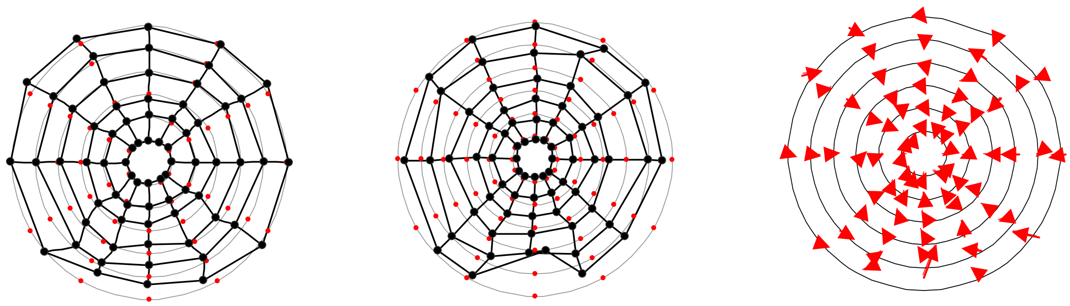
Figure 9. Spatial distortions for the amblyopic and the non-amblyopic eye, and relative amount of spatial distortions indicated as vectorial subtraction of the distortion maps of participants RS and SB. Positional means of the spatial distortions are connected by lines for better comparison. Tips of the arrows indicate the positional mean in the amblyopic eye, the bases refer to the non-amblyopic eye. Left: settings in the non-amblyopic eye. Middle: settings in the amblyopic eye. Right: vectorial subtraction of the distortion maps.

Participant SB had not only problems in adjusting radial distances, but also in adjusting the tangential position of the circle points, especially in the amblyopic eye. However, there was no nasal-temporal asymmetry observable in the data of both amblyopes.

b) Accommodative strabismic amblyopes: DS, an amblyope with a visual acuity of 0.25 in his right eye, has a high ametropia in both eyes. He showed some overestimation of the circles that was very consistent over the different radii gradations, however somewhat higher in the right lower visual hemifield. Tangential adjustments on the horizontal and vertical axis were adjusted with a smaller amount of spatial error than on the other positions. Participant MK, who is hyperopic with astigmatism, had larger localisation errors. The subjective circle positions in the amblyopic eye were rotated clockwise by some degree, and radii from 8-12 deg were underestimated especially on the horizontal and the vertical axis (figure 10).

Esotropic amblyope DS

temporal nasal nasal temporal



Esotropic amblyope MK

temporal nasal nasal temporal

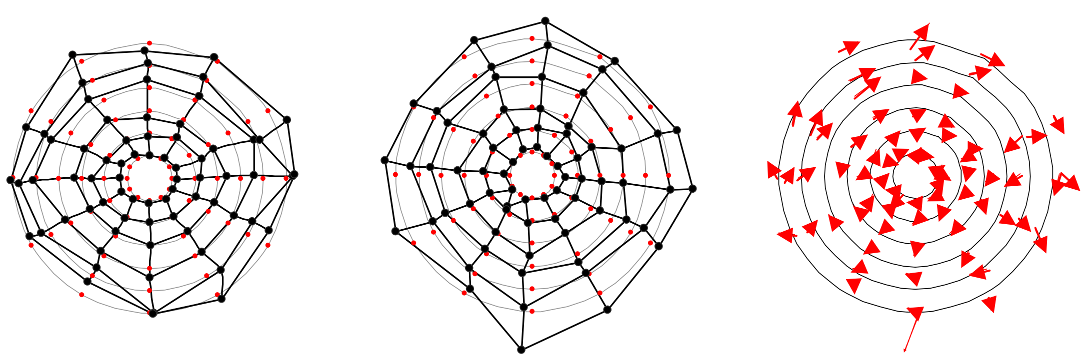


Figure 10. Spatial distortions and vectorial subtraction of the distortion maps of participants DS and MK. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

c) Primarily strabismic amblyopes: Participants LP and AF, both primarily strabismic with a visual acuity of 0.25 and 0.32 of the amblyopic eye, were characterised by an underestimation of the circles in the amblyopic eye. A minimally oval, lengthened shape of the adjusted circles was visible in both participants. Tendency of the adjustments was to the horizontal axis, yet this tendency was more pronounced in participant LP (figure 11).

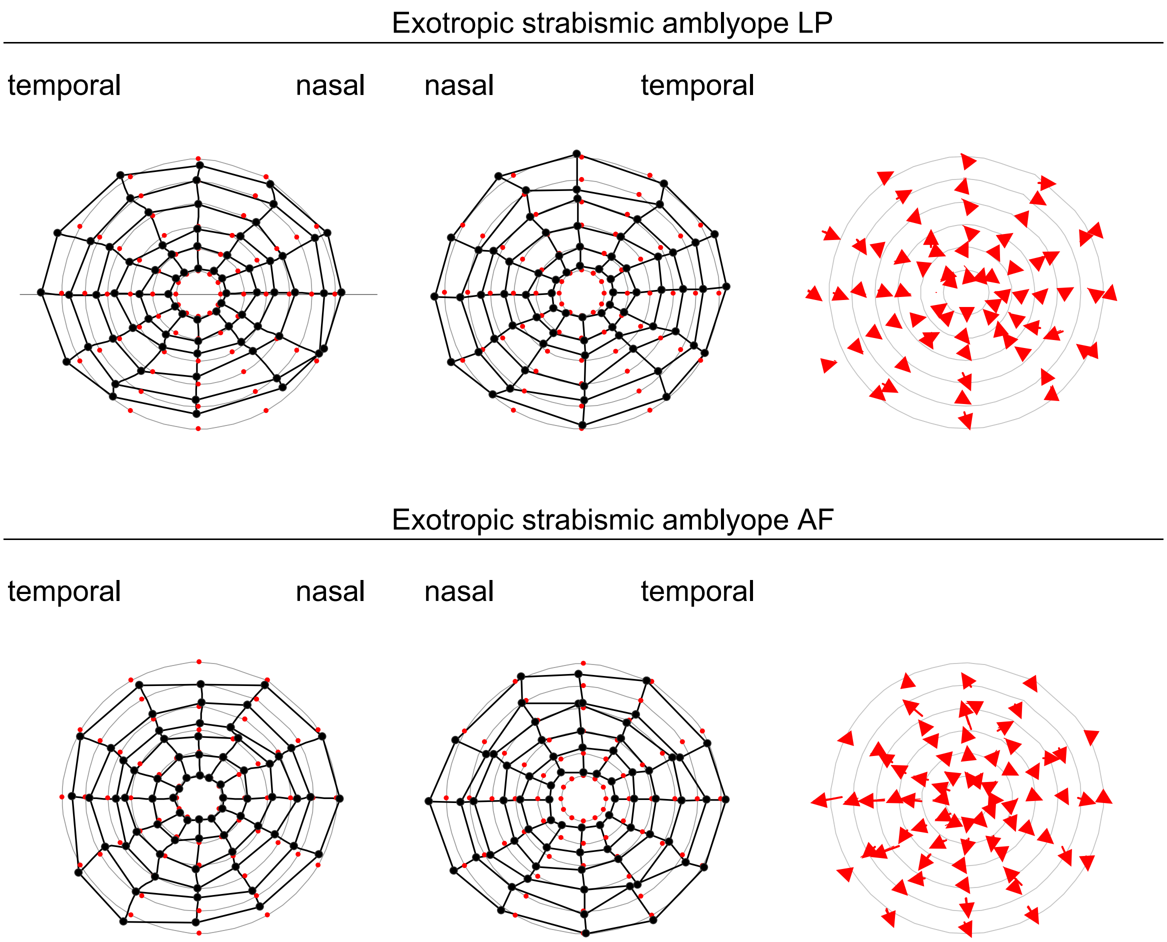


Figure 11. Spatial distortions and vectorial subtraction of the distortion maps of participants LP and AF. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

All strabismic amblyopes were quite precise in the position adjustment of the horizontal and the vertical axis. Participants RS, SB, and DS showed an overestimation of the circles, while participants MK, LP, and AF underestimated the radii of the circles. Except amblyope MK, all other strabismic amblyopes had a tendency to set vertical distances smaller than horizontal distances (also found by Lagrèze & Sireteanu, 1991). No nasal-temporal asymmetries were observable in all of the strabismic amblyopes.

Strabismic-anisometropic amblyopes

BB, with an acuity of 0.08 in the right amblyopic eye, showed a pattern in the non-amblyopic eye which was similar to the normal observers' (figure 12). In contrast to that, the pattern of the amblyopic eye was fairly distorted, with a slight S-shape of the vertical axis and an overall oval shape of the whole circle patterns. That is, the horizontal positions were underestimated while distances on the vertical meridian were overestimated for more than 2 deg.

Strabismic-anisometropic amblyope BB

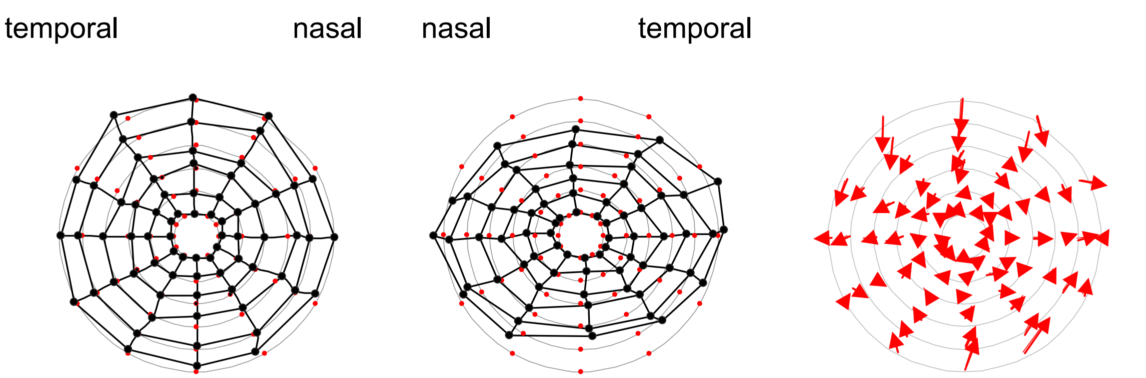


Figure 12. Spatial distortions and vectorial subtraction of the distortion maps of strabismic-anisometropic amblyope BB. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

Participants MH and CL showed quite similar patterns of their subjective adjustments (figure 13), even if they differ a lot in their orthoptic status, as MH is microstrabismic and has a visual acuity of 0.08 and CL shows a large-angle esotropia and an acuity of 0.5. They both underestimated the horizontal meridian. Albeit being quite precise with the tangential adjustments on the vertical and the horizontal axis, the adjusted points on the intermediate axis showed a more distorted pattern.

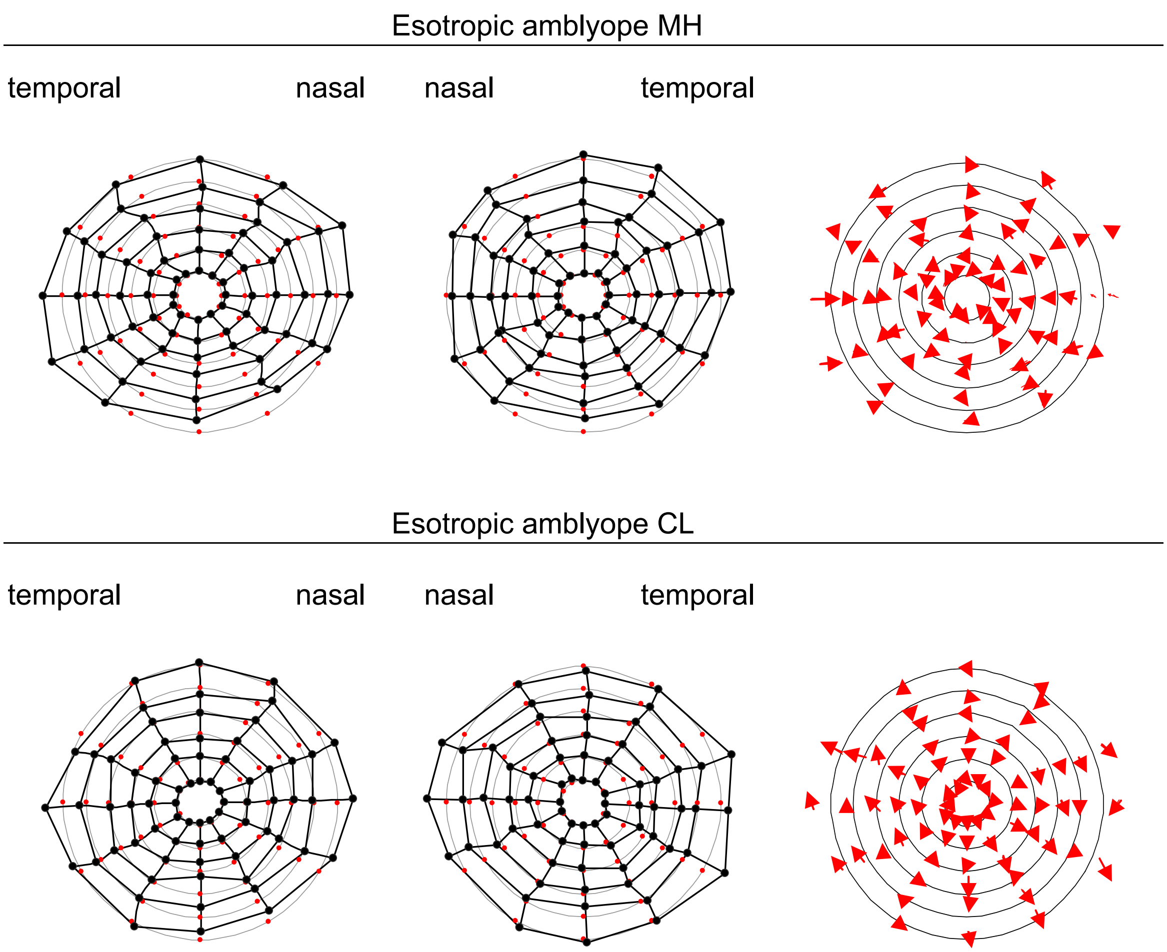


Figure 13. Spatial distortions and vectorial subtraction of the distortion maps of amblyopes MH and CL. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

All strabismic-anisometropic amblyopes had a tendency to set vertical distances smaller than the horizontal distances. However this tendency was most pronounced in amblyope BB as the circles were nearly ovally shaped, amblyopes CL and MH showed this pattern to a much smaller amount. As for the strabismic amblyopes, there were no nasal-temporal asymmetries in the circle adjustments of the strabismic-anisometropic amblyopes.

Anisometropic amblyopes

TS, who is anisometropic with a visual acuity of the left amblyopic eye of 0.4, showed the highest overestimation of the circles of all anisometropic amblyopes. This overestimation was quite pronounced in both eyes, however circle positions in the amblyopic eye were even more shifted to the horizontal axis (figure 14). This pattern of spatial misperceptions was similar to that of strabismic participant AF.

