## THE CONTROL OF EYE MOVEMENTS

Edited by

PAUL BACH-Y-RITA CARTER C. COLLINS JANE E. HYDE The Control of Eye Movements

The Symposium on the Control of Eye Movements was held under the auspices of the Smith-Kettlewell Institute of Visual Sciences of the Pacific Medical Center and the Department of Visual Sciences of the University of the Pacific Graduate School of Medical Sciences, San Francisco, California, November 10-11, 1969.

The Symposium was sponsored by DHEW, National Institutes of Health Grant Number 1 R 13 ET 00512-01A1.

Publication costs of this volume were defrayed in part by USPHS General Research Support Grant Number 5 SO1 FR 05566.

# The Control of Eye Movements

## EDITED BY PAUL BACH-Y-RITA **CARTER C. COLLINS**

Smith-Kettlewell Institute of Visual Sciences University of the Pacific Graduate School of Medical Sciences San Francisco, California

Associate editor JANE E. HYDE

Smith-Kettlewell Institute of Visual Sciences University of the Pacific Graduate School of Medical Sciences San Francisco, California



**Academic Press** New York and London

1971

COPYRIGHT © 1971, BY ACADEMIC PRESS, INC. ALL RIGHTS RESERVED NO PART OF THIS BOOK MAY BE REPRODUCED IN ANY FORM, BY PHOTOSTAT, MICROFILM, RETRIEVAL SYSTEM, OR ANY OTHER MEANS, WITHOUT WRITTEN PERMISSION FROM THE PUBLISHERS.

ACADEMIC PRESS, INC. 111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by ACADEMIC PRESS, INC. (LONDON) LTD. Berkeley Square House, London W1X 6BA

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 73-117101

PRINTED IN THE UNITED STATES OF AMERICA

## CONTENTS

CONTRIBUTORS
PART I. PHYSIOLOGICAL ASPECTS OF EYE MOVEMENT CONTROL
The Probable Role of Muscle Spindles and Tendon Organs in Eye Movement Control
Neurophysiology of Eye Movements
The Structure of the Extraocular Muscle Fibers of Mammals 4 Lee Peachey
Central Oculomotor Pathways
Vestibulo-Ocular Relations
EEG, Evoked Potentials, and Eye and Image Movements
Supranuclear Disorders of Ocular Control Systems in Man: Clinical, Anatomical, and Physiological Correlations
The Pharmacology of Extraocular Muscle
Eye Movements and Perception

#### CONTENTS

#### PART II. THE HUMAN EYE MOVEMENT CONTROL SYSTEM

Introduction	277
Orbital Mechanics	283
Extraocular Muscle Forces in Strabismus	327
The Saccadic System	343
The Control System for Versional Eye Movements	363
Pursuit Eye Tracking Movements	429
Second Thoughts on Smooth Pursuit	445
Control of Vergence Eye Movements	447
Discussion of the Control of Eye Vergence Movements	473
Vestibular and Proprioceptive Stabilization of Eye Movements <i>Jacob L. Meiry</i>	483
Organization of Neural Control in the Vestibulo-Ocular Reflex Arc . G. Melvill Jones	497
Models of Oculomotor Neural Organization	519
Time Delays in the Human Eye-Tracking System	539
SUBJECT INDEX	545

### CONTRIBUTORS

- Paul Bach-y-Rita, Smith-Kettlewell Institute of Visual Sciences, University of the Pacific Graduate School of Medical Sciences, San Francisco, California
- Malcolm B. Carpenter, Department of Anatomy, Columbia University, New York, New York
- Bernard Cohen, Department of Neurology, Mt. Sinai School of Medicine, New York, New York
- Carter C. Collins, Smith-Kettlewell Institute of Visual Sciences, University of the Pacific Graduate School of Medical Sciences, San Francisco, California
- Robert B. Daroff, Neurology Service, Miami Veterans Administration Hospital, and Department of Neurology, University of Miami School of Medicine, Miami, Florida
- Kenneth E. Eakins, Department of Ophthalmology, College of Physicians and Surgeons, Columbia University, New York, New York
- Derek H. Fender, Booth Computing Center, California Institute of Technology, Pasadena, California
- Leon Festinger, The New School of Social Research, New York, New York
- Albert F. Fuchs, Department of Physiology and Biophysics and Regional Primate Research Center, University of Washington, Seattle, Washington
- Ragnar Granit, Department of Physiology, Nobel Institute, Stockholm, Sweden
- William F. Hoyt, Department of Ophthalmology and Neurosurgery, University of California Medical Center, San Francisco, California
- G. Melvill Jones, Aviation Medical Research Unit, McGill University, Montreal, Canada

