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Synchronizing the tracking eye movements with the motion of a visual target: Basic neural processes

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28 **Abstract**

29 In primates, the appearance of an object moving in the peripheral visual field elicits an
30 interceptive saccade that brings the target image onto the foveae. This foveation is then
31 maintained more or less efficiently by slow pursuit eye movements and subsequent catch-up
32 saccades. Sometimes, the tracking is such that the gaze direction looks spatiotemporally
33 locked onto the moving object. Such a spatial synchronism is quite spectacular when one
34 considers that the target-related signals are transmitted to the motor neurons through multiple
35 parallel channels connecting separate neural populations with different conduction speeds and
36 delays. Because of the delays between the changes of retinal activity and the changes of
37 extraocular muscle tension, the maintenance of the target image onto the fovea cannot be
38 driven by the current retinal signals as they correspond to past positions of the target. Yet, the
39 spatiotemporal coincidence observed during pursuit suggests that the oculomotor system is
40 driven by a command estimating continuously the current location of the target, i.e., where it is
41 here and now. This inference is also supported by experimental perturbation studies: when the
42 trajectory of an interceptive saccade is experimentally perturbed, a correction saccade is
43 produced in flight or after a short delay, and brings the gaze next to the location where
44 unperturbed saccades would have landed at about the same time, in the absence of visual
45 feedback. In this chapter, we explain how such correction can be supported by previous visual
46 signals without assuming “predictive” signals encoding future target locations. We also
47 describe the basic neural processes which gradually yield the synchronization of eye
48 movements with the target motion. When the process fails, the gaze is driven by signals related
49 to past locations of the target, not by estimates to its upcoming locations, and a catch-up is
50 made to reinitiate the synchronization.

51 **Keywords**

52 Tracking, saccade, pursuit, foveation, neurophysiology, synchronization, prediction

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Over the course of their phylogenetic and ontogenetic evolution, the animals were faced with the need to manage an environment which is not composed of static objects. In their world (*Umwelt*), the significant events occur most often when something moves (whether it is animal or not, predator, prey, congeners, or other) or when themselves, they move. In front of this dynamism, the animals exhibit the ability to pursue and catch a prey, to avoid a predator, in flight for some of them. How are such performances, spatiotemporally accurate, possible? Should we believe that the functioning of the brain sets general frames (such as space and time) and principles similar to those used by the Newtonian mechanics for describing the motion of a rigid body? In this chapter, we will explain how the neurophysiology of eye movements made toward a moving visual target addresses these fundamental questions. A new line of investigation is proposed to identify the neurophysiological processes which underlie the ability to produce a visuomotor behavior which is accurate both spatially and temporally.

1. SPATIOTEMPORAL “DILUTION” OF VISUAL SIGNALS IN THE BRAIN.

Most visually guided actions consist of localizing and aiming at selected objects in the external world while avoiding obstacles, and grasping them once their location becomes within reach. They involve a multitude of saccades whereby the gaze is oriented toward selected parts of the external world. By bringing the object within the central visual field, each saccade leads to a situation where the target excites a larger population of neurons. In the visual areas of the cerebral cortex and in the superior colliculus (SC), more neurons are indeed sensitive to stimuli located within the central visual field (McIlwain, 1976). If the target is static, the primary saccade is often completed by a small secondary saccade (also called correction saccade). If the target is moving, the interceptive saccade is followed by a slow movement of the eyes and later by a small catch-up saccade. We will avoid considering this sequence of eye movements as the signature of a purposive process whereby a desired future state would drive the evolution of the current state. Instead, we will try to view it as an inevitable process unfolding in the inhomogeneous structure of the visuomotor system, through parallel streams of activity constrained by the brain connectivity.

From the excitation of ganglion cells in the retina to the recruitment of motor neurons (MNs) in the reticular formation and the contraction of extraocular muscles, multiple trains of action potentials are conveyed by parallel channels connecting, with different conduction speeds, assemblies of diverse types of neurons characterized by different response times (Nowak and Bullier, 1997; Pellionisz and Llinas, 1982; Schmolesky et al., 1998). The generation of saccadic and slow eye movements indeed involves streams of activity which, on

their way from the optic nerve toward the oculomotor nerves, mobilize several populations of neurons in the thalamus, the cerebral cortex, the basal ganglia, the cerebellum, and the reticular formation (Büttner-Ennever, 2005; Krauzlis, 2004; Lynch, 2009; Moschovakis et al., 1996; Wurtz and Goldberg, 1989). Thus, the activity yielded by the projection of a small static spot of light on the retinal surface, spatially delimited, spreads out and becomes largely distributed (spatially and temporally) in the brain networks before converging onto the groups of premotor and MNs, and causing the contraction of two pairs of six extraocular muscles (Goffart, 2017).

< Figure 1 approximately here >

Beyond the apparent entropy exhibited by this spatiotemporal “dilution” of afferent signals within the cerebral medium, the massive interconnectedness of neural populations actually facilitates the persistence of visual activity for a duration which largely exceeds the actual duration of even a brief spot of light in the external world. Unlike the artificial light which turns off immediately after an electric switch is pressed, the visual activity persists and continues its diffusion within the brain networks. Fig. 1 shows examples of saccades aimed at a target LED that was flashed for a short duration (50 ms) in the peripheral visual field of two macaque monkeys (Be and E). From the onset of the target to the beginning of the saccade toward its location, the saccade latency is the time interval for localized changes in retinal activity to be transmitted to the muscle fibers and initiate their contraction. The contraction lasts for a duration which is sufficient to rotate the eyes and accurately direct the foveae toward the target with a time course which does not slow down with longer latencies. Regardless of its onset time, the saccade indeed consists of a sudden increase in angular velocity (acceleration) followed by a decline (deceleration). The persistence of the target-related activity is nicely appreciated when the intensity of visual signals is reduced. Indeed, the use of LEDs allows testing the influence of target energy (Barnes, 1995), and discovering that low-intensity targets lead to saccades which are not characterized by a slower rise in eye velocity and a longer deceleration; it is their onset which is actually delayed (the latency increases). The variability of latencies also increases when the target contrast is reduced (see gray traces in Fig. 1). Interestingly, the latency of the first spike of the response of neurons in the primary visual cortex is also variable and can be correlated with the saccade latency (Lee et al., 2010). Of course, this attractive influence of such a dim spot of light has been amplified by the fact that the monkey learned that it was a signal whose foveation led to a reward. This artificial association would have hardly been observed in the wilds; such a transient stimulus would have likely been unnoticed. Beyond the rigorous description of a behavioral response, the point that we want to address here concerns the identification of the propagation of signals within

the cerebral medium (see also Van Rullen et al., 2005) for that specific case when an orienting response is being elaborated and made toward a visual target.

