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Anomalous Retinal Correspondence (Reprint)

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ANOMALOUS RETINAL CORRESPONDENCE

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Abstract. This paper presents an overview of anomalous retinal correspondence in strabismus. Definitions, certain testing techniques, and a review of underlying theory are outlined. It is concluded that ARC is not well understood and represents an area still open for investigation.

INTRODUCTION

Anomalous correspondence has been a topic of considerable interest to both clinicians and vision researchers for quite some time; the result is a variety of strongly held theories that tend to be contradictory. Some recent, excellently detailed reviews (Nelson, 1981; Jennings, 1985) have addressed various areas of research. However, anomalous correspondence transcends several research arenas; the object of this review is to correlate findings from several disparate disciplines into one parcel.

Binocular single vision normally is obtained on the horopter, a locus of points in space whose retinal images fall on pairs of corresponding points. A stimulus affecting one corresponding point will be localized in the same direction as if it had affected the other. The horopter, however, is a limited construct for describing the process of binocular, single vision; a disparity range can be added via sensory fusion. Moreover, since sensory fusion does not cover a large range either, suppression can be used as a further supplement to avoid physiological diplopia. This normal use of suppression can be enhanced by rivalrous conditions and has been postulated to play a role in strabismus (Hallden, 1982).

Strabismus is said to be present when the line of sight of one eye fails to intersect the object of regard. When strabismus occurs in early childhood, certain adaptations can occur. Possible adaptations include amblyopia, suppression, and/or anomalous retinal correspondence. This paper will be limited to a discussion of anomalous retinal correspondence. However, it is clear that strict isolation of the possible adaptations is difficult.

Normal retinal correspondence (NRC) has been specified in a number of different ways. It has been defined as a physical point-to-point matching of the retinae of the two eyes with fovea-to-fovea correspondence (Davson, 1972). Similarly, it has been defined as a correlation of retinal points with identical local signs or visual directions, with the foveal directions designating "straight-ahead" when at least the dominant eye is in the primary position (Moses, 1970). That is, an image falling on the right fovea will be perceived to be in the same direction as an image falling on the left fovea. This normal correspondence can occur independent of ocular alignment. Electrophysiologically NRC has been defined as the convergence of essentially monocular neurons upon a single binocular unit in striate cortex (Nelson, 1981).

Anomalous retinal correspondence (ARC) describes the condition in which a control mark seen only by the deviating eye of a squinter is perceived in the binocular visual field in a direction different than that to be expected on the basis of normal retinal correspondence (Moses, 1970). The spatial localization of the deviating eye appears to have partially or fully shifted, so as to counteract the effect of the ocular deviation. This shift in directional localization is termed the angle of anomaly. If the angle of anomaly equals the angle of squint, then the anomalous correspondence compensates exactly for the squint and is described as harmonious ARC (HAC). If the angle of anomaly is greater than zero, but less than the angle of squint, then it is described as unharmonious ARC (UHAC). If the angle of anomaly is in the opposite or noncompensating direction, the correspondence is described as paradoxical ARC (PAC) (Borish, 1970).

THREE COMMON TESTING TECHNIQUES

A variety of techniques, designed to evaluate retinal correspondence, have been devised. Each testing methodology appears to be influenced by the specific definition of correspondence accepted by the developer. Testing techniques, in general, can be reviewed in Borish's *Clinical Refraction* (1970), from which three common testing methods are outlined here (Table 1).

The Hering or Bielschowsky (1937) after-image test is often used clinically because of its simplicity and apparent effectiveness in determining retinal correspondence. A bright lumi-line filament or flash attachment is used, with an opaque spot or band at the midpoint of the filament. The subject fixates the center point monocularly in order to achieve the after-image. This is commonly done with different orientations for each eye (note: For correct interpretation of this test normal or eccentric fixation must be determined prior to application.) If correspondence is normal the two after-images will form a cross; if correspondence is anomalous the two fixation points will be separated.

An amblyoscope can be used to determine the objective and subjective angles of deviation. By presenting differently oriented linear targets to each eye via separate arms of the amblyoscope, measurements can be made quickly and easily. Problems, involving either failure of image superimposition or suppression of one image, may occur and prevent the diagnosis of ARC.