#### CONTRIBUTORS

- Ronald Katz, Department of Ophthalmology, College of Physicians and Surgeons, Columbia University, New York, New York
- Dietrich Lehmann, Smith-Kettlewell Institute of Visual Sciences, University of the Pacific Graduate School of Medical Sciences, San Francisco, California
- Jacob L. Meiry, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts
- George P. Moore, Department of Engineering and Physiology, University of Southern California, Los Angeles, California
- Lee Peachey, Department of Biochemistry, University of Pennsylvania, Philadelphia, Pennsylvania
- Cyril Rashbass, Maudsley Hospital, London, England
- David A. Robinson, Department of Engineering, Johns Hopkins Medical School, Baltimore, Maryland
- Alan B. Scott, Smith-Kettlewell Institute of Visual Sciences, University of the Pacific Graduate School of Medical Sciences, San Francisco, California
- Lawrence Stark, Department of Optometry, University of California, Berkeley, California
- Gerald Westheimer, Department of Physiology, University of California, Berkeley, California
- Laurence R. Young, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts
- Bert L. Zuber, Department of Information Engineering, College of Engineering, University of Illinois, Chicago, Illinois

## PREFACE

Although a number of new contributions to the physiology of ocular kinetics have appeared in the literature, the publications have been scattered and seemingly unrelated. In 1962 a symposium on the oculomotor system was held at Mount Sinai Hospital in New York. The express purpose was assemblage of various scientists and clinicians to exchange their views on the known anatomy, physiology, and clinical applications of disorders of eye movement. Seven years later leading investigators were assembled in San Francisco for this second symposium on the control of eye movements. The twofold objectives were to provide current observations on physiological aspects and clinical correlations and to bring together a number of scientists who approach the analysis of eye movement control from the point of view of modeling.

A valuable aspect of this conference was the diversity of the participants: physiologists, pharmacologists, psychologists, biophysicists, biomedical engineers, "visual scientists," and clinicians. Such a meeting is apt to advance knowledge of functions of the oculomotor system and ultimately lead to better insight into the physiology of the total nervous system.

The first half of the volume is devoted to presentations of anatomical, physiological, pharmacological, psychological, and clinical correlations of eye movements. The material presented should provide a valuable reference source as well as increase our awareness of the need for further investigation of many aspects of the basic physiology of eye movements.

The second half of the volume presents a series of papers dealing with models of various parts of the oculomotor system. The modeling approach to control of eye movements is still in its infancy as witnessed by the fact that this work presents the first comprehensive survey of biophysical, mathematical, and engineering aspects of eye movement control. At such an early stage it is perhaps appropriate to point out some of the possible pitfalls of such an approach. For example, if a complete theory for sensory (visual, vestibular) and oculomotor system interactions is to be valid, it must be generally applicable for other sensori-motor integrations such as that involved in walking, talking, or head movement. It should also apply for all motor performances including a simple sensori-motor model. Doubtless, there are differences between limb movements which may be unilateral, individual, or partial and eye motions which are always binocular, coordinate,

#### PREFACE

and limited in type. In the view of John Hughlings Jackson, the two eyes act as a unit, performing a single action such as ocular deviation or the act of convergence. Physiologically, the important common denominator for motor performance in each instance is laterality. One cerebral hemisphere exerts control over the contralateral limb and binocular movements to the contralateral side. The concept of total function of eye movement should always be borne in mind in studies of individual or patterns of ocular movements. There are investigators who emphasize the data on a single phase of an eye movement. Such information may be extremely important, but the findings must be correlated in a setting of total patterned activity. It is to be hoped that by making available in one volume the present thoughts regarding modeling systems, as well as pointing out the limitations of such models, stimulation for thought and experimentation has been provided.

Interdisciplinary meetings should include discussions on new techniques and instrumentation, description and recording of behavioral changes under varied conditions, comparative studies in animals and man, and theoretical considerations with evaluation of new data and introduction of new concepts. This symposium has achieved many of these goals.

> Morris B. Bender Henry P. and Georgette Goldschmidt Professor of Neurology and Chairman of The Department of Neurology Mt. Sinai School of Medicine of The City University of New York

## PART I

## PHYSIOLOGICAL ASPECTS OF EYE MOVEMENT CONTROL

This page intentionally left blank

#### THE PROBABLE ROLE OF MUSCLE SPINDLES AND TENDON ORGANS IN EYE MOVEMENT CONTROL

#### RAGNAR GRANIT

It is not possible in this context to cover the information we possess on the role of muscle spindles, the gamma-loop and the tendon organs in posture and locomotion. The author has reviewed our knowledge and hypotheses in a book in course of publication (Granit, 1970) entitled, *The Basis of Motor Control*, and to this the reader is referred for the evidence behind the brief statements to be given below.

Eye muscles provided with muscle spindles are regularly found only in primates and ungulates. For these species the extrinsic eye muscles are stated to be the spindle richest in the body competing in this respect with the neck muscles. They are innervated by fusimotor gamma fibres of the static type (definitely shown) and the dynamic type (suggested by indirect evidence). It is not known whether fusimotor alpha innervation is present. The slope of curves illustrating impulse frequency in the afferent nerve fibres from spindle primaries plotted against muscle length increases a great deal, up to sevenfold, under fusimotor gamma stimulation, implying that the static sensitivity to stretch increases under pull. Impulses have never been recorded from the afferents of spindle secondaries in eye muscles, but since these are provided with a static fusimotor innervation, their impulse frequency-length curves are likely to follow those of the primaries.