2. SYNCHRONOUS POPULATION ACTIVITY AGAINST FUNCTIONAL ENTROPY

Considering that the action potentials are conducted along the axons of cells with fixed speeds of propagation, the difference of saccade latencies illustrated in Fig. 1 can be explained by changes in the excitability of neurons. One possible mechanism is that the number of ganglion cells, which, in the retina, are simultaneously excited, is larger with a high-contrast stimulus than with a low-contrast one. This synchronous activation would then facilitate the recruitment of postsynaptic neurons in the thalamus or in the SC, then in the visual cortex, etc. The same principle could be involved in reducing the delay of propagating signals between the relays interposed between the retina and the MNs: simultaneous excitatory signals from an assembly of neurons are more efficient in exciting their targeted cells than temporally scattered input. Thus, the variability of saccade onsets would depend upon the synchronies of action potentials which are transmitted to the next relay: weaker synchrony yielding scattered and longer reaction times.

Providing a direct support to this hypothesis is difficult with the contemporary electrophysiological recording techniques. However, the analysis of the effects of electrically exciting the same neural site in the SC of the macaque monkey is very instructive for that particular issue. The SC is a structure anatomically situated between the visual cortical areas of the cerebral cortex and the premotor regions in the pontomedullary reticular formation responsible for the generation of saccades (Hall and Moschovakis, 2004). In its deeper layers, one finds cells which fire selectively prior to saccades within a limited range of directions and amplitudes (Schiller and Koerner, 1971; Sparks et al., 1976; Wurtz and Goldberg, 1972). The size and the extent of this movement field depend upon the location of the cell in the SC. In the anterior region, the neurons emit a burst of action potentials during small saccades, whereas neurons located more posteriorly fire during saccades of larger amplitude. Neurons located in the medial border burst prior to upward oblique saccades, and those located on the lateral border discharge before downward oblique saccades. Interestingly, when an electrical microstimulation is applied to a particular site, a saccade is elicited with an amplitude and direction which belong to the movement field of recorded neurons (Schiller and Stryker, 1972). While the amplitude and direction of evoked saccades depend upon the stimulated site (Robinson, 1972), their latency depends upon the rate of stimulation pulses: the lower the rate, the longer the latency (Katnani and Gandhi, 2012; Stanford et al., 1996). Fig. 2A illustrates this

effect. For frequencies ranging from 300 to 500 pulses per second (pps), the electrically evoked saccades have identical velocity profiles (Fig. 2B) and thus, identical amplitude and direction (identical amplitudes of their horizontal and vertical components). However, their latencies increase when the stimulation frequency diminishes. When the frequency is reduced to 200 pps, the latency becomes more variable (Fig. 2C). The “synchronous recruitment” hypothesis described at the beginning of this section can account for this phenomenon: increasing the frequency of stimulation favors the synchrony of firing between the electrically excited neural elements (cells and axons), and this facilitates the recruitment of targeted premotor cells, shortening the latency of elicited saccades.

< Figure 2 approximately here >

To our knowledge, Schiller (1970) was the first to consider the influence of the number of neurons discharging in synchrony as an important determinant of saccade generation. And this intuition leads us to another important point, i.e., that the rate of firing is not the sole parameter by which the SC activity contributes to the generation of saccades; the number of active neurons also matters. Indeed, when a subset of the active population of neurons is inactivated by the local injection of a small volume of pharmacological agent, the velocity of saccades is reduced (Lee et al., 1988) and their latency increased (Sparks et al., 1990) in a correlated manner (Goffart et al., 2012). This influence of the number of active neurons can likewise be demonstrated with the microstimulation technique by varying the current of stimulation. When the frequency and duration of stimulation are maintained fixed, increasing the current of stimulation reduces the latency of saccades (Fig. 2D; Katnani and Gandhi, 2012; Stryker and Schiller, 1975). However, contrary to a transient visual target which leads to a complete saccade long after its disappearance (Fig. 1), electrical microstimulation in the deep SC evokes a saccade whose amplitude depends upon the stimulation duration. If the stimulation is not sufficiently long, the evoked movement is truncated; the amplitude specified by the locus of activity in the SC cannot be fully accomplished (Freedman et al., 1996; Stanford et al., 1996). Sustained activity is an important aspect of the collicular involvement in generating saccades toward the location encoded by the population of active neurons. The maintenance of firing only concerns the activity generated during saccades and not the complete activity which elapses from the target onset until the saccade end. Indeed, before the emission of their saccade-related burst, numerous neurons exhibit a reduction or even a pause of their firing after their visual response (Bell et al., 2006; Mays and Sparks, 1980). The activity during saccades steers the gaze toward a location which is specified by the current population of active neurons in the SC, whether the saccade is made toward static (Gandhi

and Keller, 1999; Glimcher and Sparks, 1993) or moving targets (Fleuriet and Goffart, 2012; Goffart et al., 2017a; see below).