The Bagolini striated glass test (Bagolini and Capobianco, 1965) makes use of plano lenses upon which striations 0.005 mm in width have been inscribed. The striations are uniform over each eye, but the axes of the striations are oriented 90 degrees away from each other. The viewing of a small fixation light creates the subjective observation of two blurred streaks with the rest of the visual scene appearing undistorted. If the two streaks cross at the fixated light, then the patient is exhibiting either NRC or ARC, depending on whether a squint is absent or present, respectively. Suppression can be a problem, but less of one than for the amblyoscope. A small suppression zone, not noticed by the patient, can be missed if a critical examination is not performed. By avoiding dissociation, this test allows a determination of correspondency under normal visual conditions.

GENERALIZED THEORIES

The earliest theories considered ARC to be innate and immutable, reflecting a congenital anomaly that was untreatable (de la Hire, 1730; Muller, 1826). Later support for this view suggested that ARC was the underlying cause of squint in cases of large angle, nonaccommodative squints (Adler and Jackson, 1947). Failure of normal correspondence to develop postsurgically also has been blamed on a congenital ARC (Bedrossian, 1954).

Later theories held an alternate view that retinal correspondence changed as a sensory adaptation to the motor error or squint so that there was a shift in the visual direction of one eye relative to the other eye (Burian, 1947). The basic idea was that correspondence could be adaptively modified over some learning period in early life (Walls, 1951). Burian popularized the idea that ARC becomes more deeply ingrained over time and that this can be quantified or graded in terms of the nature of the stimulus conditions under which it persists. A common testing hierarchy has been suggested to test the "depth" of ARC adaptation: the Bagolini striated-glass test being proposed as the most sensitive means of eliciting ARC, the synoptophore or amblyoscope test purportedly exhibiting a mid-range sensitivity, and the after-image test being the least sensitive. Patients exhibiting ARC on the after-image test were taken to have a deeply embedded ARC of long standing (Mallett, 1970; Bagolini, 1976). However, the depth of anomaly theories have been questioned

Table 1
Three Common Testing Techniques

TEST	DEVICE	PROCEDURES	RESULTS
After-image test	Bright Lumi-line filament with an opaque band at the center.	Fixate horizontal filament with preferred eye. Then fixate vertical filament with nonpreferred eye.	NRC: a cross is seen. ARC: the two lines are apart.
Amblyoscope	Major Amblyoscope	Set arms to objective angle of squint. Present a vertical line to one eye, and a horizontal line to the other.	NRC: a cross is seen. ARC: the two lines are apart.
		Present lines, let patient set arms so that a cross is formed.	NRC: if the subjective angle equals the objective angle. ARC: subjective and objective angles are unequal.
Bagolini lens test	Striated lenses and a penlight.	Fixate a small penlight while looking thru the striated lenses with axes oriented OD-45; OS-135.	Squint present: ARC, if luminous streaks cross at fixation point. NRC, if they do not. Squint absent: NRC, if luminous streaks cross at fixation point. ARC if they do not.

(Flom and Kerr, 1967) based on measurement errors, unsteady eccentric fixation, and changes in the relative position of the eyes.

Another theory was the replacement theory of Verhoeff (1935, 1938); retinal correspondence was said not to be geared to subserve fusion, but merely to perceptually relate points on each retina on an alternating basis. This idea represented the first modern rivalry theory of vision. Brock (1941) essentially agreed with Verhoeff, suggesting that anomalous cases develop the ability to identify spatial localization separately with each eye. As an extension of Verhoeff's replacement theory Travers (1938, 1940) proposed that the diplopia of a squinter was relieved by the development of a suppression scotoma at the fovea, which sequentially spread across the eye until the development of an anomalous correspondence resulted. Since this was presumably a slow process, findings of unharmonious ARC, as well as harmonious ARC, easily could be explained. The implication was that the harmonious ARC was a completely adapted state, while the unharmonious ARC was a condition that was still in transition (Ronne and Rindziunski, 1953; Cashell and Durran, 1980). It was therefore assumed, similar to the Burian theory, that the longer standing and more constant the squint, the deeper established the ARC will become (Mallett, 1970; Bagolini, 1976).

An alternative adaptive theory has been proposed by Nelson (1981) suggesting a disparity "modal tuning" mechanism that responds globally to the most active disparity contour. As a result, there is a wide range of potentially corresponding states; specific conditions govern which correspondence state would be expressed at any one moment. An interpretation of Nelson's theory is similar to the hysteresis effect reported by Fender and Julesz (1967) with random dot stereograms. Once fusion is established, it can be maintained through an induced range of increasing disparity; once fusion is lost, the disparity must be decreased considerably before fusion can be reestablished. There may be, perhaps, a flexible and responsive stretching or shifting in correspondence that is capable of occurring only under specific conditions. Indeed, Campos (1982) has shown that strabismics have a wider Panum's area than normals. As are several other theories, this is consonant with harmonious ARC patients remaining harmonious despite the angle of squint changing from far to near, looking up and down (Mallett, 1967; Bagolini, 1976), or with and without spectacles (von Noorden, 1967). In support of the responsive correspondence shift theory is the finding of Maraini and Santori (1967) that ARC spontaneously may shift to NRC when the patient is forced to fixate with the normally deviating eye.

