Chapter 4
Taxonomy and Models of Eye Movements

Almost all normal primate eye movements used to reposition the fovea result as combinations of five basic types: saccadic, smooth pursuit, vergence, vestibular, and physiological nystagmus [(miniature movements associated with fixations; Robinson (1968)]. Vergence movements are used to focus the pair of eyes over a distant target (depth perception). Other movements such as adaptation and accommodation refer to nonpositional aspects of eye movements (i.e., pupil dilation, lens focusing). With respect to visual display design, positional eye movements are of primary importance.

4.1 The Extraocular Muscles and the Oculomotor Plant

In general, the eyes move within six degrees of freedom: three translations within the socket, and three rotations. There are six muscles responsible for movement of the eyeball: the *medial* and *lateral recti* (sideways movements), the *superior* and *inferior recti* (up/down movements), and the *superior* and *inferior obliques* (twist) (Davson 1980). These are depicted in Fig. 4.1. The neural system involved in generating eye movements is known as the oculomotor plant. The general plant structure and connections are shown in Fig. 4.2 and described in Robinson (1968). Eye movement control signals emanate from several functionally distinct regions. Areas 17–19 and 22 are areas in the occipital cortex thought to be responsible for high-level visual functions such as recognition. The superior colliculus bears afferents emanating directly from the retina, particularly from peripheral regions conveyed through the magnocellular pathway. The semicircular canals react to head movements in three-dimensional space. All three areas (i.e., the occipital cortex, the superior colliculus, and the semicircular canals) convey efferents to the eye muscles through the mesencephalic and pontine reticular formations. Classification of observed eye movement signals relies in part on the known functional characteristics of these cortical regions.

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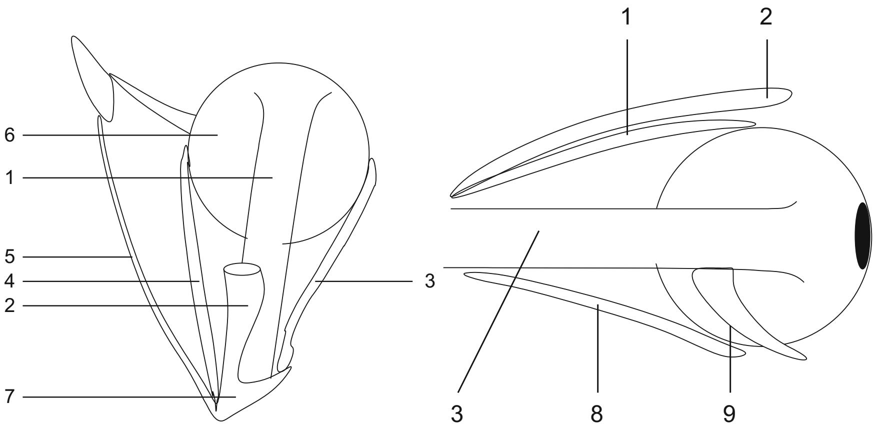

Fig. 4.1 Extrinsic muscles of the eye. Adapted from Davson (1980) with permission ©1980 Academic Press. *Left* (view from above): *1*, superior rectus; *2*, levator palbebrae superioris; *3*, lateral rectus; *4*, medial rectus; *5*, superior oblique; *6*, reflected tendon of the superior oblique; *7*, annulus of Zinn. *Right* (lateral view): *8*, inferior rectus; *9*, inferior oblique

Two pertinent observations regarding eye movements can be drawn from the oculomotor plant's organization:

1. The eye movement system is, to a large extent, a feedback circuit.
2. Signals controlling eye movement emanate from cortical regions that can be functionally categorized as voluntary (occipital cortex), involuntary (superior colliculus), and reflexive (semicircular canals).

The feedbacklike circuitry is utilized mainly in the types of eye movements requiring stabilization of the eye. Orbital equilibrium is necessitated for the steady retinal projection of an object, concomitant with the object's motion and movements of the head. Stability is maintained by a neuronal control system.

4.2 Saccades

Saccades are rapid eye movements used in repositioning the fovea to a new location in the visual environment. The term comes from an old French word meaning "flick of a sail" (Gregory 1990). Saccadic movements are both voluntary and reflexive. The movements can be voluntarily executed or they can be invoked as a corrective optokinetic or vestibular measure (see below). Saccades range in duration from 10 to 100 ms, which is a sufficiently short duration to render the executor effectively blind during the transition (Shebilske and Fisher 1983). There is some debate over the underlying neuronal system driving saccades. Saccades have been deemed ballistic and stereotyped. The term stereotyped refers to the observation that particular movement patterns can be evoked repeatedly. The term ballistic refers to the presumption