3. REDUCING THE LAG BETWEEN THE PAST AND THE PRESENT

The conduction delays between the firing of retinal ganglion cells and the burst discharge of ocular MNs make impossible that the gaze is driven by the contemporary retinal signals during its saccadic shifts. The problem becomes sharper when one considers the generation of saccades toward a moving target. If the saccades were aimed at the locations traveled by the target, they would always fall short and miss it with an error which would depend upon the target speed and the time of saccade “landing.” Yet, despite that the retinal signals yielded by a moving target always correspond to its past locations, the interceptive saccades can be as accurate, though not as precise, as saccades toward a static target (e.g., Barmack, 1970; Cassanella et al., 2008; Fuchs, 1967; Keller and Johnsen, 1990; Robinson, 1965). Fig. 3 compares the landing errors between saccades made toward a static target (red symbols) and saccades made toward a target moving with a constant speed of 21 degrees (deg)/s (blue) in the same region of the visual field (Fleuriet et al., 2011). After a step of 16 deg along the vertical (Fig. 3A) or horizontal meridian (Fig. 3B), the target moved horizontally or vertically (respectively), i.e., along the axis orthogonal to the step. In comparison to saccades toward the static targets, the interceptive saccades can be accurate (overlap of error values), with a tendency for more frequent undershoots (negative values of error). However, the quasi-absence of overshoots (positive values) whose size is larger than the errors of saccades toward a static target indicates that the interceptive saccades are not aimed at a future location of the target, contradicting the claim that “in [their] programming, target motion is used to predict the future target position so as to assure a spatial lead of the gaze at the saccade end, instead of attempting a precise capture of the target” (Klam et al., 2001). In fact, the idea that the brain would predict the future location of a moving target, and, accordingly, that it would issue a command corresponding to a kind of foresight (Berthoz, 2012; Optican and Pretegeiani, 2017) lacks of any empirical evidence.

< Figure 3 approximately here >

Electrophysiological recording studies teach us that any saccade made toward a static target is commanded by a population of neurons in the SC (Anderson et al., 1998; McIlwain, 1976, 1991; Sparks et al., 1976, 1990). Some cells discharge maximally before and during the movement, while others fire less. Those which burst the most vigorously are located at the center of the active population, surrounded by the others. Let's consider five hypothetical

neurons, A, B, C, D, and E; the neuron B firing maximally during a 10 deg rightward saccade, the neuron A during a 8 deg rightward saccade, and C during a 12 deg rightward one. The neurons D and E prefer slightly oblique rightward saccades: D when the 10 deg rightward saccade has a 2 deg upward component, and E when it has a 2 deg downward component. The activity of each neuron can be symbolized by a vector with two coordinates, each corresponding respectively to the horizontal and vertical component of the saccade during which it fires maximally: (8,0) for A, (10,0) for B, (12,0) for C, (10,2) for D, and (10, -2) for E. According to the vector-averaging hypothesis (Pitts and McCulloch, 1947; Sparks et al., 1976, 1997), the direction and amplitude of the ensuing saccade is specified by the average activity of the population of firing neurons. A 10 deg rightward saccade would involve our five neurons A, B, C, D, and E. The discharge of neuron B would be the most vigorous, while A, C, D, and E would fire less. Situated outside the active population, the other neurons (e.g., F: (10,6), G: (10,-6), H: (10,4), and I: (10,-4)) would be silent. Let's consider now that an identical 10 deg rightward saccade is made toward a target which moves downward, along a path parallel to the vertical meridian. If the same vector-averaging principle steers the interceptive saccade, then a larger population of active neurons should be observed in the SC. The moving target indeed traveled locations in the upper visual field which correspond to vectors like (10,6) and (10,4), involving the activity of neurons F and H. Thus, for generating exactly the same horizontal saccade, the neurons (G and I) coding for the vectors (10,-6) and (10,-4) should also fire, even though the target did not yet "reach" their response field. In other words, these neurons should fire action potentials during interceptive saccades and not during identical saccades made toward a static target. Their movement field should exhibit a shift of their boundary in the direction opposite to the target motion direction. But the available evidence argues against this scenario; the boundaries of the neurons' response field are not shifted in the direction opposite to the direction of the target motion. Many neurons do not exhibit any shift. Other neurons do, but the shift is in the same direction as the direction of the target motion. In other words, the active population in the SC is dynamical and consists of a continuum of neurons issuing commands ranging from vectors related to the past location of the target to vectors related to its present location (Goffart et al., 2016, 2017a; Keller et al., 1996), amending the suggestion that the locus of activity in the SC would only encode the location that the target occupied in the past, at the time of its appearance (Optican, 2009; Optican and Pretegeiani, 2017). Finally, the empirical data do not refute the vector-averaging hypothesis because different weights can be attributed to the spikes that the saccade-related neurons emit during the interceptive saccade.

4. CAPTURING A MOVING TARGET HERE AND NOW

The majority of behavioral studies show that in response to a moving target, the gaze does not land on a location where it will be in the future. The world of living animals contains too many uncertainties that they do not behave as if their prey, predator, or congeners were moving along predetermined routes comparable to public transportation lines. The most spectacular ability with which animals are endowed is to physically capture one to several moving objects. By reducing both the delay between the detection and the reaction to a moving object, and by maintaining it within the central visual field, the object becomes quasi-stable, both spatially and temporally. Instead of considering processes which “predict” or “foresee” the future location of moving target, we propose that tracking a moving target consists of establishing spatial synchrony with it (see also Becker and Fuchs, 1985). The fact that engineers found procedures and built machines which can point toward the future location of an object does not necessarily imply that the same “computation” happens in the brain when a moving target is being captured.