Nelson (1981) also proposed an alternative explanation for the varied test results that Burian ascribed to a deepened adaptation. Nelson suggested that the varied stimulus conditions differentially stimulate a global match response. The stimulus condition that best allows global matching to occur will be the most sensitive means of eliciting ARC; conversely, stimulus conditions that prevent global matching will fail to elicit ARC. Others have suggested the varied test results to be totally artefactual because the different tests are evaluating different aspects of visual system performance (Duke-Elder, 1949).

Counter to all the adaptive or sensory theories, a motor theory has evolved suggesting an ARC that varies with the sensed position of the squinting eye. Briefly, eye position information could potentially change correspondence by influencing the correction from oculo-centric to ego-centric localization. In other words, the motor innervational pattern is proprioceptively registered so that the "turned eye" reports that what it sees is displaced with respect to the other eye (Duane, 1932). There is debate as to whether there is an adequate proprioceptive system within the extraocular musculature to provide such registration. Morgan (1961) considered eye movements and eye position to be registered because of innervation to the extraocular muscles; in effect an efference copy signal.

Boeder (1964, 1966) proposed a slightly different motor theory whereby a response shift always results when the eye is in a position different from the one called for by ocular innervation. Boeder feels that confirmation of his response shift hypothesis can be found in certain visual attributes of the strabismic patient: past pointing, monocular diplopia, and strabismic amblyopia.

Motor theories, in general, provide for an incorporation of an awareness by the visual system of some sort of kinesthetic signal, or an efference copy signal which allows a correspondence shift to take place. General motor theory evidence is the maintenance of correspondence when an eye is externally moved by tweezers grasped onto the conjunctiva when under local anesthesia; such an experiment acts to eliminate both proprioception and efference copy (Pasino and Maraini, 1965).

Both general theory types, adaptive and motor, have specific merit; clearly additional work is needed in order to reconcile the data. Initial attempts to "tease out" the determining factors have met with mixed results.

One means of differentiating the underlying issues is to determine whether there is a fusional movement of the eye or a change in correspondence when anomalous binocular vision is maintained under altered viewing conditions. Maraini and Pasino (1964) tried to separate the two possibilities. An after-image produced around the fovea of an ARC subject's deviating eye was located with respect to a fixation light viewed binocularly through Bagolini-striated lenses. The introduction of six prism diopters base-out before the deviating eye of an ARC strabismic would have two possible effects if anomalous binocular single vision is maintained. If the after-image to fixation light separation remains constant, then a compensatory fusional movement has occurred. If the after-image to fixation light separation decreases by six prism diopters, then a compensatory shift of correspondence has occurred. Of eleven subjects evaluated, three showed a compensatory fusional movement, four showed a compensatory shift in correspondence, and the others showed a combination of the two. Other studies have shown similar conflicting results (Johnston, 1970; Kerr, 1980; Kenyon, Ciuffreda, and Stark, 1981). Since neither adaptive nor motor theories could be ruled out by this investigative means, it is unknown whether they apply to extremes of a single population distribution, or to separate physiological conditions. A similar parallel can be found elsewhere in the vision literature; anisometropic amblyopia and strabismic amblyopia have been suggested to represent separate conditions with overlapping symptoms.

All of the issues raised thus far have been based on results using subjective methodologies. Issue clarification might be obtained via objective evaluation techniques. Visual evoked potential data could prove to be useful since scalp topography of the VEP is known to reflect retinotopic mapping in the visual cortex (Jeffreys and Axford, 1972). Campos (1980) has detected binocular enhancement of pattern VEP's in ARC subjects, and also has routinely found binocular summation of VEP's in the same subjects (Campos and Chiesi, 1983; Chiesi et al, 1984). Yet, psychophysical investigations have failed to reveal any kind of summation in ARC subjects (Levi, 1987); very recent electrophysiological data, as well, have suggested that VEP summation is not representative of the activation of binocular cortical neurons (Shea, Aslin, and McCullouch, 1987). Additionally, McCormack (1987) has demonstrated that VEP scalp topographies do not differ for separate foveal stimulation of each eye in an ARC subject.