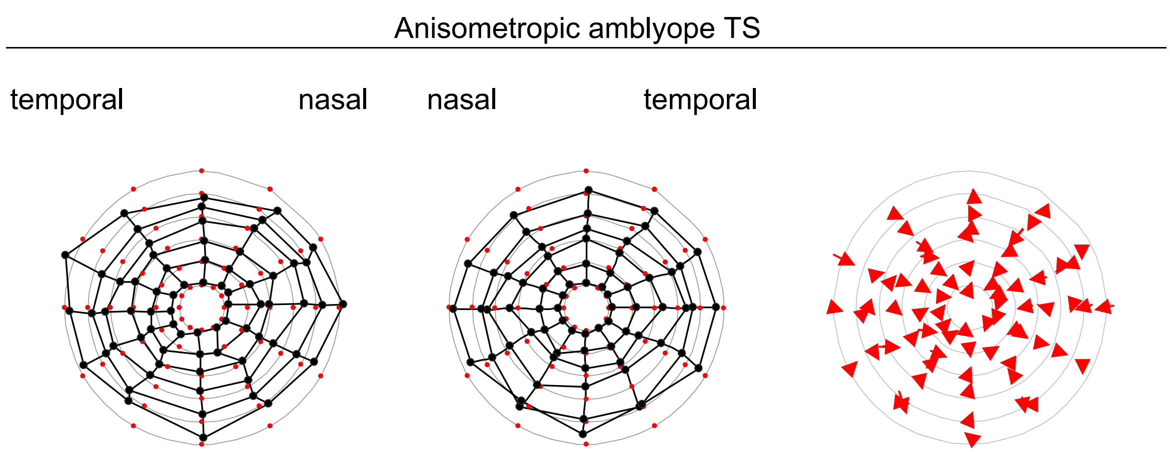


Figure 14. Spatial distortions and vectorial subtraction of the distortion maps of anisometropic amblyope TS. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

Both participants HL (visual acuity of the left amblyopic eye is 0.25) and JB (visual acuity of the left amblyopic eye is 0.5) showed an underestimation of the 2 deg circle with the amblyopic eye relative to the non-amblyopic eye. The difference between the eyes was very small: in the amblyopic eye spatial distortions were just slightly more pronounced than in the non-amblyopic eye. Participant MB, with an acuity of 0.5 in his left eye, exhibited a pattern that was fairly similar to those of the normally sighted participants. The amblyopic and the non-amblyopic eye showed both quite regular position adjustments of all circles with a slight overestimation of the larger 10-12 deg circles (figure 15).

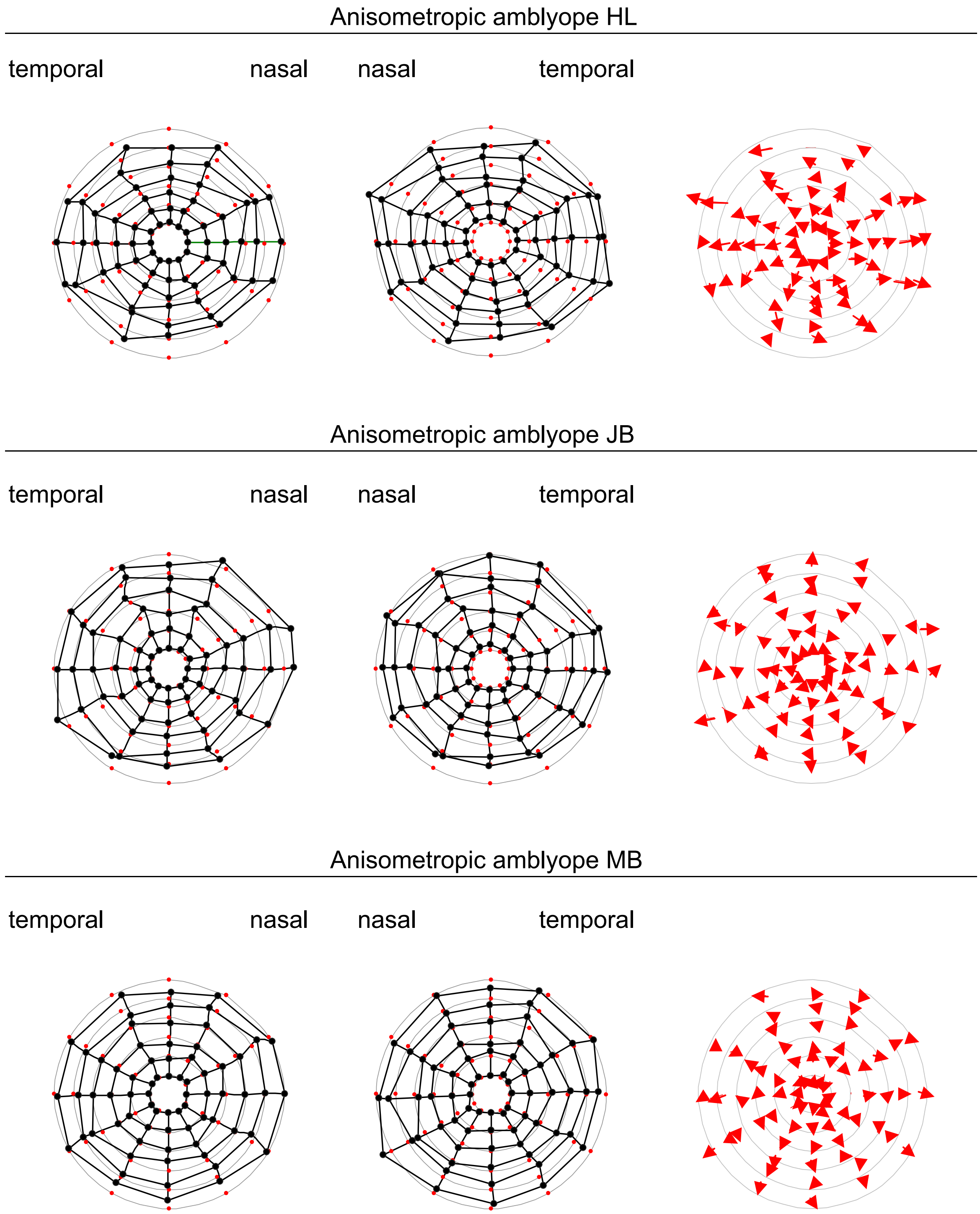


Figure 15. Spatial distortions and vectorial subtraction of the distortion maps of anisometropic amblyopes HL, JB, and MB. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

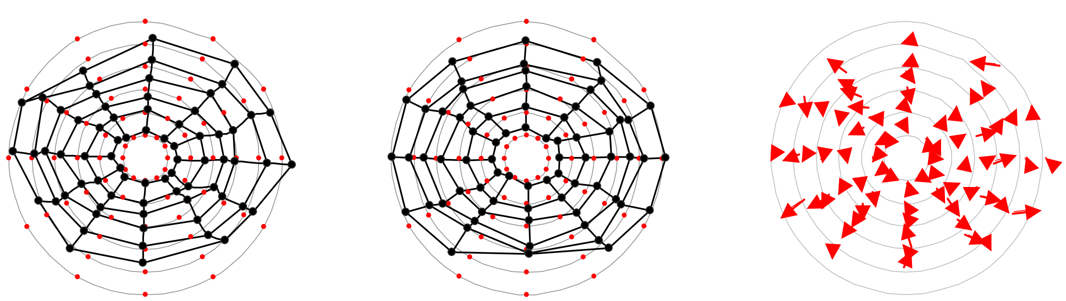
The differences between the amblyopic and the non-amblyopic eyes were quite small in the anisometropic amblyopes, especially for participant MB. All anisometropic amblyopes had a tendency to overestimate the radial circle positions, and also had a tendency to set the vertical distances smaller than the horizontal ones, resulting in an oval shaped circle pattern.

Strabismic alternators

Strabismic alternators did not show such a clear distortion pattern. All showed an underestimation of the smallest circle, getting less for the larger radii (see figure 16). Participant MO showed an oval shape of the circles in both eyes, the vertical meridian was fairly overestimated here. Participant RF showed similar tangential errors in the left and right eye in the intermediate meridians of the circles. The positions on these axes had a strong tendency away from vertical and the horizontal to the middle. JZ exhibited a pattern contrary to that of RF. He adjusted the positions on the intermediate meridians accordingly to their main neighbour axis (vertical or horizontal); that was more to the vertical and the horizontal meridian, respectively.

Strabismic alternator MO

temporal nasal nasal temporal



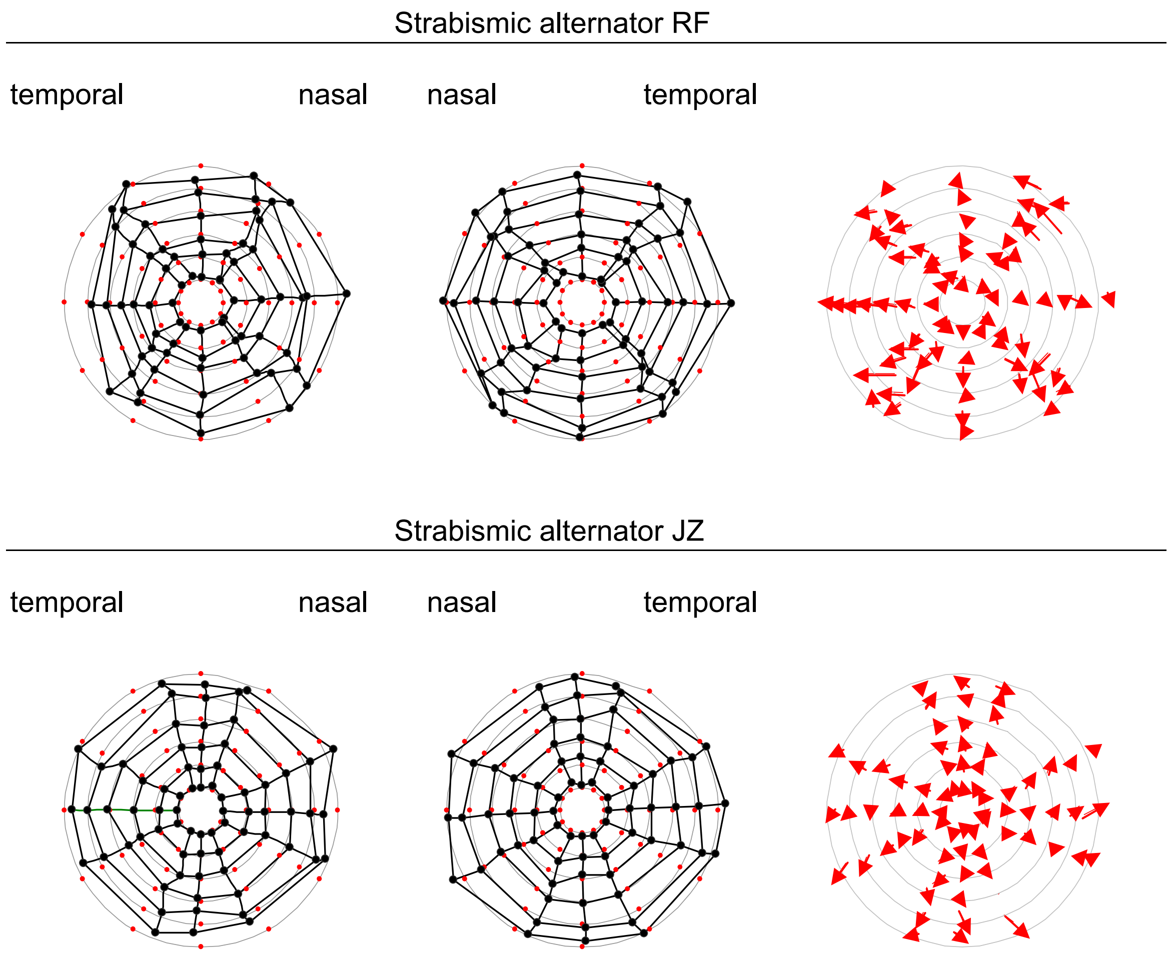


Figure 16. Spatial distortions and vectorial subtraction of the distortion maps of strabismic alternators MO, RF, and JZ. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

In total, each amblyopic participant and strabismic alternator, respectively, had his/her individual pattern of spatial distortions. A group analysis revealed that the difference between the amblyopic and the dominant eye in amblyopic participants was highly significant for the spatial distortions ($F\,(1{,}23) = 8.88$, $p = .007$, $\eta^2 = .279$) and for the spatial uncertainty, indicated as standard deviation of the positional mean (Fs > 7.09, ps $< .01$, $\eta^2 > .25$). Means of the different groups for the spatial distortions and spatial uncertainty are shown in table 13.

Table 13. Amount of spatial distortions (difference of adjusted point to target point) and spatial uncertainty (standard deviation) for the amblyopic and non-amblyopic eyes.

	Strabismic	Anisometropic	Strabismic-anisometropic	Strabismic alternator
Amblyopic eye	*M* = 2.41 *SD* = .45	*M* = .72 *SD* = .31	*M* = .52 *SD* = .37	*M* = .91 *SD* = .37
Non-amblyopic eye	*M* = .79 *SD* = .38	*M* = .19 *SD* = .32	*M* = .57 *SD* = .29	*M* = .19 *SD* = .34

Group data

a) Spatial distortion and spatial uncertainty: For group data, the absolute value of the difference between the amblyopic and the dominant eye was used for the calculation of spatial distortion and spatial uncertainty. The spatial distortions (linear distance from the adjusted point to the target point) and spatial uncertainty (standard deviation of adjusted points) were most pronounced in strabismic and strabismic-anisometropic amblyopes, for the radius (figure 15) as well as for the angle (figure 16) of the adjusted circle points. As reported in previous research (Lagrèze & Sireteanu, 1991), also in this sample strabismic and strabismic-anisometropic amblyopes show considerable spatial distortions and uncertainty in contrast to the anisometropic amblyopes and normally sighted participants.

As figure 15 shows, mean error in localisation (with spatial uncertainty in brackets) for radial position was M = .12 deg (SD = .07 deg) for strabismic amblyopes, M = .07 deg (SD = .08 deg) for strabismic-anisometropic amblyopes, M = .06 deg (SD = .04 deg) for strabismic alternators, M = .03 deg (SD = .01 deg) for anisometropic amblyopes and M = .02 deg (SD = .01 deg) for normally-sighted participants. Strabismic alternators which have a history of strabismus but no amblyopia, showed the same amount of distortions as strabismic-anisometropic amblyopes (mean difference = .002, p = 1.00).

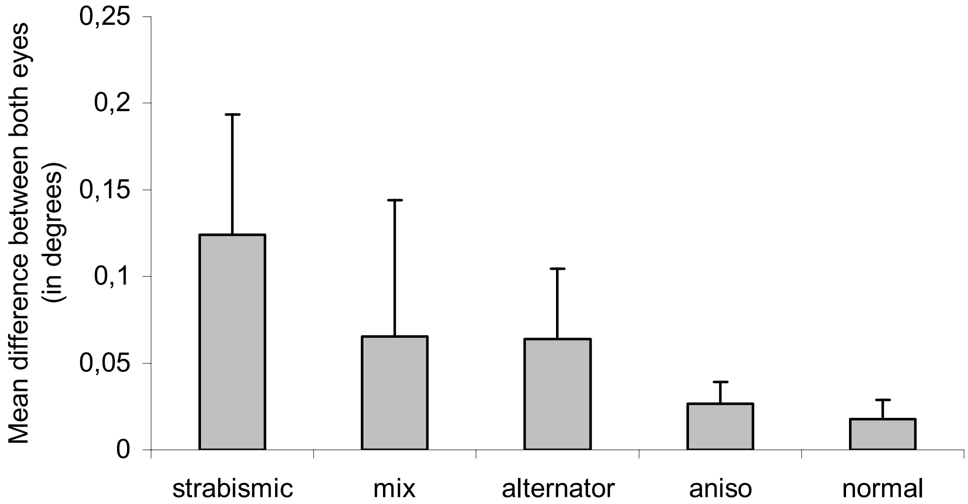


Figure 15. Amount of spatial distortion (linear distance from adjusted point to target point) and spatial uncertainty (standard deviation) for radial position.