< Figure 4 approximately here >

This fact that the saccades do not target the future but the current location of a moving object is strongly suggested by the results of experiments which tested the robustness of interceptive saccades in the monkey (Fleuriet and Goffart, 2012). When a saccade toward a moving target is perturbed by a brief microstimulation in the SC, the electrically induced change in eye position is corrected in flight or after a short delay, bringing the direction of gaze toward the location where unperturbed saccades would have landed at about the same time. In particular, when the microstimulation is applied in a site which is not involved in the generation of saccades with amplitude and direction close to those of interceptive saccades (when the direction of the perturbation is opposite to the saccade direction), after the electrically induced change in gaze direction, most correction saccades do not overshoot along the motion path. They either fall short or “land” accurately on the moving target. Fig. 4 shows examples of such corrections observed in one experiment (see Fleuriet and Goffart, 2012 for other examples). The experiment was composed of trials which started with the fixation of a central target for a variable interval (the latter is a methodological precaution for avoiding the generation of premature saccades). At the end of the fixation interval, the central target was turned off and, at the same time, a peripheral target appeared 12 deg along the vertical meridian (downward or upward) and moved horizontally to the left or to the right with a constant velocity of 20 deg/s. To avoid the use of visual signals in the guidance of corrections during the perturbed trials, the target became invisible 150 ms after the onset of its motion and for an interval lasting 300 ms. After this interval of target invisibility, the target reappeared moving in the same direction and

with the same velocity for 500 ms. The monkey's task was to make a saccade toward the target and to pursue it until it reached its destination (trial end). In 50% of the trials, the interceptive saccade was perturbed by an electrical microstimulation in the deep SC at the onset of the blank interval (i.e., 150 ms after the target motion onset). For both unperturbed and perturbed trials, a fruit juice reward was delivered to the monkey at the end of the trial. Interestingly, the microstimulation evoked saccades whose amplitude and direction were influenced by the target motion (compare the eye displacements indicated by the black arrows). When the target moved in the upper right quadrant (Fig. 4B), the stimulation evoked a saccade with small upward and rightward components. When the target moved in the upper left quadrant (Fig. 4A), the horizontal component almost disappeared. When it moved in the lower left quadrant (Fig. 4C), both horizontal and vertical components were strongly reduced; the interceptive saccade was delayed. These different perturbation vectors illustrate interactions between the electrically-evoked and target-elicited activities. Their study should be informative because they illustrate the dynamics (rise and decline) of target-related signals, as previously documented with a static target (Nichols and Sparks, 1995, 1996; Schlag et al., 1998; Sparks and Mays, 1983; Sparks et al., 1987). Following the perturbation, a correction saccade was made that brought the gaze direction, not where the target will reappear (future location), but toward a location close to those captured by unperturbed saccades.

Two groups of signals can participate in the elaboration of the command which guides the interceptive saccade toward the transiently invisible target regardless of whether its trajectory is perturbed or not: (1) the target motion-related signals that precede the blank interval and (2) mnemonic signals that the target is expected to reappear and continue to move along the same path. As explained in the first section, the massive interconnectedness of neural populations in the brain facilitates the persistence of visual activity for duration which largely exceeds the actual duration of an event in the external world. Thus, it is quite possible that after the moving target disappears, the visual activity persists and continues its diffusion within the brain networks. Presumably, the diffusion is not isotropic but biased by the target motion direction. It has indeed been shown that the pursuit eye movement persists beyond the time and location where a moving target has disappeared (e.g., Mitrani and Dimitrov, 1978). The activity driving this persistent slow movement of the eyes is likely not restricted to the ocular MNs; it must be driven by premotor neurons, which themselves could be driven by persisting activity of visual neurons. Thus, the correction saccades observed after the "spatiotemporal" perturbation induced by electrical microstimulation in the dSC (Fig. 4; Fleuriet and Goffart, 2012) could well be driven by residual activity from the visual signals which preceded the target disappearance. Later experiments testing saccades toward a transient moving target showed indeed a large number of landing positions situated beyond the location

where the target disappeared. When the target moved at constant speed, the saccades landed approximately where the target would be if it were still moving during the next 100 ms (see Fig. 8B, E, and H in Quinet and Goffart, 2015a). Therefore, the visual signals that persisted after the target disappearance could contribute to guide the correction saccades reported in Fleuriet and Goffart (2012) because the added delays did not exceed 100 ms (see our Fig. 4 and Figs. 6 and 7 in Fleuriet and Goffart, 2012). In addition, the target disappeared for a short interval and reappeared 150 or 300 ms later, continuing its motion along the same path with the same velocity. There was no uncertainty about whether the target would reappear and keep moving along the same path. The monkeys never experienced cases where the target would start moving backward or change its direction during the interval of invisibility.

Moreover, the monkeys were not tested to only make a saccade toward the transient moving target (like in the study of Quinet and Goffart, 2015a). They were used to continue their tracking after the target reappearance, until the end of the trial. In other words, it is possible that additional central factors contributed to the robustness of interceptive saccades. Fig. 4 indeed shows that the monkey made catch-up saccades when the target was not visible, during unperturbed trials (green arrows) but also during perturbed trials (blue arrows). Following the target disappearance, the diffusion of residual signals could merge with prelude signals related to the upcoming target reappearance. Thus, the interval of invisibility would be “filled” by a kind of interpolation, driving the activity of premotor neurons and guiding the eye movement (saccadic or slow) in the absence of target-related retinal signals. Therefore, the command which encodes at best the expected and current (here-and-now) location of the target and drives the premotor neurons when a visual target is being temporarily occluded corresponds to a combination of signals related to the recent past with mnemonic signals carrying an expectancy built upon the past and repeated experience.

5. BEYOND THE NOTION OF INTERNAL MODEL

Several studies show cases where the eyes rotate smoothly and in spatial synchrony with the motion of a visual object, as if no delay separated the time-varying changes of target location and the time-varying changes of extraocular muscle tension. The gaze direction seems to be locked onto the present location of the target, i.e., where it is here and now. Obviously it is not the retinal signals yielded by the external target which drive this spatiotemporal coincidence.

According to the most popular view, the ability to perform visually guided eye movements which are spatiotemporally accurate rests upon a putative internal model of the

moving target. The major concern of this explanation is that it leads to a dead end insofar as it refers to an entity which is neurophysiologically intractable. Nowadays, the notion of internal model is used like a shortcut, barely helpful to identify and characterize the underlying neurophysiology. The major obstacle which compromises this possibility is the distributed nature of the representation of a visual target in the brain activity (e.g., Nowak and Bullier, 1997; Schmolesky et al., 1998; Sparks et al., 1976). A moving visual target involves flows of neural activity which do not remain local but propagate both “vertically” (i.e., across the successive relays interposed between the retina and the extraocular MNs) and “horizontally” (diffusion within each relay). In other words, in the brain activity, the neural image (in the mathematical sense) which corresponds to an object in the external world, even static, is not reducible to a vector with independent spatial and temporal coordinates (Pellionisz and Llinas, 1982). It involves entangled flows of neural activity which are spatiotemporally distributed in the brain, from the retinal ganglion cells to the oculomotor neurons. Furthermore, the involvement of a measurable movement (like a saccade) is critical to guarantee that the associated neural activity corresponds to a real object and not to an illusion. The interceptive saccades have indeed been shown to be immune to strong visual illusions: they aim at the physical, not the perceived location of the target (Lisi and Cavanagh, 2015).