The statements to the effect that stretch reflexes are absent in extrinsic eye muscles need not be taken too seriously. Stretch reflexes are absent also in the skeletal musculature of normal subjects, unless the fusimotor neurons are specifically activated and the alpha motoneurons (of the extrafusal musculature) in an active state, i.e., sufficiently depolarized. Normally only the brief stretch reflexes known as "tendon jerks" can be elicited. Good stretch reflexes are obtained in normal subjects by activating muscle spindles by rapid vibrations applied at the tendons. All the evidence at present available shows that the stretch reflex is an adjunct to contraction and that alpha and gamma motoneurons are activated together in working muscles. This is the concept of alpha-gamma linkage. Thus, for instance, in respiration gamma activated spindles fire in the contraction phase of intercostal muscles; in volitional activation of muscles of the extremities the spindles likewise fire during contraction, as shown by recent successful attempts to record spindle impulses in man. Many other examples could be mentioned. Essentially, the gamma-activated spindle mechanism may be regarded as a governor of

muscular performance both in tone and locomotion. As long as we do not possess as precise information of spindle and tendon organ functions in the normal operations of eye muscles as we have for muscles of the extremities and the ribs, the best one can do in order to understand the role of these organs in eye movements is to apply the principles derived from the other fields of study to the case in hand.

One of the best known tasks of the gamma-assisted stretch reflex is to provide a stable length-setting at any desirable length of the muscle. This is determined by the amount of gamma-bias applied. If the contracting muscle is stretched by a load, the spindles produce automatic *load compensation;* if it is contracted in excess of the applied gamma bias, the silent period *unloads* the spindles thereby preventing excitation of the muscle's alpha motoneurons. It seems more than probable that settings of the gaze are servo-assisted in this manner. The reason for this conclusion is that these two operations will all be automatic as soon as the spindles are under fusimotor influence.

Good evidence for feedback control of the eye muscles is provided by Dr. Carter Collins at this Symposium (Chapter 10). He and his co-workers have shown that in man the tension-extension curves of an extrinsic eye muscle in man are parallel at whatever angle of gaze stretching is begun. The experience from experimental work with the muscle-nerve preparation or with so-called alpha rigidities of cats tells us that in pure alpha activity stretch should produce a set of curves of different slopes depending on the number and firing rate of the alpha fibres. Parallel curves are a definite sign of proprioceptive control, probably executed jointly by spindles and tendon organs on the alpha motoneurons, the former excitatory, the latter inhibitory.

When two antagonist forces are active, as in non-reciprocal eye movements, the consequent variations of loading will automatically activate the muscle spindles and then fusimotor "settings" across the gamma-loop will determine the sensitivity of the muscle to changes of length. In reciprocal action the opposing force will be the elastic pull on bulbar tissue and this, too, will contribute to determining the static sensitivity in relation to angle of gaze.

Eyes without spindles can provide but a crude imitation of the mechanism of the gamma-controlled stretch reflex. This reflex at any one length (angle of gaze) lacks the automatic control that the gamma-spindle mechanism provides for this particular task.

The unvolitional saccadic movements in the eye of the cat are far less prominent and of much lower frequency than in man. Even though these movements are centrally induced and symmetrical in the two eyes, they are likely to make use of the built-in spindle control of the muscular acts which then would operate on binocular alpha-gamma linkage controlled from the same central station. The higher the sensitivity of the fusimotor setting, the greater would be the frequency of the saccades.

There has been no work specifically on muscle spindles in extrinsic eye muscles as involved in the actual process of controlling eye movements. But

#### THE CONTROL OF EYE MOVEMENTS

it is known from work on ungulates (goat) that the static sensitivity, also called the position sensitivity, may increase up to seven times under the influence of fusimotor gamma activity. A powerful augmentation of this order of magnitude can hardly be negligible for the motoneurons controlling the extrinsic muscles, unless the spindle input differs fundamentally from its central distribution elsewhere in the body where spindle projections go to the motoneurons of their own muscle. Regrettably we have no precise information on this important issue and the suggestions given above presuppose that spindle afferents project on the motoneurons of the eye muscles in which these organs are situated. They likewise presuppose that spindle primaries are excitatory and tendon organs inhibitory in the stretch reflex, as these organs are elsewhere in the body. As long as it has not been shown that in this respect these proprioceptors possess central projections differently organized from what they are elsewhere, it is necessary to assume that they are similar, that is, both mono- and polysynaptic.

Finally, it should be pointed out that dynamic fusimotor fibres sensitize the spindle primaries to velocity of stretch. As to the spindle secondaries, which only possess static sensitivity, some doubt may be entertained about their role in eye muscle control. These organs have been found to be excitatory on flexor muscles and inhibitory on extensor muscles. For this there is no obvious parallel in the organization of eye movements.