Overall there were no significant differences between the five different groups of participants (F (4,23) = 1.95, p = .14, η^2 = .25). Even if there is a visible difference in the amount of spatial distortions (especially between strabismic amblyopes and normally sighted participants), this difference did not reach a significant level for pairwise comparisons (all ps > .13).

Mean error in localisation (with spatial uncertainty in brackets) for the tangential positions was M = 1.19 deg (SD = .086 deg) for strabismic amblyopes. Strabismic-anisometropic amblyopes showed with M = 1.96 deg (SD = 1.12 deg) the highest amount of spatial distortions and spatial uncertainty, while strabismic alternators were much more precise in their tangential position adjustment, M = .57 deg (SD = .01 deg). Anisometropic amblyopes and normally sighted participants showed an error in localisation with M = 1.12 deg (SD = .10 deg) and M = .17 deg (SD = .15 deg), respectively. Again, there is no significant difference in the amount of spatial distortions between all groups, F (4,23) = 2.28, p = .09, η^2 = .28. All pairwise comparisons did not reach a significant level (all ps > .24).

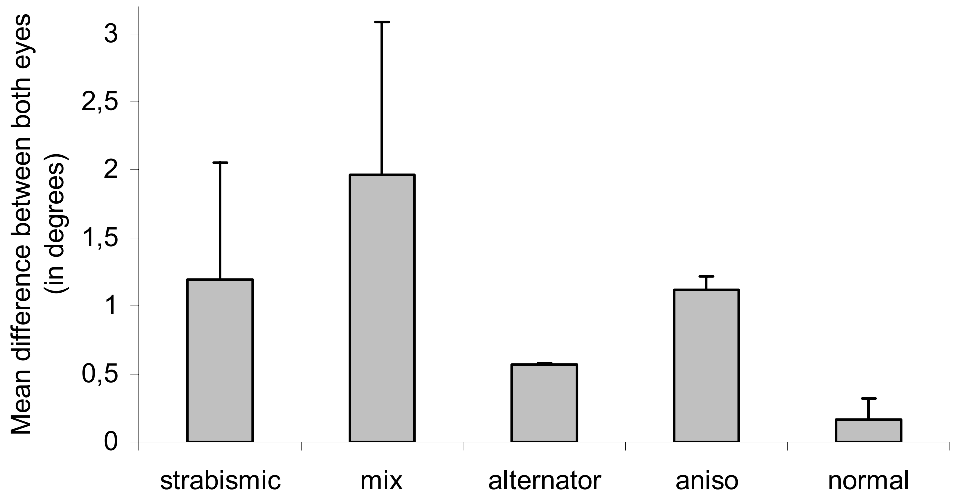


Figure 16. Amount of spatial distortion (linear distance from adjusted point to target point) and spatial uncertainty (standard deviation) for tangential position.

b) Temporal instability: On the basis of these findings, data were analysed regarding the perception of temporal instability. The amblyopic participants were grouped in two groups depending on their subjective perception of temporal instability when viewing with the amblyopic eye. This was done based on the results of the qualitative reports in study 1. The group with amblyopes perceiving no temporal instability consisted of eleven amblyopes: strabismic amblyopes LP, AF, RS, and SB, strabismic-anisometropic amblyope MH, anisometropic amblyopes JB, HL, and MB, and strabismic alternators MO, RF, and JZ. Five participants were in the temporal-instability group: strabismic amblyopes MK and DS, strabismic-anisometropic amblyopes BB and CL, and anisometropic amblyope TS.

Amblyopes who perceived temporal instability had much more difficulties in adjusting the tangential position of the test point (figure 17). Compared to amblyopes without temporally instable perception, they showed a significantly lowered performance, F (1, 14) = 5.42, p = .03, η^2 = .28. Mean spatial distortion (with spatial uncertainty in brackets) for tangential position was M = 2.29 deg (SD = 1.12 deg) for amblyopes who perceive temporal instability and M = .39 deg (SD

= .28 deg) for those who have a stable but distorted perception. However, there was no difference in the reconstruction of the radial positions between amblyopes with stable distortions and those with temporally instable ones, *F* (1,14) = .39, *p* = .54, η^2 = .03. Mean spatial distortion (with spatial uncertainty in brackets) for radial position was *M* = .1 deg (*SD* = .07 deg) for the temporal instability group and *M* = .07 deg (*SD* = .02 deg) for amblyopes with stable distortions.

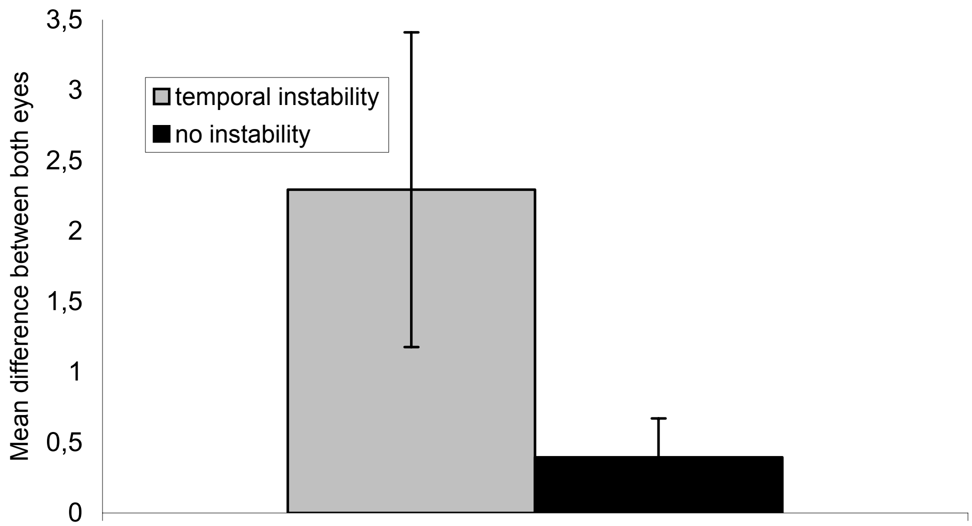


Figure 17. Amount of spatial distortion (linear distance from adjusted point to target point) and spatial uncertainty (standard deviation) for the adjustment of the tangential positions.

Note that the tangential position of the test point was presented auditively, while the radial position was presented in a visual way. In general, for both groups, adjusting the tangential, auditively presented position of the test point was much harder than adjusting the radial, visually presented position. However, amblyopes who perceived temporal instability showed an additional impairment in adjusting the auditively presented tangential positions than those who did not.

More specifically, the values of both groups have the same trends over the different radius gradations (from 2° to 12°), but differ only in their amount. As reported above, there is a main effect for the factor “group” for spatial uncertainty in tangential position, but there is also an effect for the interaction between group and tangential position, which is nearly significant ($F(5,8) = 3.06$, p = 07, η^2 = .66). The impairment of performance for the temporal instability group in the reconstruction of the angle was only true for circles smaller than 8°. That is, the performance of the amblyopic eye appeared to be especially impaired in the central visual field, while in the peripheral field the differences disappeared (figure 18).

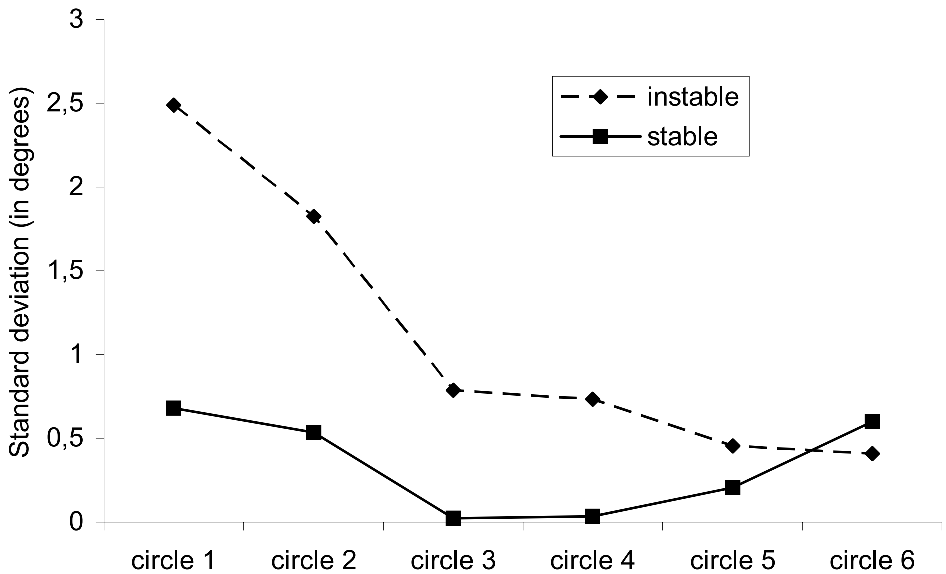


Figure 18. Amount of spatial uncertainty for different radius gradations for amblyopes with (N = 5) and without (N = 8) perception of temporal instability.

5.1.3 Discussion

In general, the amount of spatial distortions and spatial uncertainty between the amblyopic and the non-amblyopic eye were significantly different in all amblyopic participants. However as reported in previous research (Lagrèze & Sireteanu, 1991), the spatial distortions and spatial uncertainty were most pronounced in amblyopes with a history of strabismus. Strabismic and strabismic-anisometropic amblyopes showed higher spatial distortions and uncertainty in contrast to anisometropic amblyopes and normally sighted participants.

Individual analysis of spatial distortions

Normally sighted participants do not show differences in spatial vision between both eyes, still they show, albeit very small, systematic spatial distortions in the perception of the circles. The distortions were in a way, that participants underestimated smaller circles in the central visual field - especially positions on the horizontal axis - and overestimated positions on the vertical axis of the bigger circles.

In contrast to the normally sighted participants, strabismic amblyopes in this sample showed strong misperceptions. These were especially pronounced for the two refractive strabismic amblyopes, who overestimated nearly all circle positions except the ones of the smallest circle of 2°. The patterns of the circles were distorted in a quite irregular way, a pattern known from previous literature (Bedell & Flom, 1983; Lagrèze & Sireteanu, 1991). Bedell and Flom (1983) showed that „spatial errors need not to be in the same direction within a single eye“ (p. 427). The other strabismic amblyopes also showed a high level of spatial errors, but this was accompanied by an underestimation of the circle positions and by a systematic clockwise rotation or lengthened ovally shape of the circles, respectively. The strabismic-anisometropic participants showed patterns which were much more ovally shaped than those of the purely strabismic amblyopes. They had a higher accuracy in adjusting the positions on the horizontal and vertical axis, and therefore had a lower amount of misplacement of individual circle positions. In all anisometropic participants who experienced some stereo vision, differences between the two eyes was quite small and spatial distortions were only slightly more pronounced in the amblyopic eye. The patterns were fairly similar to those of the normally sighted participants as the circle positions were regularly adjusted with a slight overestimation of the outermost circles – the same overestimation visible in the normal participants. Only anisometropic amblyope TS, who experienced temporal instability of his amblyopic perception, had a more pronounced overestimation of the circle positions and showed an ovally shaped pattern similar to those of the strabismic amblyopes.

Analysis of the perception of temporal instability

As the perception of temporal instability seems to have a large influence on the spatial distortions of the amblyopic participants (see study 1), the data were analyzed regarding the perception of temporal instability on the basis of the findings of spatial distortions. Participants who perceived temporal instability showed a worse performance in the auditive reconstruction of the angular circle points. They had much more difficulties in adjusting the auditively presented angle of the test point. This was only true for smaller circles with a radius lower than 8°. This might suggest that the small inner circles which affect especially the central visual fields of the eyes are most affected by the distorted amblyopic perception. These results are in accordance with findings from Bradley and Freeman (1985), Fronius and Sireteanu (1989), and Fronius and Sireteanu (1994). Both groups found that the performance of the amblyopic subjects is worse the smaller the targets and the more targets are located in the central part of the retina (Bradley & Freeman, 1985). In this central visual areas, amblyopia is thought to be most severe (Sireteanu & Fronius, 1981) and therefore the monocular geometry e.g. in a line alignment task (Fronius & Sireteanu, 1989) is more distorted in the central visual field than in the periphery. In the periphery, the judgments of the amblyopic and the non-amblyopic eye became very similar. Fronius and Sireteanu assume that the retinal correspondence is one factor that can explain those centrally located monocular distortions (see also Lagrèze & Sireteanu, 1991).

However, there was no difference in the visual reconstruction of the radius between amblyopes with stable distortions and temporally instable ones. This suggests that amblyopes with temporal distortions may need visual cues for handling this construction task as accurately as amblyopes with stable perception. In comparison with the non-instability-group, they had more problems in adjusting the auditively presented cues, but not the visually presented ones. Maybe both the group of strabismic-anisometropic amblyopes as well as the group of strabismic alternators experience similar distortions in perception. On the one hand it is the amblyopia, on the other the strabismus that may influence the distortions. Strabismic amblyopes who suffer from both, amblyopia as well as strabismus, show a higher amount of spatial and temporal distortions than the other groups in this study, like anisometropic amblyopes or strabismic alternators, who have to deal only with one of the problems.

5.2 Study 4: Circle experiment (visual instructions)

Circle experiment # 2 was planned to carry on with the psychophysical task of the preceding experiment but to change the experimental settings in such a way, that the reconstruction of the circle is based on visual instructions. Thus, a combination of visual-auditive modalities (radius based on visual input vs. angle based on auditive input) will be avoided, and participants have the visual guidance of radius and angle within the whole experimental task (visual-visual modalities). The question was whether there is a difference between amblyopes with and without the perception of temporal instability when the modalities are visual-visual (i.e. the adjustment of the radial as well as the tangential position depend on visual stimulation).

5.2.1 Method

Participants

Participants for a pretest were 15 adults with normal or corrected to normal vision (age 19 to 37, two of them male, all right-handed). Participants for the main experiment were in the group of amblyopes with stable distortions participants RS, LP, SB, JB and MB. Participants DS, BB, MK, CL and TS were in the group of amblyopes with temporal instability (classification of stable or instable misperception is due to the results of experiment 1). Amblyopes AF, MH, and HL were not able to participate in this study 4, as were strabismic amblyopes MO, RF, and JZ.

Apparatus and Stimuli

The apparatus and the red-green goggles were as described in experiment 2. Stimuli for radial reconstruction were circles as described in experiment 3 with a radius of 2, 4, 6, and 8 degrees, respectively. Stimuli for the reconstruction of angles were lines, extending from the fixation point in the center of the screen to the margin of the monitor. Corresponding to the previous experiment, direction of the lines were 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330°, respectively. Lines had the same colour as the circles; red lines and circles (RGB = 242, 0, 0) were shown to the dominant eye, green lines and circles (RGB = 0, 249, 177) were shown to the amblyopic eye.