The neurophysiological characterization is also complicated by the changing location of the object. The time course of the motion can indeed look smooth and continuous, but such retrospective evaluation does not guarantee that the neural image follows a similar dynamics. In the case of tracking a moving target, we will see in the next section that the visuo-oculomotor brain does not spontaneously transform the smooth motion of a small object into a continuous smooth movement of the eyes. A complete dynamic morphing requires several days of training (Bourrelly et al., 2016a,b). Synchronizing the eye movements with the motion of a target is the outcome of a gradual process during which the brain activity assimilates the combination of visual and oculomotor signals. Contemporary habits of language and the Newtonian mechanics lead us to consider that an object is moving within a three-dimensional, homogeneous, isotropic and neutral “receptacle,” changing discretely its location in such a way that when it is here and now, it is not anymore where it was before, nor where it will soon be. In the brain activity corresponding to this object, there is no such thing as a “here and now” local point (Pellionisz and Llinas, 1982). The neural image obviously does not change as fast as its associated object in the external world; some residual activity persists “behind” (Goffart et al., 2016, 2017a; Keller et al., 1996). It also expands toward neighboring cells, driving the gaze toward locations in the external world where the target never went (Mitrani and Dimitrov, 1978; Quinet and Goffart, 2015a). Given the complexity of the problem when one considers the neural image of a real object moving in front of our eyes, how do we address the problem

of a putative internal model without doing disappointing parodies of the neurophysiological processes and their oculomotor expression?

Because of all these complications, we will avoid considering the notion of internal model to understand how the brain endows the animals with the ability of maintaining the direction of their gaze toward the present location of the target, i.e., where it is here and now. Instead, our working hypothesis is that spatiotemporally accurate actions result from an adaptive process which consists in synchronizing the outcome of visuomotor flows of activity with the target dynamics.

6. LEARNING TO TRACK THE CHANGING LOCATION OF A MOVING TARGET

A target moving in the visual field triggers an interceptive saccade that brings the target image onto the fovea. Then, this foveation is more or less efficiently maintained by two types of eye movements: low-velocity (pursuit) and high-velocity movements (catch-up saccades). Fleuriet and Goffart (2012) hypothesized that the oculomotor system is driven by an estimate of the expected current target location, and subsequent experiments indicated that this command is merging signals from the recent past with mnemonic signals carrying an expectancy built upon repeated experience.

It is indeed obvious that the ability to continuously encode, in spite of neural conduction and stabilization delays, the “here-and-now” location of a moving target, requires that its trajectory is already known. To further develop this hypothesis, we studied how inexperienced monkeys learned to track a target which always moved along the same path. During these experiments, each trial started with the foveation of a central target which, after a variable interval, stepped on the vertical meridian (upward or downward) and immediately after, moved horizontally with a constant, increasing or decreasing velocity (Bourrelly et al., 2016a,b). The target moved toward the left or the right for 800 ms before disappearing. The monkey was rewarded if, after making a saccade in the appropriate visual quadrant, it tracked the target until its ultimate location. During the first days, the tracking was composed of saccades separated by periods during which gaze moved slowly in the same direction as the target. Except for the brief periods during which fairly accurate saccades occurred, the gaze lagged behind the target most of the time.

< Figure 5 approximately here >

Fig. 5 illustrates qualitatively with example trials recorded in five monkeys, how the oculomotor tracking changed between the first and last sessions of the training procedure, when the target moved with a constant speed. During the first session (left column), after the interceptive saccade, the eye followed the target with a velocity which was not sufficient to maintain its image on the fovea. The velocity of the postsaccadic movement did not match the target speed. Contrary to the experiments where the target moved with an increasing speed (Fig. 6), the eye did not increase the velocity of its movement before the subsequent catch-up saccade. After several daily training sessions (right column), the monkey was able to smoothly track the target immediately after the interceptive saccade; the catch-up saccades either disappeared or their amplitude was largely diminished. This saccade-free tracking was rarely, if ever, observed during the first session. The reader will find in Bourrelly et al. (2016a) a detailed description of how tracking eye movements changed during the course of one trial, during the course of the first and last sessions and across the successive sessions. Fig. 6 illustrates the same evolution when an accelerating target is tracked (Bourrelly et al., 2016b). After the interceptive saccade, contrary to the experiments which tested the tracking eye movements made in response to a target moving with a constant speed, the postsaccadic eye movements could accelerate when the target accelerated, but not sufficiently to match the increasing target speed. With repeated practice, i.e., with a larger number of trials and over the consecutive days, the pursuit gain (ratio of eye to target velocities during the intersaccadic intervals) enhanced while the number and amplitude of catch-up saccades diminished (Bourrelly et al., 2016a). The evolution of tracking from an intermittent to a continuous “here-and-now” mode is actually inevitable because the saccades exert a facilitative influence on pursuit eye movements. This facilitation is twofold, visual and motor. On the one hand, saccades bring the target image within the central visual field, where the visual motion signals are more effective for driving slow eye movements compared with signals from the peripheral field (Lisberger and Westbrook, 1985). On the other hand, the slow eye movements match the target speed better when they are preceded by a saccade (Lisberger, 1998). We will see in the next section the neurophysiological process which possibly underlies this facilitation.