#### REFERENCE

GRANIT, R. (1970) The Basis of Motor Control. Academic Press, London.

This page intentionally left blank

#### NEUROPHYSIOLOGY OF EYE MOVEMENTS

#### PAUL BACH-Y-RITA

The oculomotor system has long attracted the attention of many physiologists. The study of this highly precise system offers both challenges and rewards to the basic scientist in addition to providing background essential to the clinical understanding of disorders of oculomotion. The extremely fine coordination of the oculorotary muscles of the two eyes, the variety of types and speeds of movements which are mediated by a very limited number of muscles, and the differences between cranial and spinal motor systems are only a few of the factors influencing some of us to devote our attention to the physiological analysis of the oculomotor system.

Neurophysiological studies of ocular motility present several unique problems to the investigator. The nerves leading to the eye muscles are short, completely embedded within the cranium, and without separate motor and sensory roots. In contrast, the long spinal nerves are surrounded by bone for only a small part of their course, and have dorsal roots conveying afferent information and ventral roots carrying efferent impulses. The three pairs of cranial nuclei providing motor innervation to the extraocular muscles (EOMs) are deeply buried in the brainstem, and are not readily accessible even with the use of stereotaxic techniques. The central connections, both afferent and efferent, have proven difficult to trace. Marked species differences exist with respect to the presence and distribution of sensory receptors in the EOMs. Finally, there is one extraocular muscle, the retractor bulbi, which is found only in some species; even in these its structure is not uniform.

In spite of the difficulties inherent in physiological analyses of ocular movements, this motor system appeared to offer solutions to a number of questions fundamental to an understanding of movement in general, as well as of movement of the eyes. What is the significance of ocular proprioception? i.e., what role is played by sensory receptors in oculorotary muscles? What can we determine of the fundamental physiological properties of the oculorotary muscles? What type of peripheral innervation supplies the EOMs so that they can move with the swiftness of a saccade or the slow smoothness of a following movement? To what extent can we correlate structure with function?

The present chapter represents a summary of efforts to date which

The research reported on in this paper was largely supported by Public Health Service Program Project Research Grant No. NB 06038 and Research Career Program Award No. K3-NB-14,094.

#### PAUL BACH-y-RITA

attempt to answer some of these questions. Inasmuch as the majority of studies from our laboratory have concentrated on the peripheral neuromuscular apparatus, the primary emphasis will be on afferent and efferent innervation of the EOMs. Results of studies of stretch receptors and their pathways, types of motor innervation, and muscle fiber types will be presented. A few pertinent aspects of CNS control will be included, although the subject of supranuclear control of eye movements has been extensively reviewed in other chapters of this volume (Cohen; Carpenter) as well as in earlier published summaries (Whitteridge, 1960; Bender, 1964).

#### AFFERENT MECHANISMS

#### Background

The importance of proprioceptive muscle afferents in the control of eye movements has been debated since the last century. The two principal opposing views were held by Helmholtz and Sherrington. Helmholtz (1962) suggested that proprioception from the eye muscles was unnecessary because of the presence of the retina (a highly efficient exteroceptor) and the ability of the central nervous system to monitor the efferent outflow from the brain stem. Sherrington (1918), on the other hand, minimized the importance of monitoring the efferent outflow, and strongly supported the concept of a perceptual role for EOM proprioception.

The confusion in regard to the presence or absence of eye muscle "proprioception" has been due in part to differences in definition (Christman and Kupfer, 1963). To some, proprioception means conscious position sense; to others it signifies subconscious nervous control of muscular contraction. The muscle spindle has been thought to be the principle afferent receptor of proprioception in somatic muscles. In the past both conscious and subconscious roles have been assigned to this receptor. Currently, however, the principal function of limb muscle spindles is believed to be in the subconscious nervous control of muscular contractions, rather than in conscious position sense (Matthews, 1964). This is consistent with recent evidence that there is no conscious perception of eye position (Brindley and Merton, 1960), although human eye muscles are richly endowed with muscle spindles.

The role of muscle afferents in the control of eye movements is further complicated by the fact that muscle spindles are present in the eye muscles of some species but not of others, and that the presence or absence of these organs does not appear to be related either to phylogeny or to discreteness of eye movements. Thus, spindles are present in the eye muscles of man, some monkeys, goats and cattle, but not in cat, dog, rat or certain of the monkeys (Cilimbaris, 1910; Cooper and Daniel, 1949; Cooper, Daniel and Whitteridge, 1955; Greene and Jampel, 1966; Cooper and Fillenz, 1955; Bach-y-Rita, 1959). Indeed the eye muscles of the squirrel monkey not only appear to lack spindles, but there is no evidence for any other type of stretch receptors (Ito and Bach-y-Rita, 1969).