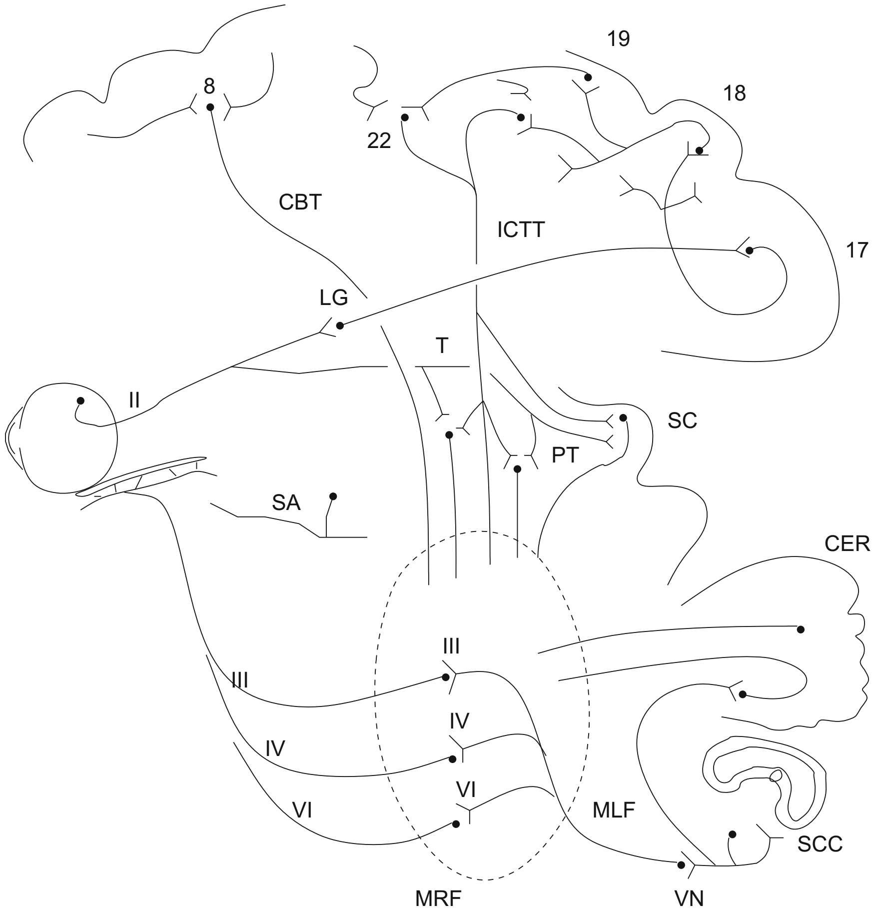

Fig. 4.2 Schematic of the major known elements of the oculomotor system. Adapted from Robinson (1968) with permission © 1968 IEEE. *CBT*, corticobular tract; *CER*, cerebellum; *ICTT*, internal corticotectal tract; *LG*, lateral geniculate body; *MLF*, medial longitudinal fasciculus; *MRF*, mesencephalic and pontine reticular formations; *PT*, pretectal nuclei; *SA*, stretch afferents from extraocular muscles; *SC*, superior colliculi; *SCC*, semicircular canals; *T*, tegmental nuclei; *VN*, vestibular nuclei; *II*, optic nerve; *III*, *IV*, and *VI*, the oculomotor, trochlear, and abducens nuclei and nerves; *17, 18, 19, 22*, primary and association visual areas, occipital and parietal (Brodmann); *8*, the frontal eye fields

that saccade destinations are preprogrammed. That is, once the saccadic movement to the next desired fixation location has been calculated (programming latencies of about 200 ms have been reported), saccades cannot be altered. One reason behind this presumption is that, during saccade execution, there is insufficient time for visual feedback to guide the eye to its final position (Carpenter 1977). One the other hand, a saccadic feedback system is plausible if it is assumed that instead of visual feedback, an internal copy of head, eye, and target position is used to guide the eyes during a saccade (Laurutis and Robinson 1986; Fuchs et al. 1985). Due to their fast velocities, saccades may only appear to be ballistic (Zee et al. 1976).