< Figure 6 approximately here >

7. NEURAL BASIS OF SACCADIC AND PURSUIT EYE MOVEMENTS

The gaze direction is determined by the cooperative action of six muscles attached to each eyeball. These muscles are called extraocular muscles, to distinguish them from those located inside the eye and which influence the diameter of the pupil or the lens curvature. Two pairs of muscles are involved during horizontal rotations of the eyes (i.e., rotations about a

vertical axis through the eyeball): the lateral rectus (LR) and medial rectus (MR) muscles. Orienting gaze toward the right is accomplished in the right eye by the contraction of the LR and the relaxation of the MR, while in the left eye the MR is contracted and the LR relaxed. Conversely, orienting gaze toward the left is produced in the left eye by the LR contraction and MR relaxation concomitantly with the MR contraction and the LR relaxation in the right eye. Vertical movements of the eyes (rotations about a horizontal axis) are slightly more complex than the horizontal ones because they are the result of a synergy between the other four extraocular muscles. The joint contraction of the superior rectus (SR) and inferior oblique (IO) muscles of both eyes, combined with the relaxation of the inferior rectus (IR) and superior oblique (SO) muscles, rotate the eyes upward. The bilateral contraction of the IR and SO, combined with the relaxation of SR and IO, rotates them downward. Oblique saccades are generated by tensions simultaneously developed by the muscles rotating the eye horizontally and those rotating the eye vertically. The contraction of extraocular muscles is driven by the activity of MNs located in cranial nerve nuclei III (oculomotor), IV (trochlear), and VI (abducens).

Different populations of premotor neurons in the reticular formation are involved in the generation of saccadic and slow eye movements. The generation of saccadic eye movements involves burst discharges by neurons located in the pontomedullary and mesencephalic reticular formation, respectively, for the horizontal and vertical movements (see Goffart, 2017 for a brief review and references). Because they emit a burst of action potentials within a very short-time interval, these neurons have been called saccade-related burst neurons. Although it can be preceded by a prelude firing, it is the burst which drives the MNs and yields the rapid rise in the tension of extraocular muscles during saccades. Lesions of the regions where the burst neurons are located abolish the ability to generate saccades without compromising the ability to make slow eye movements toward a moving target (Henn et al., 1984). The generation of pursuit eye movements involves other groups of neurons called tonic neurons which are located in distinct nuclei of the reticular formation (Sharpe, 2008).

A dissociation of the neural processes leading to the generation of saccadic and pursuit eye movements is supported by multiple clinical and experimental lesion studies (e.g., Büttner et al., 1994; Henn et al., 1984; Morrow and Sharpe, 1995; Ohtsuka et al., 1992; Pierrot-Deseilligny et al., 1990; Sharpe, 2008). However, this segregation is not absolute. A coupling between the processes controlling each type of movement is indeed suggested by the existence of neurons which modulate their sustained firing rate during both types of movement. Most of these neurons have been found in the cerebellum, and more specifically in its floccular and parafloccular regions (Noda and Mikami, 1986; Noda and Suzuki, 1979) and in its

medioposterior territories, i.e., the caudal fastigial nuclei (Fuchs et al., 1994) and the posterior vermis (Suzuki and Keller, 1988). Sato and Noda (1992) also found Purkinje cells in the posterior vermis which fire during saccades and pursuit eye movements, but these cells seem to be rare since the activity of only 6.6% (44 units out of 663) was modulated during pursuit eye movements. Of these units, less than 4% were located in the oculomotor vermis (OMV). This last point is important because it led the authors to conclude that the OMV did “not qualify as a structure responsible for the control of smooth pursuit,” a conclusion which contrasts with the recent claim that “the overwhelming majority [81%] of Purkinje cells in the OMV are ‘dual’ PCs responding to both types of goal-directed eye movements” (Sun et al., 2017). Suzuki and colleagues were the first to report neurons which, in the posterior vermis, modulate their firing rate during both saccadic and slow eye movements (Suzuki et al., 1981). They report that “the nature and number [of saccade-related activities in the posterior vermis] indicate that there is only a slight overlap between the population of smooth-pursuit and vision-related units and the population of saccade-related cells previously observed in lobules VI and VII.” The observation that large lesion in the posterior vermis impairs saccadic and pursuit eye movements (Takagi et al., 1998, 2000) does not exclude the possibility of two or three segregated groups of neurons. Therefore, the role of the medioposterior cerebellum in the control of saccadic and slow eye movements requires further investigation. In the brainstem, cells modulating their firing rate during saccades and pursuit have also been reported, notably in the rostral part of the SC (Krauzlis, 2001) toward which the nucleus prepositus hypoglossi and the caudal fastigial nuclei project (Hartwich-Young et al., 1990; May et al., 1990), as well as in the nucleus raphe interpositus (RIP) where pause neurons are located. The two rostral SC participate in adjusting oculomotor commands for maintaining a target within the central visual field (Goffart et al., 2012; Hafed and Krauzlis, 2008; Hafed et al., 2008), a situation which is often encountered when a moving target is being pursued. Concerning the pause neurons, it is commonly believed that they maintain gaze steady during fixation by gating the burst of saccade-related premotor neurons. Unfortunately, this idea will remain speculative as long as the study of its inactivation has not demonstrated the presence of irrepressible saccades during delayed saccade tasks, i.e., when a peripheral target competes with a central one. The observation that pause neurons reduce their firing during the initiation of pursuit eye movements led Missal and Keller (2002) to imagine an inhibitory role of these neurons in pursuit. Unfortunately here again, this option requires further investigation because the reduced firing could merely signal the preparation of a catch-up saccade toward the moving target. Additional studies of the effects of RIP inactivation are also required to identify and characterize the neural networks to which they belong.