LABORATORY STUDIES

The field of electrophysiology also has attempted to analyze the processes governing the development of ARC. Animal experiments have suggested certain criteria are necessary for ARC development (Nelson, 1981): strabismus onset must be within the binocularity critical period, the strabismus must be small or gradually increasing, and cortical input competition must be balanced by having equal levels of monocular stimulation. The last point is perhaps the most important.

It has been shown that there is considerable overlap in ocular projections to the striate cortex that have withdrawn by termination of the binocularity critical period under normal conditions; induced strabismus has been shown to create an ocular dominance shift with the nondeviating eye gaining cortical connectivity at the expense of the deviating eye (Hubel, Wiesel, and LeVay, 1977). The presence of a strabismic condition, which meets the denoted criteria for ARC development, might interfere with the process of ocular dominance shifting, so that when the critical period is elapsed there are multiple, overlapping connections that are not present in strabismus with NRC.

Surgically induced strabismus in both cat and monkey has been shown to differentially damage the "X" visual subsystem (Brown and Salinger, 1975; Ikeda and Wright, 1976). Since this subsystem is characterized by exceptional spatial resolution and by fine disparity sensitivity (Poggio and Fischer, 1977), it is possible that strabismics exhibiting ARC are responding primarily via the "Y" visual subsystem. Since the "X" and "Y" subsystems have been postulated to provide the substrates for what has been termed "fine" and "coarse" stereopsis, respectively (Bishop and Henry, 1971), it is not surprising that certain strabismics exhibiting ARC have a rudimentary stereopsis in the threshold range of about 100 sec. of arc and exhibit some coarse peripheral depth sensitivity (Helveston and von Noorden, 1967; Epstein and Tredici, 1973; Henson and Williams, 1980; Sireteanu, 1982).

If it is accepted that there might be multiple, overlapping ocular projections to the cortex, and if those inputs might be predominantlyof the "Y-type" classification, then it would be reasonable to suggest that there is a dual neural alteration in strabismics with ARC. This dual alteration would exhibit itself as being able to provide only coarse, peripheral stereopsis; however, within this coarse framework the visual system may be able to shift correspondence tuning within the ranges of the broadly overlapping cortical projections, along the lines of Nelson's sensory fusion theory (1981). The resulting correspondence would only be "anomalous" with respect to the expected fusional limits demonstrated by "normals." Since "Y cell" input is provided both to the cortex and to the superior colliculus, it is possible that some sort of signal gating might be responsible for a sensory system and motor system match. In this manner both sensory adaptations and motor adaptations could work in tandem to provide for a shifting in correspondency. The concept, however, does not fully address motor theory issues, which are very important.

THERAPY

Theories regarding the treatment of ARC are as complicated and confusing as the theories regarding the underlying mechanism. The specific therapy techniques can include: the application of prisms, the prescribing of partially corrective lenses, the stimulation of stereopsis in a peripheral to central fashion, occlusion, bi-foveal stimulation (either in or out of instrumentation), the use of ater-images, auditory biofeedback, as well as surgery. A large part of the literature stems from anecdotal clinical case reports.

Many of the treatment modes have approached therapy with respect to the motor theories (Boman and Kertesz, 1985; Kertesz and Kertesz, 1986). Vergence movements, either fusional (Kerr, 1968) or accommodative (Daum, 1982), may be registered by the visual system, and could thus be manipulated to stimulate ocular alignment. Sensory theory applications have also produced success; traditional amblyoscope therapy has been used to establish NRC superimposition (Griffin, 1976). Other treatment modes have sought to employ both motor and sensory aspects (Brock, 1941; Walraven, 1957; Ludlam, 1961; Wick, 1974 and 1975).

Treatment success is, however, another area that is open to debate. Reported cure rates have varied from 5% (Flom, 1969) to 85% (Pigassou-Albouy, 1973). Unfortunately, the definition of a cure varies from study to study. Other important factors that obscure the effect of treatment are: the method of ARC diagnosis, and the means of demonstrating NRC. Further difficulties consist of: a lack of clinical trials, possible experimenter bias, and poor experimental design. Future work will need to address these issues.

The implication is that the management of ARC is not a simple matter. Careful diagnostic testing, under a variety of conditions, is necessary to correctly confirm the presence of ARC. Therapy requires the integration of both adaptive and motor techniques in order to maximize potential effectively.

SUMMARY

Theories of ARC fall into two broad categories: sensory adaptation, and motor response changes. Up to this point treatment modes have met with minimal overall success, largely as a result of the lack of any kind of consolidated model for ARC. Certainly, a major, organized, investigational effort is required if these issues are to be resolved.

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