Various models for saccadic programming have been proposed (Findlay 1992). These models, with the exception of ones including "center-of-gravity" coding (see, e.g., He and Kowler (1989), may inadequately predict unchangeable saccade paths. Instead, saccadic feedback systems based on an internal representation of target position may be more plausible because they tend to correctly predict the so-called double-step experimental paradigm. The double-step paradigm is an experiment where target position is changed during a saccade in midflight. Fuchs et al. (1985) proposed a refinement of Robinson's feedback model which is based on a signal provided by the superior colliculus and a local feedback loop. The local loop generates feedback in the form of motor error produced by subtracting eye position from a mental target-in-space position. Sparks and Mays (1990) cite compelling evidence that intermediate and deep layers of the SC contain neurons that are critical components of the neural circuitry initiating and controlling saccadic movements. These layers of the SC receive inputs from cortical regions involved in the analysis of sensory (visual, auditory, and somatosensory) signals used to guide saccades. The authors also rely on implications of Listing's and Donders' laws which specify an essentially null torsion component in eye movements, requiring virtually only two degrees of freedom for saccadic eye motions (Davson 1980; Sparks and Mays 1990). According to these laws, motions can be resolved into rotations about the horizontal x- and vertical y-axes.

Models of saccadic generation attempt to provide an explanation of the underlying mechanism responsible for generating the signals sent to the motor neurons. Although there is some debate as to the source of the saccadic program, the observed signal resembles a pulse/step function (Sparks and Mays 1990). The pulse/step function refers to a dual velocity and position command to the extraocular muscles (Leigh and Zee 1991). A possible simple representation of a saccadic step signal is a differentiation filter. Carpenter (1977) suggests such a possible filter arrangement for generating saccades coupled with an integrator. The integrating filter is in place to model the necessary conversion of velocity-coded information to position-coded signals (Leigh and Zee 1991). A perfect neural integrator converts a pulse signal to a step function. An imperfect integrator (called leaky) will generate a signal resembling a decaying exponential function. The principle of this type of neural integration applies to all types of conjugate eye movements. Neural circuits connecting structures in the brain stem and the cerebellum exist to perform integration of coupled eye movements including saccades, smooth pursuits, and vestibular and optokinetic nystagmus (see below; Leigh and Zee 1991).

A differentiation filter can be modeled by a linear filter as shown in Fig. 4.3. In the time domain, the linear filter is modeled by the following equation

$$\begin{aligned} x_t &= g_0 s_t + g_1 s_{t-1} + \cdots \\ &= \sum_{k=0}^{\infty} g_k s_{t-k}, \end{aligned}$$

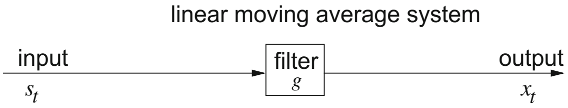

Fig. 4.3 Diagram of a simple linear filter modeling saccadic movements

where s_t is the input (pulse), x_t is the output (step), and g_k are the filter coefficients. To ensure differentiation, the filter coefficients typically must satisfy properties that approximate mathematical differentiation. An example of such a filter is the Haar filter with coefficients $\{1, -1\}$. Under the z-transform the transfer function $X(z)/S(z)$ of this linear filter is

$$\begin{aligned} x_t &= g_0 s_t + g_1 s_{t-1} \\ x_t &= (1)s_t + (-1)s_{t-1} \\ x_t &= (1)s_t + (-1)z s_t \\ x_t &= (1-z)s_t \\ X(z) &= (1-z)S(z) \\ \frac{X(z)}{S(z)} &= 1 - z. \end{aligned}$$

The Haar filter is a length-2 filter which approximates the first derivate between successive pairs of inputs.

4.3 Smooth Pursuits

Pursuit movements are involved when visually tracking a moving target. Depending on the range of target motion, the eyes are capable of matching the velocity of the moving target. Pursuit movements provide an example of a control system with built-in negative feedback (Carpenter 1977). A simple closed-loop feedback loop used to model pursuit movements is shown in Fig. 4.4, where s_t is the target position, x_t is the (desired) eye position, and h is the (linear, time-invariant) filter, or gain of the system (Carpenter 1977; Leigh and Zee 1991). Tracing the loop from the feedback start point gives the following equation in the time domain

$$h(s_t - x_t) = x_{t+1}.$$

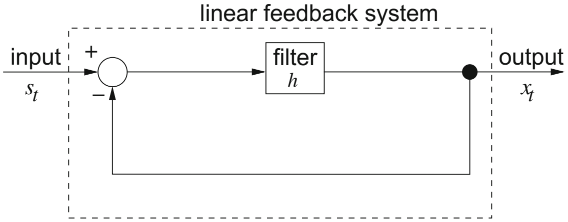

Fig. 4.4 Diagram of a simple linear feedback model of smooth pursuit movements

Under the z-transform the transfer function $X(z)/S(z)$ of this linear system is

$$\begin{aligned}
H(z)(S(z) - X(z)) &= X(z) \\
H(z)S(z) &= X(z)(1 + H(z)) \\
\frac{H(z)}{1 + H(z)} &= \frac{X(z)}{S(z)}.
\end{aligned}$$

In the closed-loop feedback model, signals from visual receptors constitute the error signal indicating needed compensation to match the target's retinal image motion.