8. ENLARGEMENT OF THE NEURONAL MASS FOR ACCURATE TRACKING

Beyond these unknowns, a general neurophysiological process can explain the changes of the saccadic and slow components of oculomotor tracking during repeated exercise. We propose that they result from an expansion of the “mass” of neural activity linked to the visuomotor representation of the central field. Several empirical facts converge to support this hypothesis. First, it is a basic fact that the saccades orient the fovea toward locations situated next to the moving target (e.g., Fig. 3). As a result, neurons which are sensitive to the visual stimulation of the fovea become excited by the presence of the target. When the target is moving, the repeated excitation of these neurons by the catch-up saccades likely contributed to delay the adaptation of their response, and the variability of saccade endpoints enlarged the population of active neurons. Such an enlargement would functionally correspond to an expansion of the central visual field, which is also known to involve neurons in the rostral SC. Thus, the increase in pursuit velocity and the reduction of saccade size observed across the learning sessions (Bourrelly et al., 2016a) could result from an enlargement of the population of active neurons in the rostral portion of the SC. The rostral SC has indeed been shown to be involved in both foveal and parafoveal pursuit (Basso et al., 2000; Hafed et al., 2008; Krauzlis et al., 2000) as well as during fixational saccades (Hafed and Krauzlis, 2012). The parallel facts that a larger target size not only improves the accuracy of pursuit eye movements (Helmick, 1951; Pola and Wyatt, 1985) but also increases the spatial spread of activity in the rostral SC (Goffart et al., 2012; Hafed et al., 2008) are consistent with this hypothesis of enlarged population.

This enlargement could be under the influence of the caudal fastigial nuclei, though nothing excludes the participation of other deep cerebellar nuclei. Concerning the cFN, their pharmacological inactivation is known to impair the generation of pursuit and saccadic eye movements (Bourrelly et al., 2017; Buzunov et al., 2013; Goffart et al., 2004; Robinson et al., 1997), as well as the direction of gaze relative to a fixated target, whether the latter is static (Guerrasio et al., 2010) or moving (Bourrelly et al., 2017; Robinson et al., 1997). This gaze “positional” disorder (called fixation offset) has been proposed to involve the fastigio-collicular connection (Guerrasio et al., 2010; May et al., 1990) because similar fixation offsets are observed in the head-restrained monkey during unilateral inactivation of rostral SC (Goffart et al., 2012; Hafed et al., 2008). But the fastigial involvement in generating accurate pursuit eye movements is not restricted to the fastigio-collicular channel; projections to precerebellar nuclei such as the nucleus reticularis tegmenti pontis or dorsal pontine nuclei have been documented (Batton et al., 1977; Noda et al., 1990; Sugita and Noda, 1991). These nuclei constitute major relays by which motion signals reach the flocculus and paraflocculus for the generation of

pursuit eye movements (Belton and McCrea, 1999; Langer et al., 1985; Mustari et al., 2009; Zee et al., 1981). There again, an enlargement of the population of active neurons could also happen under the control of caudal fastigial nuclei (as recently demonstrated for the control of the saccade size; Goffart et al., 2017b; see also Quinet and Goffart, 2015b) and possibly also of other deep cerebellar nuclei (Robinson and Fuchs, 2001). More fundamentally, regardless of the targeted neural region, an increase of the number of active neurons enhances the probability of synchronous action potentials which, as explained in the second section of this chapter, reduces the transmission delays. Thus, motion signals reach faster the tonic neurons for driving the slow movements of the eyes when a moving target is being tracked.

9. CONCLUSION

In this chapter, a new line of investigation has been proposed to identify the neurophysiological processes which underlie the ability to produce goal-directed eye movements which are accurate, spatially and temporally. We have shown that tracking the location (here and now) of a moving target is not necessarily and spontaneously smooth, that such smoothness is in fact the consequence of training. Because of the visuomotor delays, the ability to generate eye movements which are locked onto the current target location is obviously not possible unless the upcoming trajectory is already known. Several studies have shown that the velocity of slow eye movements hardly match the target speed when an unpredictable target is being tracked (e.g., Bahill et al., 1980; Barnes and Collins, 2015; Deno et al., 1995; Miall et al., 1986; Michael and Melvill-Jones, 1966; Mrotek et al., 2006; St-Cyr and Fender, 1969). The presence of numerous catch-up saccades makes the tracking look intermittent. Moreover, the absence of lead between the gaze and target directions and the frequent lags tell us that the visuomotor brain works with a very short horizon of predictability during visual tracking. Without assuming the existence of “predictive” signals or any encoding of future target locations in the brain activity, we have explained how the spatial synchronization is largely facilitated by the generation of saccades. Finally, considering that “low gain smooth pursuit is a sensitive sign of chronic diffuse brain disease that can be useful in the detection of neurological disorders” (Sharpe, 2008), for those disorders where the action is spatiotemporally detached from the current context, the rehabilitation of neurological patients may be facilitated by the development of strategies to enhance their visuomotor presence.