Procedure

Procedure was the same as in the previous experiment, except that the auditively presented number was changed into a visually presented line. The participants were seated in front of the monitor screen in an otherwise darkened room. The participants' head was rested on a chin-rest to maintain an eye-to-monitor distance of 57 cm. The procedure was adapted from the preceding circle experiment: Participants were asked to fixate on a continuously presented cross in the centre of the screen and then memorize the different circles and lines, which were displayed on the monitor (figure 19). The fixation cross indicated the midpoint of each circle. The circles were presented on the screen for five seconds. After the circle, a line with a randomized direction was shown for 5 seconds. The circles and lines were presented to the dominant eye, while the amblyopic eye did not receive any stimulus.

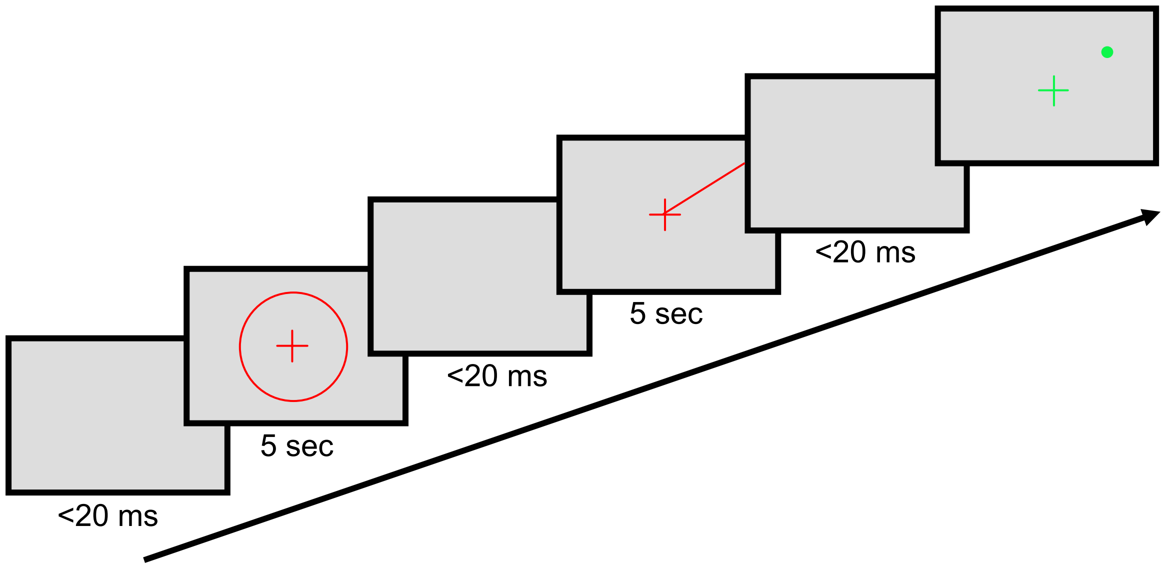


Figure 19. Presentation order of stimuli in experiment 4 (example of one trial)

The participants' task was to reproduce the circle presented to the dominant eye and reconstruct it by bringing a test point on the imaginary outline of the circle according to the angle of the line seen before. On a blank screen the test point always appeared in the middle of the fixation cross and could be freely moved on the screen. The circle reconstruction had to be done with the non-amblyopic eye as well as with the amblyopic eye and every position on each circle was shown up to three times. Informed consent was obtained from all participants after the nature and the purpose of the study had been explained. At the end of the experiment all participants were debriefed and paid 10,- € per participated hour.

5.2.2 Results

Pretest

The pretest was conducted to see if there is any difference between the auditive and the visual type of the circle experiment for normally sighted participants. Participants had to complete one session of the circle experiment with the tangential position auditively presented, as done in study 3, and one session with the tangential position visually presented.

The results of the pretest revealed that for normally sighted participants (N = 16), there is no significant difference between the auditive and the visual type of the experiment (F (1, 13) = .46, p = .51, η^2 = .03). There were no additional interactions between type of perception and other variables, e.g. eye (left or right side) or circle radius (all Fs < 2.74, ps > .12, η^2s > .14).

The results of the pretest showed that for normally sighted participants, there was no difference in solving the task based on visual or auditive perception. Participants had no difficulties in understanding and handling the two different types of the experiment.

Main experiment

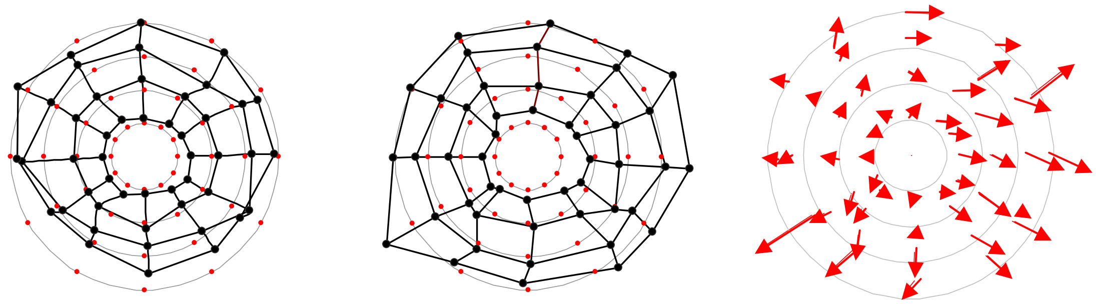
Data treatment proceeded as described in study 3 for the amount of spatial distortions (difference of the adjusted point to the target point) and the amount of spatial uncertainty (standard deviation). Dependent variables were the same as in study 3 - eye, radial position, and tangential position of the points - and, additionally, the type of presenting the tangential position. Amount of spatial distortion (difference of the adjusted point to the target point) and amount of spatial uncertainty (standard deviation) were the independent variables. Figures 19 to 24 show the subjective adjustments of the tangential and radial positions, both visually presented: individual patterns of spatial distortions and the relative amount of spatial error for amblyopes with (DS, BB, MK, CL, and TS) and without temporal instability (RS, LP, SB, JB, and MB) are displayed. The bases of the arrows indicate the mean of the tested positions in the participant's dominant eye, while the tips of the arrows indicate the mean of the tested positions in the amblyopic eye. Thus, the longer the arrow, the more pronounced the spatial distortions in the amblyopic eye in relation to the non-amblyopic eye.

Amblyopes with stable distortions

a) Refractive strabismic amblyopes: RS and SB are both refractive strabismic amblyopes with a reduced visual acuity in both eyes. RS has a visual acuity of 0.6 in the non-amblyopic eye and 0.1 in the amblyopic eye; SB has an acuity of 0.6 in her non-amblyopic eye and 0.3 in her amblyopic eye. Participant RS showed an overestimation of the inner circles especially for the amblyopic eye. For the radial adjustments there was a tendency to set the vertical distances smaller than the horizontal ones, picturing a more ovally shaped circle for the amblyopic eye (figure 20).

Esotropic and refractive strabismic amblyope RS

temporal nasal nasal temporal



Esotropic and refractive strabismic amblyope SB

temporal nasal nasal temporal

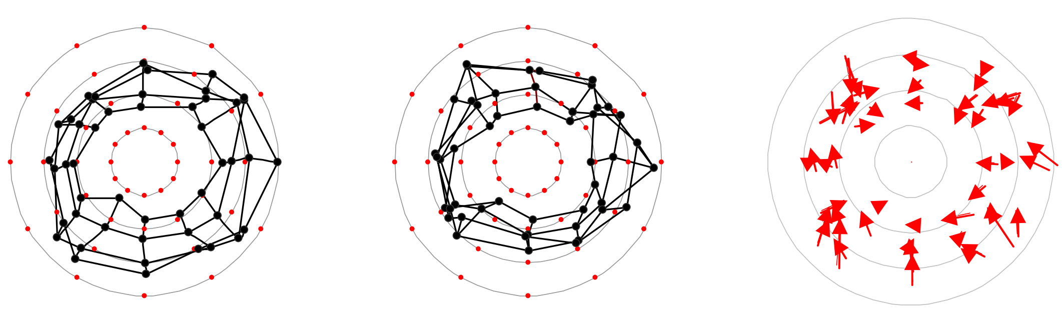


Figure 20. Visual presentation of the circle positions: spatial distortions and relative amount of spatial distortions indicated as vectorial subtraction of the distortion maps of participants RS and SB. Left: settings in the non-amblyopic eye. Middle: settings in the amblyopic eye. Right: vectorial subtraction of the distortion maps.

Amblyope SB underestimated the 2 and 4 deg circles and overestimated the 6 and 8 deg circles. It seems that she nearly did not distinguish between the four different radii of the circles. Tangential adjustments were set more precisely, especially in the non-amblyopic eye. In both subjects, no nasal-temporal asymmetry occurred in the adjustments of the circle positions.

b) Primarily strabismic amblyopes: Primarily strabismic amblyope LP (visual acuity of the amblyopic eye 0.25) showed a clear tendency in the amblyopic eye to set the vertical distances smaller than the horizontal ones. This pattern was visible especially in the amblyopic eye. The radial settings for the non-amblyopic eye were all underestimated more than for the amblyopic eye, tangential setting for the different positions were quite accurate for both eyes (figure 21).

Exotropic strabismic amblyope LP

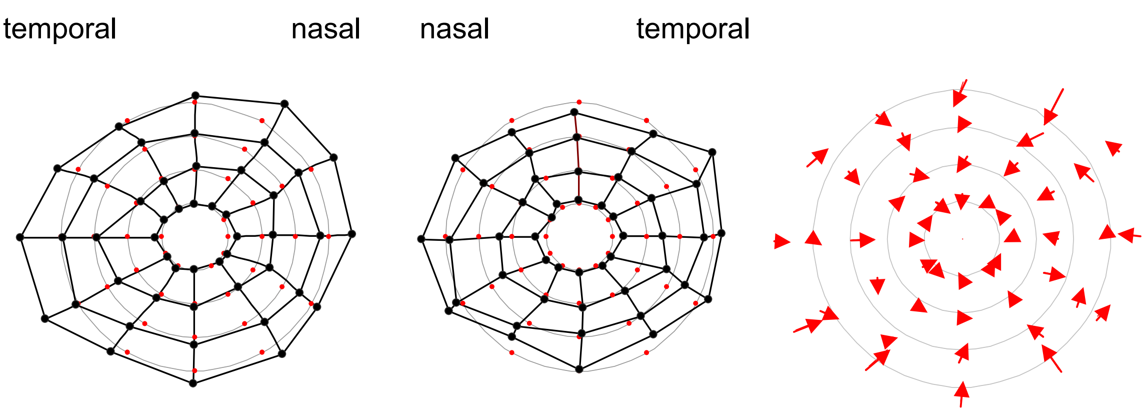


Figure 21. Visual presentation of the circle positions: spatial distortions and vectorial subtraction of the distortion maps of participant LP. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

c) Anisometropic amblyopes: Both anisometropic amblyopes, JB and MB, had a visual acuity in the amblyopic eye of 0.5. Participant JB had a slight tendency to underestimate the circle positions for the adjustments of the amblyopic eye; however the difference between the amblyopic and the non-amblyopic eye was quite low. Especially positions for the vertical and horizontal degrees visual angle are set surprisingly correct for the amblyopic eye as well as for the non-amblyopic eye (figure 22).

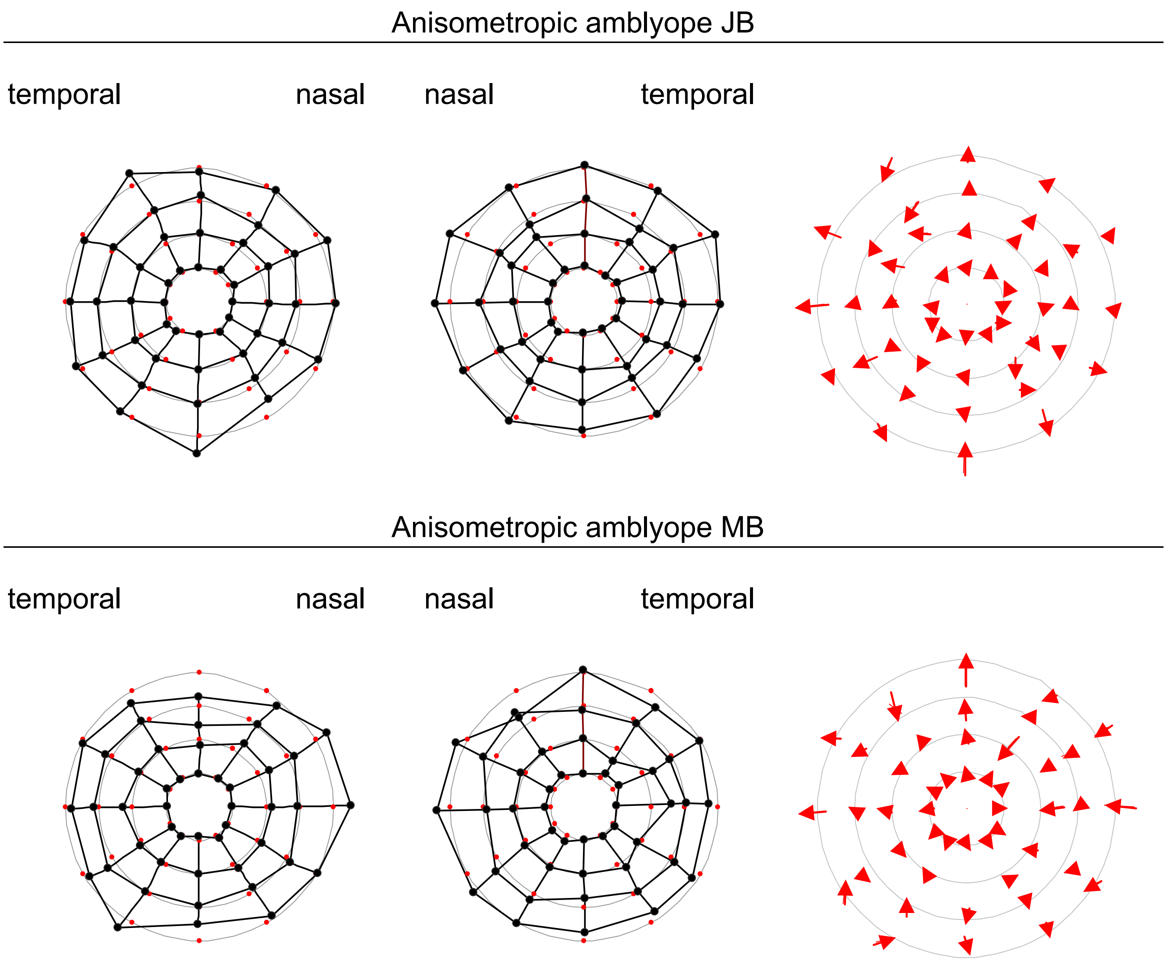


Figure 22. Visual presentation of the circle positions: spatial distortions and vectorial subtraction of the distortion maps of anisometropic amblyopes JB and MB. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

Vertical, horizontal, and all other tangential adjustments were quite correct in anisometrope MB as well. He showed a small tendency for setting the vertical distances smaller than the horizontal distances, however this pattern was more pronounced in the non-amblyopic eye. In both anisometropic amblyopes, patterns of the positions adjustments were very regular, and nearly showed a circle-shaped pattern for all different radii.