#### THE CONTROL OF EYE MOVEMENTS

Inasmuch as several thorough reviews of extraocular proprioception appeared between 1955 and 1961 (Cooper, Daniel and Whitteridge, 1955; Bach-y-Rita, 1959; Whitteridge, 1960; Hosakowa, 1961), the present paper will emphasize the principal findings of the past ten years, with a discussion of the possible role of proprioception in eye movements.

#### Stretch receptors

Encapsulated organs with several intrafusal fibers have been identified in the EOMs of several animal species as well as man. These muscle spindles differ from typical limb muscle spindles in size, motor innervation, thickness of capsule, distribution within the muscle, types of sensory endings, and morphology of the intrafusal muscle fibers.

In the eye muscles of man, the muscle spindles are small and have thin capsules; they are distributed in the proximal and distal thirds of the muscles. The intrafusal fibers are similar in diameter to the extrafusal fibers, and do not have distinct nuclear bag regions (Cooper and Daniel, 1957). The sensory endings are apparently not divided into primary and secondary terminals as they are in limb muscle spindles.

The properties of extraocular muscle spindles have been most thoroughly studied in the goat, by Cooper, Daniel and Whitteridge (1955). In the EOMs of this species the muscle spindles are relatively large and numerous; the afferent pathways are separate from the efferent (Winkler, 1937; Whitteridge, 1955).

In addition to muscle spindles and tendon organs, other morphologically distinct receptors have been identified in eye muscles (see previous reviews). Some structures earlier identified as sensory are now known to be motor, subserving the multi-innervated muscle fibers. A recent report on cat eye muscles has described the properties of stretch receptors which are neither muscle spindles nor tendon organs (Bach-y-Rita and Ito, 1966b). While these structures have not been identified histologically, the evidence suggesting that they may be a form of spiral ending is presented below.

In collaboration with Dr. Ito a study was made of the properties of 52 receptors in the inferior oblique muscles of 30 cats (Bach-y-Rita and Ito, 1966b). Between 10 and 28 receptors were noted in each, although it was possible to study only a few receptors in each muscle. Spontaneous discharge was recorded from only one receptor in each of four muscles. The conduction velocities of the afferent fibers from these four receptors ranged from 17-41 m/sec. In the remaining 26 muscles, the minimum stretch eliciting a response varied from 3 to 150 grams, with a peak at 10-20 g. Nineteen of the minimum threshold receptors were quick-adapting and 7 were slow-adapting. Conduction velocities of the corresponding afferent fibers ranged from 6.5 to 52 m/sec with a peak at 10-15 m/sec. (Fig. 1).

All of the receptors were in the muscle, none were in the tendon. It was possible to demonstrate that forty-seven receptors were in parallel, and two



Fig. 1. A. Relation between the threshold value and the conduction velocity for the minimal threshold receptors in individual inferior oblique preparations. B. A histogram of the conduction velocities of the afferent fibers from the minimal threshold receptors represented in A (29 units in the hatched area), and for all receptors tested (fifty-two cases). C. A histogram of the threshold distribution for the minimal threshold receptors represented in A. (Reprinted by permission of *J. Physiol.* 1966, **186**, 663-668).

were in series with contractile elements (Fig. 2). The dynamic and static indices of all receptors were approximately equal; both increased on increasing initial length. Thus, there did not appear to be a region of reduced viscosity which could compare to that in the equatorial region of intrafusal fibers in limb muscle spindles.

Physiologically there appeared to be a single type of stretch receptor, with or without spontaneous discharge. For the four spontaneously discharging receptors, the minimum load which produced a change in frequency was 0.4 g. Fig. 3 illustrates an increase in discharge frequency of one of these



Fig. 2. Effect of tetanic contraction of the inferior oblique muscle on the responses of an in parallel receptor during muscle stretch. A. The response of a spontaneously discharging receptor (P-25) to stretching the muscle 3 mm at 10 mm/sec fell to zero frequency during tetanic contraction of the muscle induced by maximal nerve stimulation at 100 c/s (continuous line), in comparison with the control in the absence of nerve stimulation (interrupted line). The diagrammatic representations of the length scale and the muscle contraction are derived from the original records. B. Effect of tetanic contraction of the muscle on the responses of a rapidly adapting nonspontaneously discharging receptor (P-12) after 3 mm stretch from +7 mm initial length at 10 mm/sec increased during tetanic contraction of the muscle induced by maximal nerve stimulation of *J. Physiol.* 1966, 186: 663-668.)



Fig. 3. Frequency of response of a spontaneously discharging receptor (preparation number P-25) after various loads were hung on and removed from the inferior oblique muscle. (Reprinted by permission of *J. Physiol.* 1966, **186**: 663-668).

receptors in response to loads of 1 g or more, and shows a temporary drop below the resting discharge frequency on removal of the loads.