4.4 Fixations (Microsaccades, Drift, and Tremor)

Fixations are eye movements that stabilize the retina over a stationary object of interest. It seems intuitive that fixations should be generated by the same neuronal circuit controlling smooth pursuits with fixations being a special case of a target moving at zero velocity. This is probably incorrect (Leigh and Zee 1991, pp. 139–140). Fixations, instead, are characterized by the miniature eye movements: tremor, drift, and microsaccades (Pritchard 1961; Martinez-Conde et al. 2004; Martinez-Conde and Macknik 2015). This is a somewhat counterintuitive consequence of the visual system's motion-sensitive single-cell organization. Recall that microsaccades are made due to the motion sensitivity of the visual system's single-cell physiology. Microsaccades are eye movement signals that are more or less spatially random varying over 1–2 min of arc in amplitude. The counterintuitive fact regarding fixations is that if an image is artificially stabilized on the retina, vision fades away within about a second and the scene becomes blank.

Miniature eye movements that effectively characterize fixations may be considered noise present in the control system (possibly distinct from the smooth pursuit circuit) attempting to hold gaze steady. This noise appears as a random fluctuation about the area of fixation, typically no larger than 5° visual angle (Carpenter 1977, p. 105). Although the classification of miniature movements as noise may be an oversimplification of the underlying natural process, it allows the signal to be modeled by a feedback system similar to the one shown in Fig. 4.4. The additive noise in Fig. 4.4 is represented by $e_t = s_t - x_t$, where the (desired) eye position x_t is subtracted from the steady fixation position s_t at the summing junction. In this model, the error signal stimulates the fixation system in a manner similar to the smooth pursuit system, except that here e_t is an error-position signal instead of an error-velocity signal (see Leigh and Zee 1991, p. 150). The feedback system modeling fixations, using the noisy "data reduction" method, is in fact simpler than the pursuit model because it implicitly assumes a stationary stochastic process (Carpenter 1977, p. 107). Stationarity in the statistical sense refers to a process with constant mean. Other relevant statistical measures of fixations include their duration range of 150–600 ms, and the observation that 90% of viewing time is devoted to fixations (Irwin 1992).

4.5 Nystagmus

Nystagmus eye movements are conjugate eye movements characterized by a sawtoothlike time course (time series signal) pattern. Optokinetic nystagmus is a smooth pursuit movement interspersed with saccades invoked to compensate for the retinal movement of the target. The smooth pursuit component of optokinetic nystagmus appears in the slow phase of the signal Robinson (1968). Vestibular nystagmus is a similar type of eye movement compensating for the movement of the head. The time course of vestibular nystagmus is virtually indistinguishable from its optokinetic counterpart Carpenter (1977).

4.6 Implications for Eye Movement Analysis

From the above discussion, two significant observations relevant to eye movement analysis can be made. First, based on the functionality of eye movements, only three types of movements need be modeled to gain insight into the overt localization of visual attention. These types of eye movements are fixations, smooth pursuits, and saccades. Second, based on signal characteristics and plausible underlying neural circuitry, all three types of eye movements may be approximated by a Linear, Time-Invariant (LTI) system (i.e., a linear filter; for examples of linear filters applicable to saccade detection, see Chap. 13).

The primary requirement of eye movement analysis, in the context of gaze-contingent system design, is the identification of fixations, saccades, and smooth pursuits. It is assumed that these movements provide evidence of voluntary, overt visual attention. This assumption does not preclude the plausible involuntary utility of these movements, or conversely, the covert nonuse of these eye movements (e.g., as in the case of parafoveal attention). Fixations naturally correspond to the desire to maintain one's gaze on an object of interest. Similarly, pursuits are used in the same manner for objects in smooth motion. Saccades are considered manifestations of the desire to voluntarily change the focus of attention.

4.7 Summary and Further Reading

This chapter presented a taxonomy of eye movements and included linear models of eye movement signals suitable for eye movement analysis (see also Chap. 13).

With the exception of Carpenter's widely referenced text (Carpenter 1977), there appears to be no single suitable introductory text discussing eye movements exclusively. Instead, there are various texts on perception, cognition, and neuroscience which often include a chapter or section on the topic. There are also various collections of technical papers on eye movements, usually assembled from proceedings of focused symposia or conferences. A series of such books was produced by John Senders et al. in the 1970s and 1980s (see for e.g., Monty and Senders 1976; Fisher et al. 1981). This conference series has recently been revived in the form of the (currently biennial) Eye Tracking Research & Applications (ETRA) conference.

A large amount of work has been performed on studying eye movements in the context of reading. For a good introduction to this literature, see Rayner (1992).