For the adjustments of radial positions, all amblyopes (except SB) perceiving stable spatial distortions showed a tendency to set the vertical positions of the circles smaller than the horizontal ones (see also Lagrèze & Sireteanu, 1991). The circles looked more or less ovally shaped, yet not in a very pronounced way. Additionally, they set the tangential positions adjustments quite precisely, especially for the vertical and the horizontal circle positions.

Amblyopes with temporal instability

a) Accomodative strabismic amblyopes: Comparing amblyopes DS and MK, both showed a very different pattern of the circle adjustments. DS set the position adjustments in a very consistent manner with quite regular circle-shaped patterns for the non-amblyopic as well as for the amblyopic eye (figure 23). However, he showed a slight overestimation of the circle positions for the amblyopic eye. The tangential circle positions were set quite precisely for the amblyopic as well as the non-amblyopic eye.

The circle adjustments of participant MK imaged a distinctive underestimation of all four circle radii for both eyes (see figure 23). This underestimation was even more pronounced in the amblyopic eye. The circle patterns in the amblyopic eye were also more distorted and irregularly shaped than in the non-amblyopic eye, and tangential circle positions were adjusted even more deviating compared to the non-amblyopic eye.

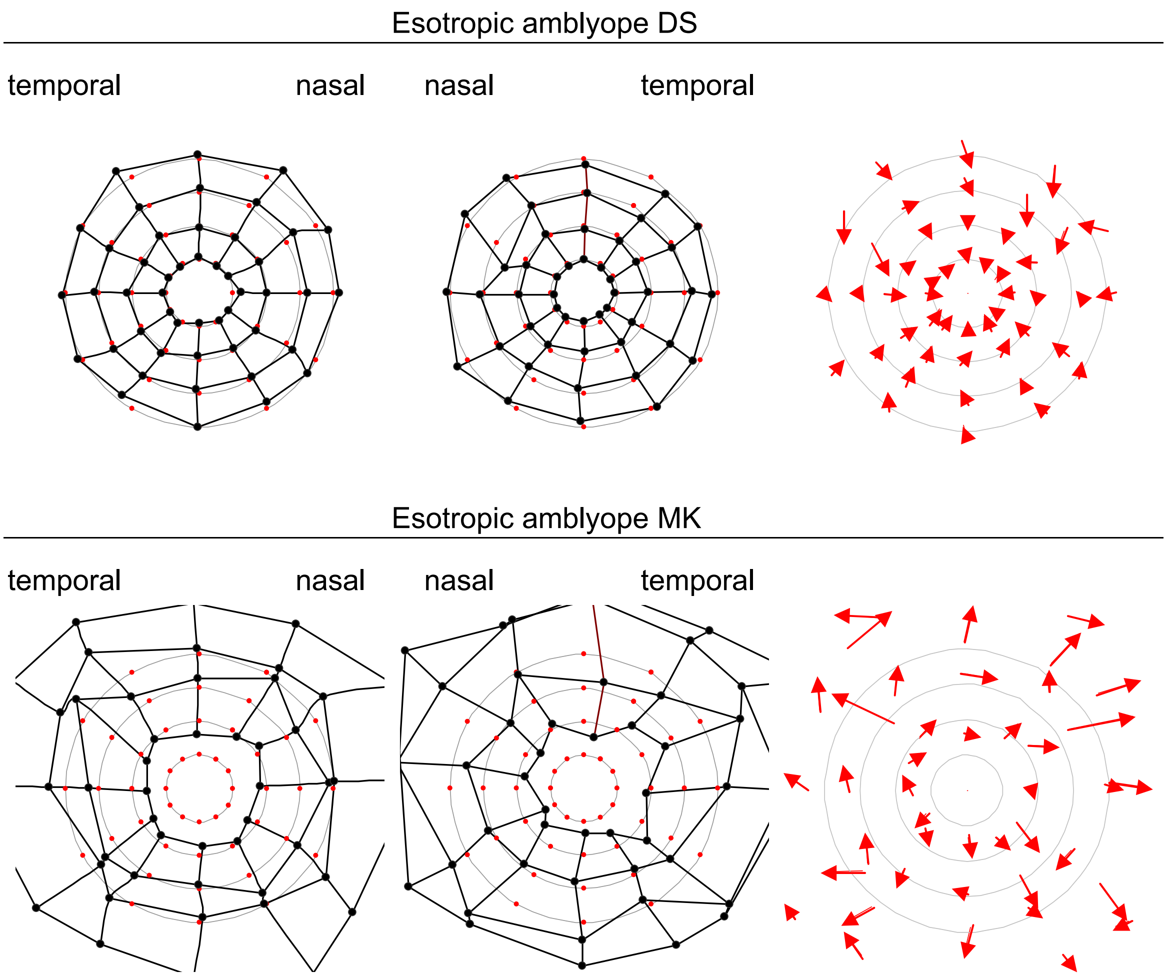


Figure 23. Visual presentation of the circle positions: spatial distortions and vectorial subtraction of the distortion maps of participants DS and MK. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

b) Strabismic-anisometropic amblyopes: Strabismic-anisometropic amblyope BB showed a pronounced tendency for the amblyopic eye to set the vertical distances smaller than the horizontal ones (figure 24). This ovally shaped pattern was also visible for the position adjustments in study 3 (see figure 12). The tangential adjustments were quite precise for the non-amblyopic eye. However, for the amblyopic eye there was a tendency to set the tangential adjustments in direction of the vertical axis. Participant CL underestimated the circle positions of the 6 and 8 deg circles. Position adjustment of the smallest 2 deg circle was very precise, while he overestimated the circle with a 4 deg radius. Tangential position adjustments were very precise for the horizontal axis, however got less precise for the other tangential adjustments. For the amblyopic eye, a slight clockwise rotation of the circle positions was observed

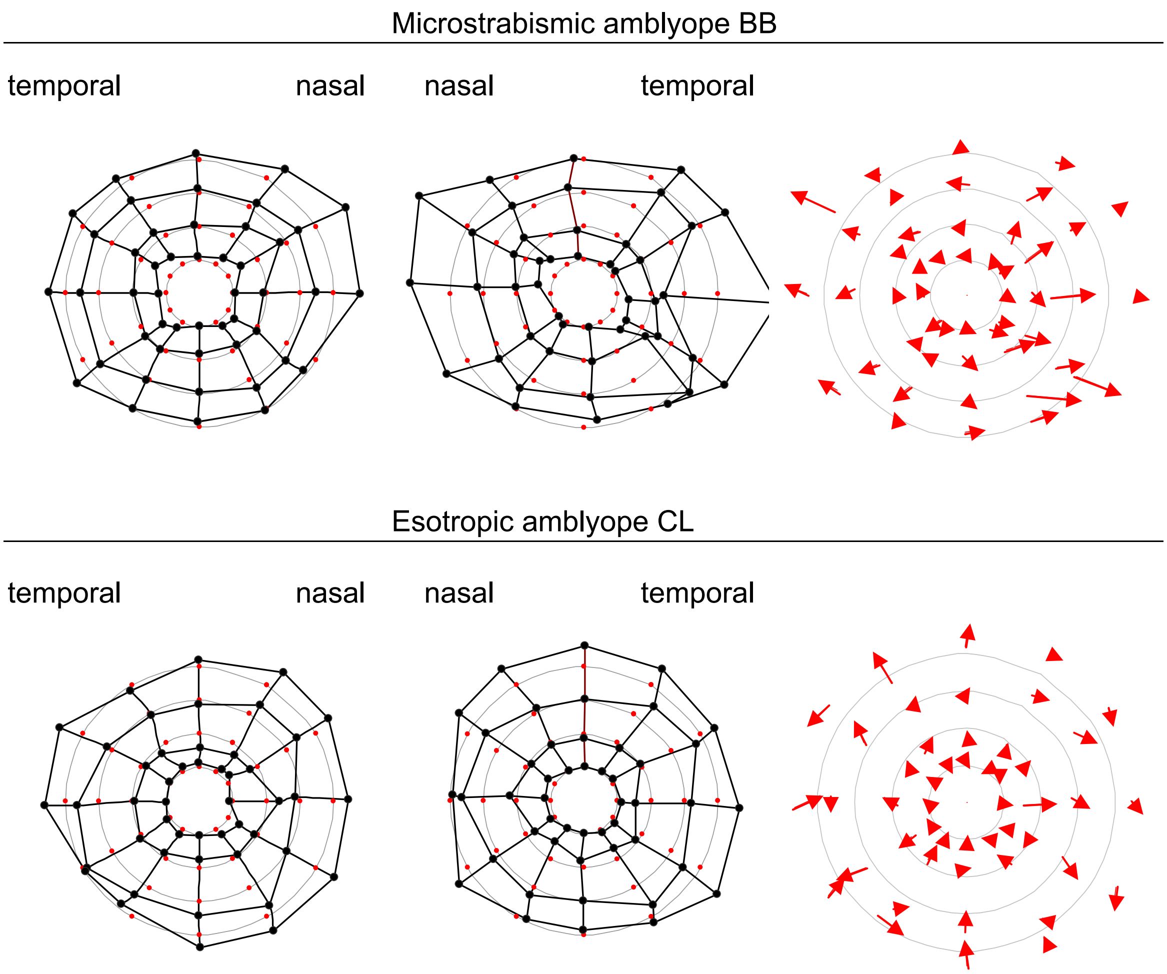


Figure 24. Visual presentation of the circle positions: spatial distortions and vectorial subtraction of the distortion maps of amblyopes BB and CL. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

c) Anisometropic amblyopes: Amblyope TS is the only anisometropic amblyope who experienced temporal instability. As most of the other participants he showed a tendency to set the horizontal distances smaller than the vertical ones (figure 25). This ovally shaped pattern of the circles is more pronounced than in the other anisometropic amblyopes JB and MB, who experienced no temporal instability. Similar to the other 4 amblyopes in the “temporal instability”-group, TS adjusted the tangential positions quite precisely in the non-amblyopic eye, however in the amblyopic eye, the tangential adjustments deviated from the target points. There was a tendency to set the tangential positions in direction to the vertical axis.

Anisometropic amblyope TS

temporal nasal nasal temporal

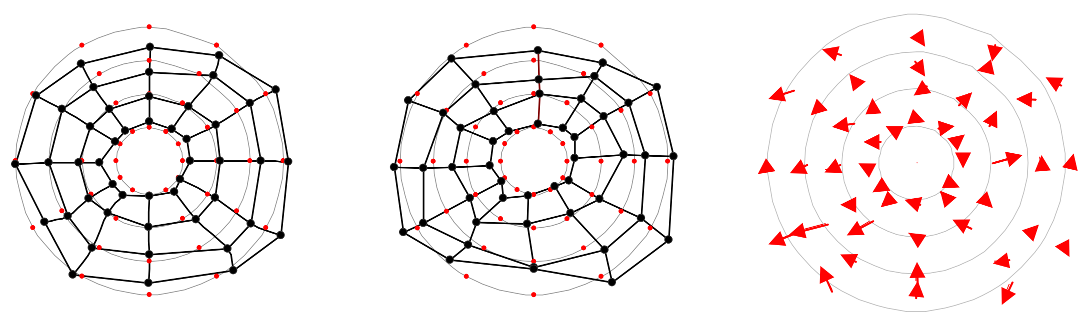


Figure 25. Visual presentation of the circle positions: spatial distortions and vectorial subtraction of the distortion maps of anisometropic amblyope TS. Left: non-amblyopic eye. Middle: amblyopic eye. Right: vectorial subtraction.

Overall, in all amblyopes position adjustments for the non-amblyopic eye were set more precisely than for the amblyopic eye. Four out of five amblyopes perceiving temporal instability showed a distorted pattern in the adjustment of the radial as well as the tangential circle positions. There was also a tendency to set the horizontal distances smaller than the vertical distances. However, amblyope DS showed a very regular pattern of the circles for all of the four different radii.

Group data

a) Spatial distortions and temporal instability: As shown in the previous experiment, a difference in the amount of spatial distortion between the amblyopic and the non-amblyopic eye was pronounced for the radial (F (1,8) = 14.08, p = .01, η^2 = .64) as well as for the tangential position adjustments (F (1,8) = 12.26, p = .01, η^2 = .61). The amblyopic eye showed much higher deviations from the target point than the non-amblyopic eye ($M_{\text{amblyopic eye}}$ = .35 and $M_{\text{non-amblyopic eye}}$ = .27 for radial positions, and $M_{\text{amblyopic eye}}$ = 4.43 and $M_{\text{non-amblyopic eye}}$ = 3.09 for tangential positions, respectively). This significant difference in perception was the same for both types of amblyopes, for amblyopes perceiving temporal instability with the amblyopic eye and for amblyopes with a stable amblyopic perception (F (1,8) < 1.30, p > .25).

For the spatial distortions, there was no significant difference in the adjustment of the radial positions between the two groups (F (1,8) = 2.05, p = .19, η^2 = .20). However, even if there was no significant difference, mean position adjustments of the group with instable perception were less precise than those of the group with stable spatial distortions (M_{instable}= .10 and M_{stable} = .05, see figure 26). For the tangential adjustment of the circle positions, difference in the amount of spatial distortions between the groups of stable and instable amblyopic perception approached nearly a significant difference (F (1,8) = 4.23, p = .07, η^2 = .35). Mean position adjustments of amblyopes with instable perception were less precise than those of amblyopes with stable spatial distortions (M_{instable}= 2.12 and M_{stable}=.55).

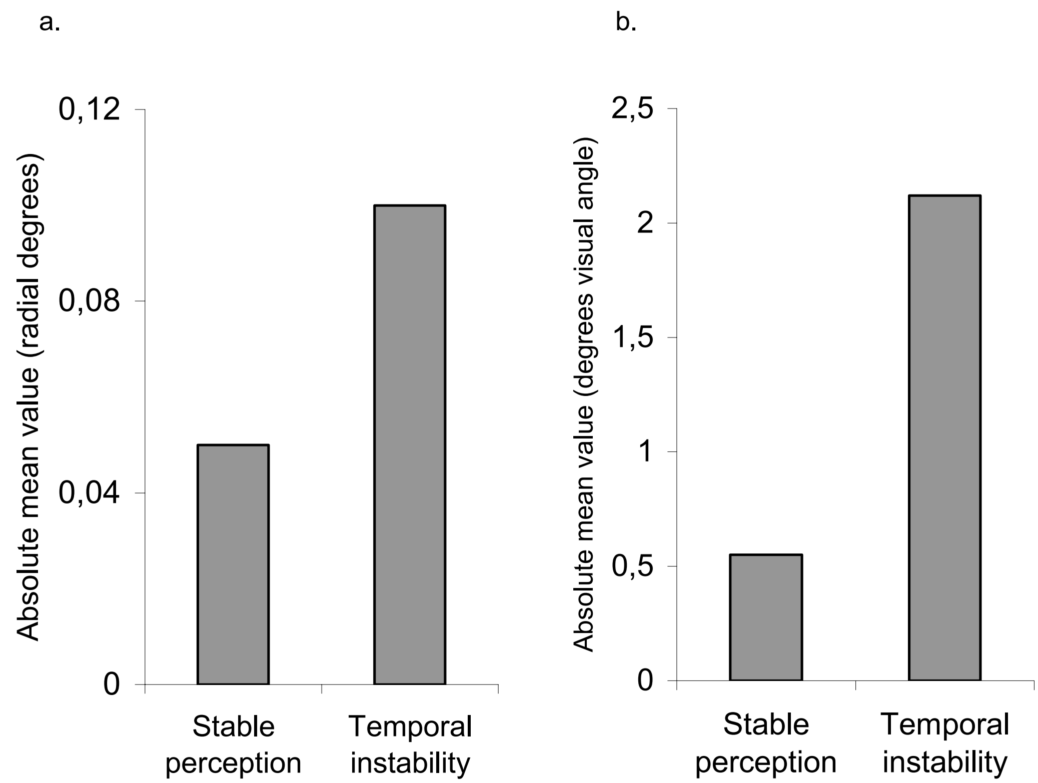


Figure 26 a & b. Amount of spatial distortions for the position adjustment of the circles, for amblyopes with constant distortions and for those with temporal instability. a. Radial adjustments. b. Tangential adjustments.