In contrast to the responses from primary endings in de-efferented limb muscle spindles, no initial acceleration in the discharge frequency was noted at the beginning of stretch of the EOM. Increasing the velocity of stretch resulted in a greater maximum discharge frequency and a greater fall-off at the end of the dynamic period. During excessive stretch the receptor appeared to "slip". This, together with the other evidence presented above, suggested to us that the receptor was a type of spiral ending (Fig. 4). We could not be certain which type of muscle fiber was surrounded by these proposed spiral type endings in cats. However, Sas and Appletauer (1963) have shown that spiral endings in the middle third of human extraocular muscles are on the peripheral, thin muscle fibers. Cooper (1966) has shown that the fibers located in the outer layers are multi-innervated, and have characteristics similar to intrafusal fibers. Thus it is possible that the receptors which produced the responses in our study (Bach-y-Rita and Ito, 1966b) were in contact with small, peripheral multi-innervated muscle fibers.

A "silent period" in receptor discharge was noted on stimulation of motor nerve fiber bundles (Bach-y-Rita and Murata, 1964; Bach-y-Rita and Ito, 1966b). Granit (personal communication) has suggested that this "silent



Fig. 4. Schematic diagram of an ending surrounding an extrafusal muscle fiber in the cat's extraocular muscle (lower figure of A) with its functional viscoelastic model (upper figure). (Reprinted by permission of *J. Physiol.* 1966, **186**: 663-668).

period" may have been due to the fact that the spiral afferent endings surround the slower twitch fibers, which may be briefly unloaded when the fast twitch fibers contract.

In the squirrel monkey, no evidence for true stretch receptors was uncovered by physiological studies of the inferior oblique and lateral rectus muscles (Ito and Bach-y-Rita, 1969). However, some receptors were noted which, while unresponsive to stretch, were highly sensitive to temperature, and were silenced by topically applied or intravenously administered adrenaline. The conduction velocities of the afferent fibers from these receptors ranged from 8.6-30 m/sec, with a peak at 15-20 m/sec. On the basis of the above evidence, we suggested that these might be blood vessel receptors (Ito and Bach-y-Rita, 1969). Sas and Appletauer (1963) have described a receptor in the vicinity of an arteriole in a human eye muscle, and Hosokawa (1961) mentions that terminal boutons have been described on EOM blood vessels. It is possible that some of our previous records from cat eye muscles (Bachy-Rita and Murata, 1964; Bach-y-Rita and Ito, 1966b) may also have been from blood vessel receptors.

#### Peripheral pathways

Winkler (1937) and Cooper, Daniel and Whitteridge (1955) have shown in goats that the afferent fibers from EOMs travel intraorbitally to a branch of the V nerve, and enter the brainstem with it. The peripheral pathways are less clear in man and in other species (Hosokowa, 1961; Bach-y-Rita, 1959). For example, in the cat there is evidence that afferent fibers cross from the eye muscle nerves to the V nerve (Kumoi and Jampel, 1966; Manni, Bortolami and Desole, 1968; Cooper and Fillenz, 1955; and others). In contrast, in the cat Bach-y-Rita and Murata (1964) have recorded lateral rectus stretch receptor responses from the VI nerve immediately external to the brain stem. The latter observation demonstrates that in cats at least some of the afferents from the eye muscles do not cross over to the V nerve peripherally. In monkeys, Tozer and Sherrington (1910) demonstrated that the III, IV and VI nerves are mixed, carrying afferent impulses to the brain stem as well as motor impulses from the brain stem to the EOM. Taren (1964) on the other hand has demonstrated afferent fibers from EOMs in the IV, V and VI nerves in monkeys, and suggests that afferent fibers in the VI nerve pass through the VI nucleus on the way to the mesencephalic nucleus of the V nerve. Hogg (1964) has observed few, if any, afferents in the III nerves of man or of albino rats.

#### Ganglion cells

The cells of origin of the EOM stretch receptors have been postulated to have various locations. Some investigators have located these in the mesencephalic nucleus of the V; others propose cells along the course of the EOM nerves. Even the brainstem motor nuclei of the eye muscles have been implicated, but the investigators who suggested the latter location presumably were misled by believing either 1) that the motor endings of the multi-innervated fibers were sensory endings; or 2) that the presence of two distinct sizes of cells in the motor nuclei indicated that one type mediated proprioception.

Manni, Bortolami and DeSole (1968) have recorded numerous afferent responses in a cellular pool in the medial dorsolateral portion of the semilunar ganglion of the V nerve in sheep and pigs, but not in cat. However, as noted above, the fact that in the cat some afferent fibers enter the brain stem via the "motor" nerves to the EOMs (Bach-y-Rita and Murata, 1964) indicates that at least in this species some of the ganglion cells must be located in the brain stem, although the exact location remains unclear.

#### Central pathways

There has been little clarification of the central nervous system (CNS) pathways for afferent stretch impulses from EOMs since the classical study of Cooper, Daniel and Whitteridge (1953a&b). These authors recorded afferent impulses from EOM in the medial longitudinal fasciculus, central tegmental tract, reticular formation, superior colliculus, occipital lobe, cerebellar tracts and cerebellum.