The main effect „presentation type“ did not show a significant influence on the radial position adjustments (F (1,8) = .47, p = .51, η^2 = .06). In the auditive presentation type, radial position adjustments were minimally less precise than in the visual presentation type (M_{auditive} = .09, M_{visual} = .06). As in the adjustments of the radial positions, all other main factors and interactions for the tangential position adjustments did not reach a significant level (all Fs > .02, ps > .14). The type of presentation had no influence on the amount of spatial distortions for the tangential adjustments (F (1,8) = .02, p = .89, η^2 = .00), means were M_{auditive} = 1.37 for the auditive type of presentation and M_{visual} = 1.31 for the visual type.

b) Spatial uncertainty and temporal instability: The amount of spatial uncertainty was significantly different between the amblyopic and the non-amblyopic eye for the tangential position adjustments (F (1,7) = 11.68, p = .01, η^2

= .63). This was not true for the radial position adjustments – here a significant level was not reached (*F* (1,7) = 2.36, *p* = .17, η^2 = .25). Still in both, the amblyopic eye showed more pronounced deviations from the target point than the non-amblyopic eye ($M_{\text{amblyopic eye}}$ = .32 and $M_{\text{non-amblyopic eye}}$ = .29 for radial positions, and $M_{\text{amblyopic eye}}$ = 4.07 and $M_{\text{non-amblyopic eye}}$ = 3.27 for tangential positions, respectively).

As expected for the radial position adjustment, there was no significant difference between the two groups in the amount of spatial uncertainty (*F* (1,7) = .12, *p* = .74, η^2 = .02). Nevertheless, mean radial position adjustments for the group with instable perception were minimally less precise than those of the group with stable spatial distortions (M_{instable}= .03 and M_{stable} = .02, see figure 27). However as in the amount of spatial distortions for the tangential circle adjustment, the difference in the amount of spatial uncertainty between the two groups for the tangential adjustment approached nearly a significant level (*F* (1,7) = 4.45, *p* = .07, η^2 = .38). Mean position adjustments of amblyopes with instable perception were clearly less precise than those of amblyopes with stable spatial distortions (M_{instable}= 1.28 and M_{stable} = .31).

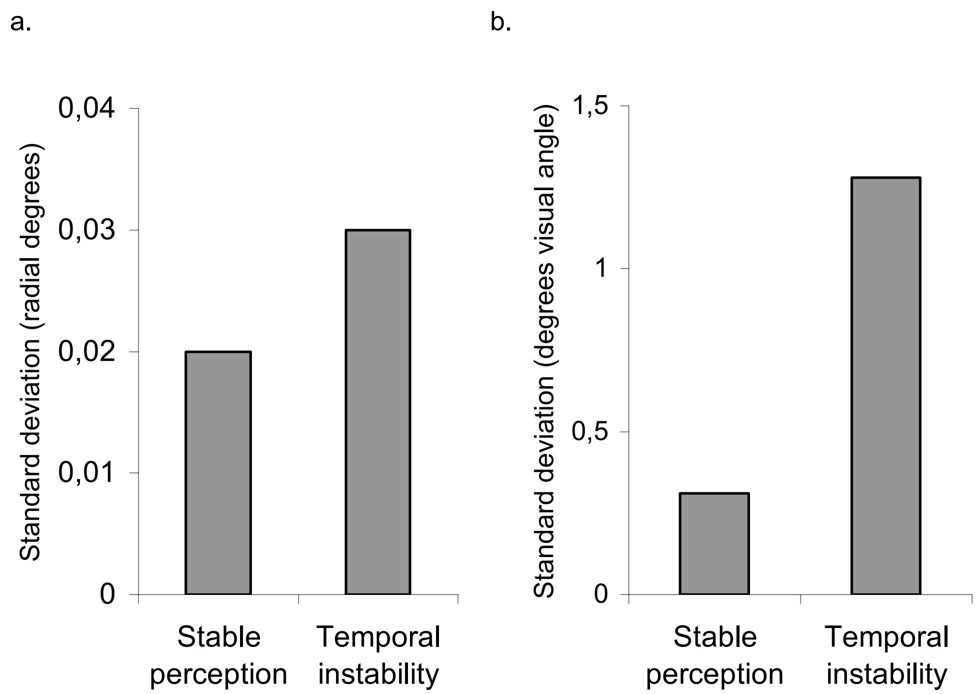


Figure 27 a & b. Amount of spatial uncertainty for the position adjustment, for amblyopes with constant distortions and for those with temporal instability. a. Radial adjustments. b. Tangential adjustments.

The main effect „presentation type“ as well as the interaction between the presentation type and the two groups did not reach a significant level for the radial position adjustments (F (1,7) = .19, p = .68, η^2 = .38, and F (1,7) = .17, p = .69, η^2 = .02, respectively). For the tangential position adjustments, the interaction between presentation type and group was not significant (F (1,7) = .57, p = .47, η^2 = .08) as well as the main effect "presentation type" (F (1,7) = 1.42, p = .27, η^2 = .17).

However even though a significant level was not reached, there was a pronounced difference in spatial uncertainty especially for the tangential position adjustments between amblyopes who perceive temporal instability and those who do not. Amblyopes with a temporally instable perception showed a higher amount of spatial uncertainty in adjusting the tangential circle positions ($M_{auditive}$ = 1.35, M_{visual} = 1.22) than amblyopes with constant spatial distortions ($M_{auditive}$ =

.60, M_{visual} = .02). This was the same for visual or auditive presentation type of the angle positions (figure 28).

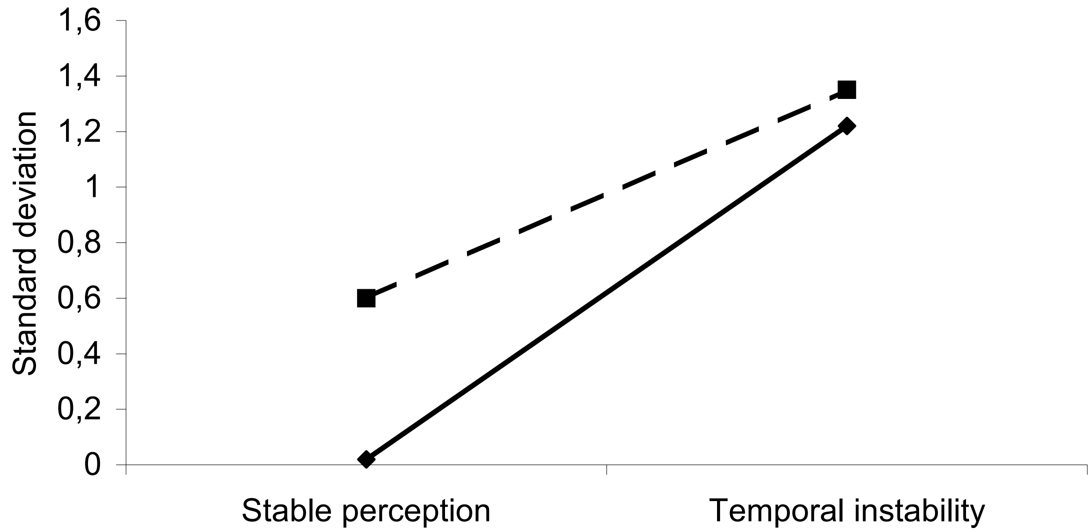


Figure 28. Amount of spatial uncertainty regarding the presentation type for tangential adjustments, for amblyopes with constant distortions and for those with temporal instability. Solid line: visual presentation, dashed line: auditive presentation.

Amblyopes perceiving temporal instability should benefit from switching to the visual presentation type and show results more similar to amblyopes with stable distortions. Yet, it was found that in the group of amblyopes without the perception of temporal instability, spatial uncertainty for the adjustment of the tangential circle positions is extremely reduced due to the visual presentation type. This was not true for amblyopes perceiving temporal instability: they only showed a marginal improvement of the tangential adjustments.

5.2.3 Discussion

Study 4 was designed to investigate if and how the performance of amblyopes perceiving temporal instability with the amblyopic eye depends on the modalities (visual and visuo-motoric versus auditive) used in a psychophysical task. This is addressed by the question: Is the change from a visual to auditive modality for amblyopes with instable perception more difficult to handle than for amblyopes with a stable amblyopic perception?

First, similar results as in study 3 were shown for the difference between the amblyopic and the non-amblyopic eye concerning the amount of spatial distortions and spatial uncertainty. Overall, the amblyopic eye showed much higher distortions than the non-amblyopic eye. This result applied for amblyopes perceiving temporal instability as well as for those without instable perception.

In general, there was no difference in spatial distortions and spatial uncertainty between the two amblyopic groups for the adjustment of the radial circle positions. For the tangential circle adjustments, a visually based presentation was much easier to handle for all amblyopes than an auditively based presentation. Amblyopes perceiving temporal instability with the amblyopic eye as well as amblyopes with stable perceptual distortions showed the same difficulties in adjusting a circle position that was presented auditively rather than visually. They had an increased amount of spatial distortions and spatial uncertainty for this auditive modality dependent task. However there was also a clear difference between amblyopes with an instable and a stable perception for the adjustment of the tangential circle positions: amblyopes with an instable perception were less precise in adjusting the tangential circle positions than amblyopes with stable spatial distortions. They showed enhanced spatial distortions and spatial uncertainty for the tangential positions. This was irrespective of a visual or auditive modality dependent presentation. Here, amblyopes with an instable perception showed a definitely increased spatial uncertainty in adjusting the tangential circle position auditively as well as visually. Nevertheless, the general pattern for larger distortions for auditive adjustments was also visible.

However, unlike for temporally instable perceiving amblyopes, for amblyopes with stable spatial distortions, spatial uncertainty in the tangential position adjustment was extremely reduced by the visual presentation. They showed nearly no uncertainty in the tangential adjustment of the circle points anymore. Overall, amblyopes perceiving temporal instability were worse in accomplishing the tangential circle positions than amblyopes with a stable amblyopic perception. Amblyopes with a stable amblyopic perception benefited largely from visual presentation; however amblyopes perceiving temporal instability also showed a small improvement for the visual presentation typ still they seemed to benefit to a much more moderate extent.

Compendiously, temporal instability in amblyopic perception had a negative impact on the performance in psychophysical tasks. This special type of temporal distortion that is added to the spatial amblyopic deficits may contribute to the inferior results of the group of amblyopes with an instable amblyopic perception. It seems that even a visually presented stimulus does not help for the psychophysical task. The performance does get better, albeit not to the same extent as for amblyopes with stable distortions. Maybe the problem lies in the nature of the visual stimulus itself: amblyopes with temporal distortions have a flickering, instable perception of the visual circle position. Due to that instable vision they are not able to point precisely on the target point but show an increased spatial uncertainty and deviation from that point. Perhaps the difficulty for amblyopes with an instable perception lies in that “pointing”-part of the experiment, not in the “presenting”-part.

The reason why there was nearly no difference between the two amblyopic groups for the radial adjustments might be that the radius was shown twelve times in each trial. This high repetition rate seems to increase the security in pointing at the right position for amblyopes perceiving temporal instability: the percent of errors was quite low and similar to that of the other amblyopes. It might be that for amblyopes with an instable perception, it is important to simplify the “pointing”-part of the experiment by a higher repetition rate of the presented circle lines. This in turn might ease and thus improve the “pointing”-part of the experiment for those participants.

Another reason for the large errors in the auditively presented tangential position adjustments of amblyopes with a stable and instable spatial perception might be deficits especially in the auditive-visual mapping. These deficits in auditory-to-visual mapping suggest an impairment of the dorsal “where” pathway, in addition to the known deficits of the ventral “what” pathway (Mishkin & Ungerleider, 1982). This possibility will be discussed in the following chapter in a general discussion of all four experiments.

6. General discussion

6.1 What it is all about

Amblyopia is a developmental disorder of the visual system that appears very early in life and leads to losses in spatial vision. Amblyopia results from an abnormal visual stimulation in early childhood. Generally, any condition which provides no adequate visual stimulation is associated with an enhanced risk for amblyopia. A number of different anomalies could cause amblyopia, but two seem especially important and are investigated in this thesis. These are an early misalignment of one eye (strabismic amblyopia), an unequal refraction in both eyes (anisometropic amblyopia), or a combination of both. In strabismic amblyopia motor fusion mechanisms are anomalous or inadequate for the maintenance of ocular alignment, while anisometropic amblyopia is due to an unequal refraction in the two eyes, probably caused by an unequal eye growth.

Performance in contrast sensitivity, spatial localisation and spatial localisation precision is disrupted in amblyopia. These deficits often occur along with perceptual distortions in amblyopic vision. Perceptual distortions have been well investigated in quantitative and qualitative approaches during the last fifty years. Possibly due to their different aetiologies, anisometropic and strabismic amblyopes show quite different results in psychophysical experiments. There is evidence suggesting that spatial capacities of amblyopes are abnormal, with strabismic and anisometropic amblyopes showing different abnormalities. In general, anisometropic amblyopes show results more similar to normal than strabismic amblyopes. Anisometropic amblyopes, but not strabismic amblyopes, perceive a reduction in contrast typical of normal vision, and strabismus and anisometropia have quite different effects on spatial interactions (Ellemberg, Hess & Arsenault, 2002). In particular, Snellen acuity is affected to a greater degree than grating acuity in strabismic but not in anisometropic amblyopes (Levi, 1991). Considerable spatial distortions and imprecision of spatial judgements characterise vision through the amblyopic eye of strabismic amblyopes but not of anisometropic amblyopes (Bedell & Flom, 1983). Anisometropic and strabismic amblyopes also differ with respect to two-dimensional spatial distortions (Lagrèze & Sireteanu, 1991). Anisometropic amblyopes, unlike strabismic amblyopes, do not show high amounts of positional uncertainty and contour integration is exhibited normally in anisometropic amblyopes (Hess & Demains, 1998). For anisometropic amblyopes, spatial integration efficiency is quantitatively similar to that of normally sighted persons, while for strabismic amblyopes, the spatial integration efficiency is markedly decreased (Wang, Levi & Klein, 1998). In addition to the pronounced spatial distortions, temporal distortions are reported frequently among strabismic amblyopes (Sireteanu, 2000a). Amblyopic patients report their vision to be temporally unstable and flickering on a short time scale (Barrett et al., 2003), and more specifically the amblyopic percept of strabismics is perceived as if “seen through hot air” (Sireteanu, 2000a, p. 71).Compared to the spatial distortions, there are no studies reporting temporal instability in strabismic and anisometropic amblyopic vision - not to mention studies investigating the temporal distortions in detail.