In most cases the responses showed characteristics and latencies suggesting that the afferent impulses had crossed at least one synapse. Identifiable first order responses were recorded in the mesencephalic nucleus of the V nerve, and from varying sites in the fifth nerve complex in the brain stem (Cooper, Daniel and Whitteridge, 1953a). It was not always possible to be sure the polysynaptic responses were produced by stretch receptors; some could have been from periosteal pain receptors (Cooper, Daniel, Whitteridge, 1953b). Recently Fuchs and Kornhuber (1969) have shown averaged evoked responses in the cerebellum on stretching eye muscles in the cat. The minimum latency was 4 msec but most of the responses occurred at 15 msec, and the responses were markedly affected by sodium pentobarbitone, indicating second order responses.

One significant advance in knowledge of CNS pathways is found in a recent study by Gernandt (1968) in cats. Gernandt noted that EOM afferent impulses interact in the brain stem with impulses traveling over the slower of the two routes from the vestibular system to the eye motor nuclei. The reticular formation route (the slower of the two routes) was greatly inhibited by preceding EOM stretch, whereas when vestibular stimulation preceded EOM stretch, there was little or no effect on the reticular formation neurons or on EOM motoneurons responding to strong muscle stretch.

#### Functional role

While the functional role of EOM stretch receptors remains almost as unclear today as when reviewed ten years ago (Bach-y-Rita, 1959), there have been some advances in recent years. Thus it is now evident that the EOM stretch receptors do not mediate conscious position sense (Brindley and Merton, 1960), and there is little evidence that messages from muscle spindles reach consciousness (Cooper, Daniel and Whitteridge, 1955). Matthews (1964), in a discussion of limb muscle spindles, suggested that the main function of muscle spindles was in relation to the subconscious nervous control of muscular contraction. Christman and Kupfer (1963) among others have pointed out that conscious position sense is mediated by capsular receptors in contact with the articulation between two bones, and these are absent in the oculomotor apparatus.

Various postulations on the functional role of EOM stretch receptors have been suggested. Thus Fuchs and Kornhuber (1969) propose that these receptors play a role in a cerebellum-mediated proprioceptive feedback loop for the control of eye movements, providing information to the cerebellum as to the magnitude or the end point of saccades. Christman and Kupfer (1963) offer the theory that the stretch receptors may have a role in fixation micronystagmus. Gernandt (1968) postulates that they may dampen and correct overshoot of eye movements and oscillation. Fender and Nye (1961) propose that EOM proprioception provides negative feedback, especially for small deviations from fixation, but propose further that this negative feedback becomes very slight with large deviations. Otherwise, heavy damping would prevent execution of rapid eye movements. Sasaki (1963) and Sears, Teasdale and Stone (1959) suggest that EOM stretch receptors inhibit motor neurons to the eye muscles. Sasaki (1963) noted that, in the cat, EOM stretch could produce hyperpolarization of motor neurons in the III nucleus. However, Whitteridge (1962) has evidence that the muscle spindles in goat EOMs do not influence the spontaneous discharges of motor neurons. Bach-y-Rita

and Ito (1966) have postulated a possible "protective" function of the spiral endings in cat eye muscles to prevent overstretch, similar to the function of Golgi tendon organs in limb muscles. Hyde and Davis (1960) indicated, in cats, a possible role of EOM proprioception in the determination of the end point of movement of the eyes.

There are some species, such as the cat, in which the EOMs have no true muscle spindles, but do have stretch receptors in contact with muscle fibers. It is possible that these extrafusal fibers are playing a role similar to the intrafusal fibers found in other somatic muscles. The equivalent of a "gamma bias" may be mediated by the gamma range nerve fibers to the slow multi-innervated twitch fibers; the latter may have dual properties, whereby the individual fibers can contract both segmentally and with propagated impulses (see below). There are examples of such duality in other species. For example, Ginsborg (1960) has noted such fibers in avian muscles and Koketsu and Nishe (1957b) have suggested that they exist in frog muscle spindles. In frog tongue muscles, Siggins, Berman and McKinnon (1968) have observed fibers with multiple "en grappe" endings and resting potentials averaging -63 mv that produced propagated action potentials. Finally, rabbit limb muscle spindles have been shown to contain only one type of muscle fiber, with only primary sensory endings, but with both "en grappe" and "en plaque" endings on the same fiber. These fibers are capable of mediating all of the phenomena that utilize separate nuclear bag and chain fibers in other species (Edmonet-Denard, LaPorte and Pages, 1964). Granit (this symposium) has analyzed the data obtained from human EOMs by Collins (this symposium) and finds evidence for both muscle spindle (facilitation) and tendon organ (inhibition) type responses.

Thus it is evident that much attention has been lavished on the possible functional roles of the EOM stretch receptors. The role of neck muscle stretch receptors in control of eye position and posture has generally been considered to be minor. For example, Sherrington (1918) assigned the neck receptors a minor role in the control of posture in comparison to the three primary factors of retinal impulses, proprioception from EOMs and impulses from the otic labyrinth. However, several authors (de Kleyn, 1908; Cohen, 1961; Biemond and DeJong, 1969) have presented evidence that proprioceptive impulses from the neck may indeed be of considerable importance in eye movement control and spatial orientation, as well as posture.