The permanent spatial and temporal perceptual deficits may be a result of the abnormal visual experience during visual development. The main reason for the development of amblyopia seems to be an abnormal neuronal processing of the visual information in the cortex. The neurophysiological substrate corresponding to the visual deficits is still a matter of investigation. The neuronal processes underlying amblyopia and especially the neural site of amblyopia are not known yet (Hess, 2001). There is some evidence from imaging studies that the main site of the abnormal developmental changes is V1, in that the striate cortex shows reduced activity in human strabismic amblyopes (Barnes, Hess, Dumoulin, Achtman & Pike, 2001).

However, recent support is coming from brain-imaging studies that the deficit is also beyond V1 in the extra-striate cortex, and that the relative reduction of responses to the amblyopic eye increases from striate to extrastriate areas (e.g. Imamura, Richter, Fischer, Lennerstrand, Franzén, Rydberg, Andersson, Schneider, Onoe, Watanabe & Långström, 1997). Sireteanu et al. (1998) found neural deficits in strabismic and anisometropic amblyopia first appearing in V2 and then becoming more pronounced with increasing hierarchical cortical levels (Muckli, Kiess, Tonhausen, Singer, Goebel & Sireteanu, in press). However, it is still unclear whether dorsal and ventral processing streams are affected equally. Several findings suggest that the ventral visual pathway is more affected in strabismic amblyopia. The ventral “what” pathway extends from the primary visual cortex to the inferior temporal cortex of the temporal lobe. It functions in the identification of pattern and shape discrimination, resolution of fine detail and acuity, colour perception, and visual memory. For strabismic amblyopes Altmann and Singer (1986) proposed a deficit of the P-type cells response. Corresponding to these psychophysical studies, Sireteanu (1991) and Schröder, Fries, Roelfsema, Singer and Engel (2002) found the ventral pathway more affected in strabismic amblyopic cats than the dorsal pathway. On the other hand, there are studies suggesting deficits in the dorsal pathway accompanying strabismic amblyopia (for a review see Asper, Crewther & Crewther, 2000b). The dorsal “where” stream is primarily involved with perception of motion, depth, control of eye movements, localisation of targets in space, and attention shifts. Sharma, Levi and Klein (2000) found strabismic amblyopes to underestimate the number of features with the amblyopic eye, and argued that this inability to count features depends on the malfunction particularly of the dorsal, parietal cortex.

Thus, psychophysical, imaging and animal data report impairment of functions attributed to both ventral and dorsal pathways (Asper et al., 2000b). Therefore the four studies in this thesis were undertaken to get clearer evidence for either pathway, or more precisely, to investigate the perception of temporal instability as well as its relationship to the spatial distortions which occur in amblyopic vision. Both qualitative and quantitative approaches were accomplished to get a broader view on these different types of perceptual distortions.

6.2 Spatial distortions and spatial uncertainty in amblyopia

Four different types of distortions became apparent in the experiments. These were a) blurring of patterns, b) wavy and jagged appearance of horizontal and vertical lines, c) distortions due to superimposed lines or contours, and d) errors in orientation. Similar spatial distortions have been found and were classified (see also Barrett et al., 2003). One surprising result in this thesis was that in study 2 the amblyopic participants perceived spatial distortions less pronounced than in study 1. But the structure and complexity of the spatial distortions remained the same throughout both experiments, and the four categories of distortional errors can still be considered as likely. When one looks at the nature of the spatial distortions, it can be said that all spatial distortions that came up in any of the experiments are characterised by quite an amount of irregularity (see also Bedell & Flom, 1983; Lagrèze & Sireteanu, 1991). In contrast to the anisometropic amblyopes, this was especially true for the strabismic amblyopes.

On the one hand, it was possible for the results of the qualitative part to build categories for the distortions to fit in: blurring of patterns, wavy and jagged appearance, superimposed lines, and errors in orientation. For the results of the quantitative part one could also categorise that strabismic participants underestimate the circle positions while anisometropic participants slightly overestimate the outermost circles. Anisometropic amblyopes are more similar to the normally sighted participants. Additionally, anisometropic and strabismic-anisometropic amblyopes show patterns that are more ovally shaped, while those of the purely strabismic amblyopes are - as pointed above - distorted in an irregular way or rotated in a clockwise direction. But on the other hand, in both qualitative and quantitative approaches results of the spatial distortions were also very individual (Sireteanu et al., 1993). Each amblyopic subject has his/her individual pattern of distortions. These findings are in accordance with previous results of Lagrèze and Sireteanu (1991) as well as others (e.g. Barrett et al., 2003).

There was also an effect of the modality concerning the spatial distortions and the spatial uncertainty. Depending on a visual or auditive modality, the spatial distortions and uncertainty were increased or on a more normal level, respectively. Presenting the stimulus auditively, an increased amount of distortions and spatial uncertainty was recorded. This was not the case for a visual stimulus presentation. This suggests that amblyopes might have difficulties with this auditive modality dependent task, and, more specifically, might have problems with auditive-to-visual mapping.

For the spatial uncertainty, strabismic and strabismic-anisometropic amblyopes show considerable uncertainty, in contrast to the anisometropic amblyopes and normally sighted participants. This finding was achieved in each of the four experiments done in this thesis. Recently, Simmers and Bex (2004) confirmed the widely believed assumption that spatial uncertainty is most pronounced in amblyopes. They suggested that the spatial deficit accompanying amblyopia underlies this increased spatial uncertainty. Fronius, Sireteanu and Zubcov (2004) found this even in the amblyopic perception of children with strabismic amblyopia. In their study, increased spatial uncertainty outside the normal range occurred which is similar to that in adult amblyopes.

Overall, spatial localisation deficits (comprising both spatial distortions and spatial uncertainty) were most pronounced in strabismic amblyopes for all kinds of experimental approaches. Strabismic and strabismic-anisometropic amblyopes showed considerably higher spatial distortions and uncertainty than do anisometropic amblyopes. They were especially pronounced in the central visual fields (see also Fronius & Sireteanu, 1994). This is in accordance with other results from the literature (Lagrèze & Sireteanu, 1991; Sireteanu et al., 1993; Demanins & Hess 1996).

6.3 Temporal instability in the amblyopic percept

For the perception of temporal distortions, two types of instability have been found: a) jitter of the whole pattern, and b) moving of single lines or parts in the pattern. They occurred only at high spatial frequency patterns, at low spatial frequency patterns simply stable spatial distortions were perceived with the amblyopic eye. That is similar to the findings of Bradley and Freeman (1985). They concluded that when the experimental stimulus is either large enough for the amblyopic participant to perceive or consists of low spatial frequencies, no temporal deficits emerge in the amblyopic perception. These temporal distortions emerged in addition to the spatial distortions, and moreover, the data in this thesis suggest that the perception of temporal instability seems to have quite an influence on the perception of spatial distortions. Especially the central visual field of the amblyopic eye is most affected by the distorted spatial perception, and additionally amblyopes perceiving temporal instability show an even increased amount of spatial distortions in the central visual field.

It can be said that almost half of the amblyopic participants experienced temporal instability. But there is clearly a preponderance of strabismic amblyopes perceiving temporal distortions. It seems that these instability phenomena occur mainly in strabismic and strabismic-anisometropic amblyopes. In addition, other than one would expect, a deep visual acuity loss seems not to be a good predictor of temporal distortions. Temporal distortions rather occur more often in moderate amblyopes, while spatial distortions are associated with moderate-to-deep acuity loss. This fits also to the findings reported in study 1 that temporal instability is associated with a mild loss in contrast sensitivity. Thus, moderate acuity loss and mild loss of contrast sensitivity seem to point to the perception of temporal instability. A possible explanation for this finding might be that due to the lower suppression of the amblyopic perception, an instable perception is coming up. Kilwinger, Spekreijse and Simonsz (2002) found that for the occurrence of strabismic suppression, the similarity of the images of both eyes has to be detected by the visual system. They suggested that “two mechanisms must be at work, a ‘similarity detector’ and a ‘suppressor’” (p.2011), and that the location of these two mechanisms might be in the lateral occipital cortex. If the loss in visual acuity in not that extreme and therefore suppression lower, rivalry between the two eyes might come up. This might result in an instable percept of the amblyopic eye that has to deal with other occurring rivalling visual inputs coming from the “better” non-amblyopic eye. The findings of Ellemberg et al. (2000) also fit in this interpretation. In their studies they found that deep visual deprivation has much smaller effects on neuronal mechanisms that mediate temporal vision than on those that mediate spatial vision.

One quite different but nevertheless very interesting and important finding in this thesis was that the eye dominance might be a crucial factor for the development of a temporally instable perception. It might be the interaction between opposite sides of hand and eye dominance together that leads to one of the two types of temporal distortions. Crossed dominance was also found to be related to other neuronal disorders that begin quite early in life like dyslexia (Stein, Richardson & Fowler, 2000).

An additional visual disturbance that came up in some of the temporal distortions is the perception of colour illusions. Some participants perceiving temporal instability also reported the perception of coloured lines or contours. These illusions were appearing in all kinds of colours in the rainbow spectrum or in just one or two colours like red, green or yellow. As Eagleman (2000) stated “illusions, often, are those stimuli that exist at the extremes of what our system has evolved to handle. Sometimes illusions stem from assumptions made by the visual system; at other times they represent an active recalibration” (p. 920). But what does this mean for the colour illusions reported by the amblyopes in the studies of this thesis? It is true that amblyopes and especially strabismic amblyopes perceive an increased amount of spatial uncertainty. This uncertainty was even more increased in amblyopes perceiving temporal instability. It might be that due to this highly increased uncertainty in the perception of the amblyopic eye additional visual phenomena like those of the visual illusions come up, spontaneously activated by cortical cells sensitive to colours, even in absence of any adequate stimuli (Sireteanu, Bäumer & Sârbu, 2005). Probably in the amblyopic perception a neuronal pathway is affected and spuriously activated that is sensitive to temporal properties and colour processing. Due to its functions and important role in vision, especially in the perception of motion, this might be the magnocellular-processing stream including area MT, but also parts of the ventral pathway, involving V4.

6.4 Conclusions

There are several models that attempt to explain the visual deficits found in the perception of strabismic and anisometropic amblyopes. The two most popular ones for explaining the losses of amblyopic spatial vision are the topographical disarray model (Hess et al., 1978) and the undersampling model (Levi & Klein, 1986; Sharma, Levi & Coletta, 1999). It is possible that strabismic deficits reflect a topographical disorder or jitter of the cortical receptive fields, which appear to be uncalibrated (Levi & Carkeet, 1993; Hess & Field, 1994). The failure of the calibration process might come up in early visual development as a result of the eye misalignment. This means that there is an early developing scrambling of the retinotopic map, which in turn results in an enhanced positional uncertainty (Hess, Field & Watt, 1990). Alternatively, the undersampling model hypothesises that amblyopic vision is due to a reduced cortical spatial sampling density (Levi, Klein & Sharma, 1999). Evidence for this spatial undersampling comes mainly from experiments showing that amblyopes are not efficient in using all visual information that defines an image (Levi et al., 1999; Wang et al. 1998). Sharma et al. (1999) showed that there is a sparse sampling by cortical neurons in the foveal representation of the amblyopic eye. The authors suggest that this undersampling may be the reason for the spatial distortions in the perception of strabismic amblyopes.

However, there are controversies regarding these hypotheses, and neither of the two models can account for all of the results found in the qualitative and/or quantitative parts of the experiments in this thesis. It might be possible to explain some data in terms of the topographical disarray or positional uncertainty, respectively, or in terms of the spatial undersampling model, but it is not clear how they deal with most of the higher-order deficits found to appear in the spatial vision of strabismic and anisometropic amblyopes. That is especially the deficits in auditory-to-visual mapping and the perception of jitter and coloured illusions in two-dimensional black-and-white patterns. There is also the unexplained observation of crossed hand and eye dominance on the occurrence of temporal distortions, and the finding of a low loss in acuity as well as in contrast sensitivity in relation to the perception of temporal instability.

What do these different findings tell us about the possible cortical site of the spatial and temporal deficits in strabismic and anisometropic amblyopic vision? In general, it can be said that the different results of the four experiments and reported deficits in the amblyopic vision suggest an impairment of the dorsal “where” pathway, which comes up in addition to the known deficits of the ventral “what” pathway (Mishkin & Ungerleider, 1982). This is especially true for amblyopes perceiving temporal instability. First, amblyopes with the perception of temporal instability had difficulties in the psychophysical task that was based on an auditive rather than on a visual modality. In comparison to amblyopes perceiving only spatial distortions, they showed an increased amount of spatial distortions and spatial uncertainty for the auditive modality dependent task. This was even more pronounced for tangential positions adjustments. It seems that amblyopes with temporal instabilities might have deficits especially in the auditory-to-visual mapping. This suggests that cortical cells on the dorsal pathway might be affected and that higher-order, multisensory association areas in the posterior parietal cortex might be involved (Sireteanu, Bäumer & Sârbu, 2005).

Second, colour illusions in combination with temporal instability also suggest an impairment of the magnocellular-processing stream, probably caused by increased uncertainty in the visual process of the amblyopic perception. It might be that, due to this increased uncertainty, visual hallucinations of colour-like contours are coming up. They might be spontaneously activated by cortical cells in the dorsal pathway which are sensitive to colours, and occur even in absence of any adequate stimuli. So, there seems to be an impairment in the dorsal pathway where cortical cells might be spuriously activated, being sensitive to temporal properties and colour processing together. However, these two different deficits might also mean that more than one pathway is affected and that both, the dorsal as well as the ventral pathway contribute to the spurious perception of colour-like, moving contours.

To conclude, it seems that perception of temporal instability can occur in addition to the spatial distortions in amblyopia. Regarding the visual deficits found in strabismic and anisometropic amblyopes, the spatial and temporal deficits might be located not only in V1 but also beyond the striate cortex in higher extra-striate areas including the parietal cortex. It seems that both, the ventral and the dorsal pathway contribute to the different spatial and temporal deficits in amblyopic perception, depending on the type and amount of spatial or temporal errors the amblyope perceives.

6.5 What comes next?

The results of these psychophysical experiments, quantitative as well as qualitative ones, suggest that one should find an impairment of the ventral pathway for amblyopes perceiving stable spatial distortions and spatial uncertainty. Also, in amblyopic participants perceiving temporal instability in addition to spatial distortions, there should be an additional impairment of the dorsal pathway. Regarding the temporal instabilities, this should include deficits in activation for the areas MT and MST for the amblyopic eye. The best way to investigate these questions would be a combination of psychophysical, computational and functional imaging techniques. This is exactly what the group of Sireteanu is doing right now: ongoing studies in their laboratory suggest that “mapping of auditory onto visual signals is likely to be disturbed in amblyopic subjects experiencing anomalous perception, thus suggesting an involvement of higher-order, multisensory areas in the posterior parietal cortex” (Sireteanu, Bäumer & Sârbu, 2005).

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Lebenslauf

Persönliche Daten:

Adresse: Claudia Christina Bäumer
Kaiserstr. 36
69115 Heidelberg
Tel. 06221 / 4332061
E-Mail: claudia.baeumer@t-online.de

Geburtsdatum: 11.06.1977 (München)
Familienstand: ledig, eine Tochter
Staatsangehörigkeit: deutsch

Schulausbildung:

1983 - 1987 **Besuch der Feldmochinger-Grundschule in München**

1987 - 1996 **Besuch des Maximiliansgymnasiums in München**
Abschluss des Abiturs mit Gesamtnote "gut" (2,4)

Hochschulausbildung:

Okt.´96 - Sept.´98 **Psychologie-Grundstudium an der TU Darmstadt**
Abschluss des Vordiploms mit Gesamtnote „gut“

Okt.´98 - Apr.´02 **Psychologie-Hauptstudium an der Uni Heidelberg**
Abschluss des Diploms mit Gesamtnote "sehr gut"
Schwerpunktfächer: Klinische & Pädagogische Psy.
Nebenfach: Psychopathologie
Diplomarbeit: "Überprüfung zweier kognitiver Zeitschätzungstheorien anhand einer klinischen Stichprobe"

seit Juli ´02 **Promotionsstelle am Max-Planck-Institut für Hirnforschung, Frankfurt**
Doktorarbeit: „Temporal and spatial distortions in adult amblyopia“ (Betreuerin: Prof. Sireteanu)

Berufliche Tätigkeiten:

seit Juli ´02	**Wissenschaftliche Mitarbeiterin an der Universität Frankfurt,** Psychologisches Institut (Fachbereich Physiologische Psychologie) im DFG-Projekt "Wahrnehmungsverzerrung bei Schielamblyopie: Psychophysik und bildgebende Verfahren"
seit Feb. ´04	**Selbständige Mitarbeiterin bei der Psycholog. Beratungsstelle der Psychosozialen Hilfe e.V.** Tätigkeit: Durchführung von Erstgesprächen, weiterführende Beratung

Wissenschaftl. Tätigkeiten:

Mai `97 - Juli `98	**Beschäftigung als studentische Hilfskraft** im Bereich "Pädagogische Psychologie" bei Prof. B. Schmitz
Okt.`99 - Juni `01	**Beschäftigung als stud. Hilfskraft** im Bereich "Sozialpsychologie" bei Prof. T. Betsch (DFG-Projekt 504) Tätigkeit: Durchführung einer experimentellen Studie zum Thema Entscheidungsfindung

Praktika:

Aug. - Sept.´97	**Praktikum bei der *Daimler Benz AG*** im Bereich "Unfallforschung" Tätigkeit: Durchführung und Auswertung von Interviews mit verunfallten Autofahrern
Feb. - März ´99	**Praktikum am *Max-Planck-Institut für psychologische Forschung*** im Bereich "Kognition und Handlung" Tätigkeit: Konzeption und Durchführung einer experimentellen Studie zum „Tapping“
Aug. - Sept.´99	**Praktikum am *Wilhelm-Griesinger-Krankenhaus*** *Berlin* im Fachbereich "Klinische Neuropsychologie" Tätigkeit: Diagnostik, therapeutische Betreuung von Patienten und deren Angehörigen in der neurologischen Frührehabilitation

Deutsche Zusammenfassung der Dissertation „Temporal and spatial distortions in adult amblyopia“ von Claudia Bäumer

I. Einleitung

Amblyopie ist definiert als die Schwachsichtigkeit eines oder beider Augen, welche ohne organische Fehler im Auge auftritt. Die Entstehung einer Amblyopie kann unter anderem durch Anisometropie (anisometrope Amblyopie) oder Strabismus (Schielamblyopie) in der frühen Kindheit hervorgerufen werden. Verlust der Binokularität, verminderte Sehschärfe und Kontrastsensitivität des nicht-dominanten Auges, und speziell das Auftreten räumlicher Verzerrungen sind kennzeichnend für die Wahrnehmung von Amblyopen und im besonderen von Schielamblyopen (Sireteanu, 2000). Eine zusätzliche zeitliche Instabilität des Seheindrucks wurde zwar vereinzelt berichtet (Barrett, Pacey, Bradley, Thibos & Morill, 2003; Hess, Campbell & Greenhalgh, 1978, Sireteanu, 2000), jedoch nicht tiefergehend untersucht. Ziel der Dissertation ist es, die amblyope Wahrnehmung mit Fokus auf die zeitliche Instabilität näher zu untersuchen, und somit einen Beitrag zum Verständnis der räumlichen und zeitlichen Wahrnehmungsverzerrungen bei der Benutzung des amblyopen Auges zu erbringen.

Die genaue Erfassung und Visualisierung von zeitlicher Instabilität im Seheindruck amblyoper Personen wurde bis jetzt noch nicht umgesetzt: diese beschrieben ihren Seheindruck des amblyopen Auges als zeitlich instabil, das heißt, die Bilder flimmern, als würden sie durch heiße Luft betrachtet (Sireteanu, 2000). Zudem konnte bis zum jetzigen Zeitpunkt noch kein eindeutiges neuronales Korrelat des amblyopen Defizits identifiziert werden. Die bisherigen Ergebnisse legen allerdings nahe, dass dieses Defizit nicht auf der Ebene der primären Sehrinde, sondern auf höheren, extrastriären Arealen lokalisiert ist (Muckli, Kiess, Tonhausen, Singer, Goebel & Sireteanu, in press). In der Dissertation wurde versucht, diese Fragen über zwei unterschiedliche methodischer Arten anzugehen: es wurden vier psychophysische Experimente durchgeführt, wobei jeweils zwei die amblyope Wahrnehmung quantitativ bzw. qualitativ erfasst haben.

II. Teil 1: Qualitative Methodik

Orthoptische Voruntersuchungen

Die Aufstellung einer empirischen Datenbasis durch Rekrutierung und orthoptische Untersuchung amblyoper Probanden ging den psychophysischen Experimenten voraus. Insgesamt wurden 41 Personen orthoptisch untersucht, von diesen kamen 18 für die Experimente in Frage. Es konnten somit 7 Schielamblyope, 4 Schielamblyope mit zusätzlicher Anisometropie, 4 anisometrope Amblyope und 3 Schieler mit alternierender Fixation ohne Amblyopie rekrutiert werden. Zu Kontrollzwecken wurden zudem 30 normalsichtige Personen orthoptisch untersucht. Zudem wurde das Kontrastsehen unter zu Hilfenahme des „Vision Contrast Test Systems“ für Ferne und Nähe sowohl monokular für das rechte und linke Auge als auch binokular überprüft.

Experiment 1

14 amblyopen Personen wurden im ersten Experiment Schwarz-Weiß-Muster verschiedener räumlicher Frequenzen gezeigt. Die Probanden wurden

gebeten, ihre individuelle Wahrnehmung der Muster mit dem amblyopen Auge mitzuteilen und aufzuzeichnen.

Hinsichtlich der räumlichen Fehler konnten verschiedene Arten an Wahrnehmungsverzerrungen feststellt werden: gerade Linien erscheinen als wellenförmig oder ausgefranst, überlagernde Konturen verzerren das Erscheinungsbild, und Teile der Scharz-Weiß-Muster bzw. das Gesamtmuster sind unscharf (siehe auch Barrett et al., 2003, Sireteanu, Lagrèze & Constantinescu, 1993).

Drei von vier Schielamblyopen und zwei von drei Schielamblyopen mit Anisometropie berichteten zudem über zeitliche Instabilitäten, die zusätzlich zu den räumlichen Verzerrungen auftraten. Die zeitliche Instabilität trat nur bei hohen räumlichen Frequenzen der Schwarz-Weiß-Muster auf. In der Gruppe der anisometropen Amblyopen dagegen zeigte sich nur bei einem von vier Anisometropen eine Instabilität der Wahrnehmung. Es konnten zwei Arten von Instabilität in der amblyopen Wahrnehmung feststellt werden: entweder wurde das gesamte Muster als instabil wahrgenommen oder einzelne Linien oder Bereiche schienen sich innerhalb des Musters zu bewegen. Zudem nehmen einige Ambylope farbliche Veränderungen in den Mustern wahr.

Die Ergebnisse machen deutlich, dass vor allem Schielamblyope und Schielamblyope mit zusätzlicher Anisometropie zeitliche Instabilitäten in ihrer Wahrnehmung mit dem amblyopen Auge haben. Diese Instabilitäten in der Wahrnehmung treten zusätzlich zu den allgemein bekannten räumlichen Verzerrungen im amblyopen Seheindruck auf. Zudem zeigte sich, dass ein zeitlich instabiler Seheindruck vor allem in Verbindung mit höheren räumlichen Frequenzen auftritt.

Experiment 2

In einem Matching-Experiment wurden dem nicht-amblyopen Auge der Probanden unterschiedliche Verzerrungsgrade ihres individuellen Seheindrucks am Computer präsentiert. Die Probanden wurden dann gebeten, diese verschiedenen Modelle mit dem Seheindruck ihres amblyopen Auges abzugleichen. Dieser Vorgang wurde solange wiederholt, bis der computer-generierte Seheindruck mit dem tatsächlichen amblyopen Seheindruck übereinstimmte.

Überraschenderweise zeigten die amblyopen Probanden hier vor allem in den Schwarz-Weiß-Mustern mit geringen räumlichen Frequenzen nur noch minimale räumliche Verzerrungen. Dies war besonders deutlich bei „einfacheren" Verzerrungen wie wellenförmigen oder ausgefransten Linien. Allerdings konnten verzerrende überlagernde Konturen mit dieser Methode gut abgebildet werden; diese traten auch eher in höheren räumlichen Frequenzen auf. Anscheinend ist die quantitative Erfassung der subjektiven amblyopen Wahrnehmung sehr schwer möglich und spiegelt diese nicht in ausreichendem Maße wider (Hess, Pointer, Simmers & Bex, 2003).

III. Teil 2: Quantitative Methodik

Experiment 3

In einem dritten Experiment wurden die Versuchsteilnehmer vor die Aufgabe gestellt, geometrische Kreise verschiedener Größe sowohl mit dem amblyopen als auch mit dem dominanten Auge zu rekonstruieren. In diesem Experiment wurden die konsistenten Fehler („spatial errors"), die räumliche Ungenauigkeit („spatial uncertainty") und die zeitliche Flüchtigkeit („temporal instability"), die in der amblyopen Wahrnehmung auftreten, erfasst.

Aufbauend auf früheren Projekten (Lagrèze & Sireteanu, 1991; Sireteanu et al., 1993) wurden die Methoden der vorangegangenen Studien übernommen. Auf einem Computerbildschirm wurden dem nicht-amblyopen Auge Kreise dargeboten, welche die Probanden memorisieren mussten. Anschließend sollten diese Kreise monokular Punkt für Punkt, wie die Zahlen einer Uhr, rekonstruiert werden (d.h. mit der Maus am Bildschirm eingestellt werden). 6 vorgegebene Radii von 2, 4, 6, 8, 10 und 12 Grad Sehwinkel und 12 Positionen pro Radius wurden getestet. Der Radius wurde visuell am Bildschirm präsentiert, die jeweilige Kreisposition auditiv über Kopfhörer vorgespielt. Zur Ermittlung der räumlichen Unsicherheit wurde jede Position sowohl dem amblyopen als auch dem nicht-amblyopen Auge fünfmal präsentiert.

Die Abweichung der gemittelten Einstellung durch das amblyope Auge von der gemittelten Einstellung durch das nicht-amblyope Auge ergab das Maß für die konsistenten räumlichen Fehler in der amblyopen Wahrnehmung („spatial errors“). Die zwei-dimensionale Streuung dieser Mittelwerte ergab das Maß der räumlichen Unsicherheit („spatial uncertainty“). Zur Erfassung des Einflusses der zeitlichen Instabilität („temporal instability“) wurden die Probanden nach der Stabilität ihrer Wahrnehmung befragt und in zwei Gruppen eingeteilt: amblyope Wahrnehmung mit zeitlicher Instabilität und ohne Instabilität. Räumliche Unsicherheit und lokale Fehler in der Wahrnehmung wurden daraufhin hinsichtlich beider Instabilitätsgruppen ausgewertet.

Konkret zeigte sich, dass die räumlichen Fehler („spatial distortions“) und die räumliche Unsicherheit („spatial uncertainty“) bei Schielamblyopen wesentlich ausgeprägter waren als bei anisometropen Amblyopen oder alternierenden Schielern. Das selbe traf für die Wahrnehmung zeitlicher Instabilität zu. Es konnte gezeigt werden, dass Schielamblyope signifikant mehr lokale räumliche Fehler aufweisen und eine höhere räumliche Unsicherheit zeigen als anisometrope Amblyope, alternierende Schieler oder normalsichtige Probanden. Ein Einfluss der zeitlichen Instabilität in der amblyopen Wahrnehmung äußerte sich dadurch, dass Amblyope mit zeitlichen Verzerrungen wesentlich größere Schwierigkeiten hatten, die auditiv präsentierten Kreispositionen visuell umzusetzen. Dieser Einfluss war vor allem in den fovealen Gesichtsfeldbereichen zu beobachten und damit mit Ergebnissen früherer Arbeiten konsistent (siehe Fronius & Sireteanu, 1989).

Experiment 4

Hier sollte der Einfluss der zeitlichen Instabilität in der amblyopen Wahrnehmung auf die Leistung im psychophysischen Experiment genauer abgeklärt werden. Amblyope mit instabilem Seheindruck hatten im Experiment 3 wesentlich größere Schwierigkeiten, die auditiv präsentierten Kreispositionen visuell umzusetzen. Statt auditiv präsentierter Positionsreize wurden diese nun visuell als Linien dargeboten, so dass sich sämtliche Versuchsvorgänge im Bereich der visuellen bzw. visuo-motorischen Modalitäten befanden.

Die Ergebnisse des vierten Experiments machten deutlich, dass generell die visuell basierte Umsetzung der Aufgabe leichter zu lösen war als die auditive. Dies galt sowohl für Amblyope mit als auch ohne instabile Wahrnehmung. Bei auditiver Stiumulspräsentation stieg die Rate der räumlichen Verzerrungen und der räumlichen Unsicherheit wesentlich an. Beide Gruppen konnten dementsprechend von einer visuellen Stiumulspräsentation profitieren, allerdings die Amblyopen ohne zeitliche Instabilität in der Wahrnehmung zu einem wesentlich größeren Ausmaß.

VI. Diskussion

Zusammenfaasend läßt sich sagen, daß sowohl räumliche Verzerrungen und Unsicherheit als auch zeitliche Instabilität bei Ambylopen mit Strabismus eher auftreten bzw. stärker ausgeprägt sind als bei anisometropen Amblyopen. Die zeiliche Instabilität in der Wahrnehmung mit dem amblyopen Auge ist auch ein beeinträchtigender Faktor bei der Durchführung anderer psychophysischer Aufgaben.

Die Ergebnisse der vier Experimente deuten vorallem für Amblyope mit einer zeitlich instabilen Wahrnehmung auf eine Beeinträchtigung des dorsalen „Wo“-Pfades hin, welche sich zusätzlich zu Defiziten im ventralen „Was“-Pfades zeigt (Mishkin & Ungerleider, 1982). Besonders die Experimente 3 und 4 machen deutlich, daß diese Amblyopen wahrscheinlich Defizite im Bereich des visuell-auditiven-Mappings haben. Dies könnte dadurch bedingt sein, daß corticale Zellen im dorsalen Pfad beeinträchtigt sind, und extra-striäre Bereiche des posterioren parietalen Cortex involviert sind (sireteanu, Bäumer & Sârbu, 2005). Je nach Typ und Ausmaß der räumlichen und zeitlichen Verzerrungen scheinen somit sowohl der ventrale als auch der dorsale Pfad mit für den verzerrten amblyopen Seheindruck verantwortlich zu sein.

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