#### **EFFERENT MECHANISMS**

Eye movement is produced by the 4 rectus and the 2 oblique muscles as well as the retractor bulbi muscle when present. Kennard and Smyth (1963) consider that the eye lid muscle is an EOM. They have demonstrated two types of lid movements, smooth tracking and rapid step-like saccadic adjustments of position, and have demonstrated interactions between blinks and vertical following movements. However, this presentation has been limited to

#### THE CONTROL OF EYE MOVEMENTS

an analysis of the neurophysiology of only those muscles (the 4 rectus, 2 oblique and the retractor bulbi) that move the globe.

#### Muscle fiber types and neuromuscular endings

The morphological aspects of EOMs have been described in detail by Peachey (this volume), who has presented evidence for 5 types of EOM fiber types. Two widely studied fiber types are a large singly innervated and a small multi-innervated type of fibers. However, fiber bundles in EOMs are tightly packed, which complicates the identification of multiply innervated fibers. Thus both Peachey and Alvarado (personal communications) have dissected out what appeared to be single fibers, only to find on electron microscopic examination that the "single fiber" was in reality a bundle containing several fibers.

#### **Properties of EOM fibers**

#### 1. Electrical properties

Although some authors suggest, on the basis of electron microscopy, histological and histochemical evidence, that there are more than two types of fibers in the EOMs, the majority of investigators of the physiological properties of muscle fibers have not been able to clearly differentiate more than two types of fibers. Intracellular microelectrode studies of EOMs in rabbits by Matyushkin (1961) and Ozawa (1964) and in cats by Hess and Pilar (1963) have clearly established that the large singly innervated muscle fibers have high membrane potentials and respond to nerve stimulation with propagated action potentials. These authors, however, suggest that the second type of fiber (corresponding to the small, multi-innervated fibers) does not respond with propagated impulses but rather responds with slow junctional potentials, similar to amphibian slow fibers.

In collaborative studies with Dr. Ito (Bach-y-Rita and Ito, 1966a) we also found propagated impulses from the large singly innervated twitch fibers in cats. However, in contrast to the above, we were able to demonstrate that the multiply innervated fibers are also capable of producing propagated action potentials. Therefore we have labeled them "slow multi-innervated twitch" fibers. (Physiological evidence that these fibers are innervated by more than one nerve fiber is presented in a later section).

In anesthetized *in vivo* cat preparations, the inferior oblique (Fig. 5) and the superior rectus were studied (Bach-y-Rita and Ito, 1966a). The *in situ* superior rectus preparation preserved the insertion of the muscle in the globe and thus allowed intracellular microelectrode exploration of the two types of fibers in their normal anatomical relationship. We noted that the small multiinnervated twitch fibers were located predominantly in the outer (orbital) surface of the superior rectus (S.R.), in conformity with the histological evi-



Fig. 5. An illustration of the preparation. The head of the anesthetized cat is held in the stereotaxic instrument. The inferior oblique preparation: (b) micropipette; (c) indifferent electrode; (d) heater; (e) thermistor; (g) part of the stereotaxic instrument; (h) RCA 5734 strain gauge tube and holder; (i) nictitating membrane held by a suture to form an oil pool; (j) platinum electrodes holding nerve to inferior oblique. (Reprinted by permission of *J. Gen. Physiol.* 1966, **49**: 1177-1198).

dence presented by Kato (1938) and Cooper and Fillenz (1955) on the layer organization of small and large fibers in EOMs.

Namba, Nakamura, Takahashi and Grob (1968) have also noted in rat EOMs that the small multi-innervated fibers are found in greater concentration on the orbital surface, away from the globe, in all muscles except for the superior oblique (S.O.). It would therefore seem possible that some of the differences in the results of Hess and Pilar (1963) and Pilar (1967), and those of Bach-y-Rita and Ito (1966) may be due to the fact that the detailed studies of Hess and Pilar (1963) and Pilar (1963) and Pilar (1963). Which has a different fiber organization than other EOMs and contains a greater percentage of "slow" fibers (Hess and Pilar, 1963), whereas our own studies were on S.R. and inferior oblique (I.O.). Also, the *in vitro* studies of cat EOM by Hess and Pilar (1963) were performed at room temperature, which is far below the body temperature at which the muscles are normally maintained.

Cooling inhibits action potentials in mammalian (Nakanish & Norris, 1970) and frog muscle fibers (Ling & Woodbury, 1949). Indeed, this may be a natural mechanism for reducing energy consumption in cold blooded animals. For example, frogs are more sluggish in the cold, and physiologists have found differing results in studies on summer and winter frogs.

In our studies (Bach-y-Rita and Ito, 1966a) it was found that fast singly innervated and slow multi-innervated twitch fibers can be distinguished on