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613 **REFERENCES**

- 614 Anderson, R.W., Keller, E.L., Gandhi, N.J., Das, S., 1998. Two-dimensional saccade-related
615 population activity in superior colliculus in monkey. *J Neurophysiol* 80 (2), 798–817.
- 616 Bahill, A.T., Iandolo, M.J., Troost, B.T., 1980. Smooth pursuit eye movements in response to
617 unpredictable target waveforms. *Vision Res* 20(11), 923–931.
- 618 Barmack, N.H., 1970. Modifications of eye movements by instantaneous changes in the
619 velocity of visual targets. *Vision Res* 10 (12), 1431–1441.
- 620 Barnes, C.S., 1995. Human eye saccades to targets of low energy. Doctoral thesis, University
621 of Toronto.
- 622 Barnes GR, Collins S., 2015. Influence of predictability on control of extra-retinal components
623 of smooth pursuit during prolonged 2D tracking. *Exp Brain Res* 233(3), 885–897.
- 624 Basso, M.A., Krauzlis, R.J., Wurtz, R.H., 2000. Activation and inactivation of rostral superior
625 colliculus neurons during smooth-pursuit eye movements in monkeys. *J Neurophysiol* 84(2),
626 892–908.
- 627 Batton, R.R., Jayaraman, A., Ruggiero, D., Carpenter, M.B., 1977. Fastigial efferent
628 projections in the monkey: an autoradiographic study. *J Comp Neurol* 174(2), 281-305.
- 629 Becker, W., Fuchs A.F., 1985. Prediction in the oculomotor system: smooth pursuit during
630 transient disappearance of a visual target. *Exp Brain Res* 57(3), 562-575.
- 631 Bell, A.H., Meredith, M.A., van Opstal, A.J., Munoz, D.P., 2006. Stimulus intensity modifies
632 saccadic reaction time and visual response latency in the superior colliculus. *Exp Brain Res*
633 174 (1), 53–59.
- 634 Belton, T., McCrea, R.A., 1999. Contribution of the cerebellar flocculus to gaze control during
635 active head movements. *J Neurophysiol* 81(6), 3105-3109.
- 636 Berthoz, A., 2012. *Simplexity: Simplifying principles for a complex world*. G. Weiss, Trans
637 2012, Yale University Press; New Haven, CT.
- 638 Bourrelly, C., Quinet, J., Cavanagh, P., Goffart, L., 2016a. Learning the trajectory of a moving
639 visual target and evolution of its tracking in the monkey. *J Neurophysiol* 116(6), 2739-2751.
- 640 Bourrelly, C., Quinet, J., Goffart, L., 2016b. Evolution of the oculomotor tracking with an
641 accelerating or decelerating target. *J Vis* 15(12), 1016.
- 642 Bourrelly, C., Quinet, J., Cavanagh, P. and Goffart, L., 2017. Cerebellar control of the ability to
643 track a moving target: role of the fastigial oculomotor region. *Soc. Neurosc. Abstr.* 2017;
644 2017S5712SfN.
- 645 Büttner-Ennever, J., 2005. Neuroanatomy of the oculomotor system. *Progress in Brain*
646 Research Volume 151. Elsevier.

647 Büttner, U., Straube, A., Spuler, A., 1994. Saccadic dysmetria and “intact” smooth pursuit eye
 648 movements after bilateral deep cerebellar nuclei lesions. *J Neurol Neurosurg Psychiatry* 57,
 649 832–834.

650 Buzunov, E., Mueller, A., Straube, A., Robinson, F.R., 2013. When during horizontal saccades
 651 in monkey does cerebellar output affect movement? *Brain Res* 1503, 33-42.

652 Cassanello, C.R., Nihalani, A.T., Ferrera, V.P., 2008. Neuronal responses to moving targets
 653 in monkey frontal eye fields. *J Neurophysiol* 100(3), 1544–1556.

654 Cavanagh, P., Labianca, A.T., Thornton, I.M., 2001. Attention-based visual routines: sprites.
 655 *Cognition* 80 (1-2), 47-60.

656 Deno, D.C., Crandall, W.F., Sherman, K., Keller, E.L., 1995. Characterization of prediction in
 657 the primate visual smooth pursuit system. *Biosystems* 34(1-3), 107-128.

658 Fleuriet, J., Goffart, L., 2012. Saccadic interception of a moving visual target after a
 659 spatiotemporal perturbation. *J Neurosci* 32(2), 452–461.

660 Fleuriet, J., Hugues, S., Perrinet, L., Goffart, L., 2011. Saccadic foveation of a moving visual
 661 target in the rhesus monkey. *J Neurophysiol* 105(2), 883-895.

662 Freedman E.G., Stanford, T.R., Sparks, D.L., 1996. Combined eye-head gaze shifts produced
 663 by electrical stimulation of the superior colliculus in rhesus monkeys. *J Neurophysiol* 76(2),
 664 927–952.

665 Fuchs, A.F., 1967. Saccadic and smooth pursuit eye movements in the monkey. *J Physiol*
 666 191(3), 609–631.

667 Fuchs, A.F., Robinson, F.R., Straube, A., 1994. Participation of the caudal fastigial nucleus in
 668 smooth-pursuit eye movements. I. Neuronal activity. *J Neurophysiol* 72(6), 2714-2728.

669 Gandhi, N.J., Keller, E.L., 1999. Comparison of saccades perturbed by stimulation of the rostral
 670 superior colliculus, the caudal superior colliculus, and the omnipause neuron region. *J*
 671 *Neurophysiol* 82(6), 3236-3253.

672 Glimcher, P.W., Sparks, D.L., 1993. Effects of low-frequency stimulation of the superior
 673 colliculus on spontaneous and visually guided saccades. *J Neurophysiol* 69(3), 953-964.

674 Goffart, L., 2017. Saccadic eye movements: Basic neural processes. In Reference Module in
 675 Neuroscience and Biobehavioral Psychology, Elsevier.

676 Goffart, L., Cecala, A., Gandhi, N., 2016. Does the saccade-related burst in the superior
 677 colliculus convey commands related to the future location of a moving target? *Journal of Vision*
 678 6(12), 98.

679 Goffart, L., Cecala, A., Gandhi, N., 2017. The superior colliculus and the steering of saccades
 680 toward a moving visual target. *J Neurophysiol*, *in revision*.

681 Goffart, L., Chen, L.L., Sparks, D.L., 2004. Deficits in saccades and fixation during muscimol
 682 inactivation of the caudal fastigial nucleus in the rhesus monkey. *J Neurophysiol* 92(6), 3351-
 683 3367.

684 Goffart, L., Hafed, Z.M., Krauzlis, R.J., 2012. Visual fixation as equilibrium: evidence from
685 superior colliculus inactivation. *J Neurosci* 32(31), 10627–10636.

686 Goffart, L., Quinet, J., Bourrelly, C., 2017. Cerebellar control of saccades by the size of the
687 active population in the caudal fastigial nucleus. *Soc. Neurosc. Abstr.*

688 Goffart, L., Quinet J., Chavane, F., Masson G.S., 2006. Influence of background illumination
689 on fixation and visually guided saccades in the rhesus monkey. *Vision Res* 46(1-2), 149–162.

690 Guerrasio, L., Quinet, J., Büttner, U., Goffart, L., 2010. Fastigial oculomotor region and the
691 control of foveation during fixation. *J Neurophysiol* 103(4),1988-2001.

692 Hafed, Z.M., Krauzlis, R.J., 2012. Similarity of superior colliculus involvement in microsaccade
693 and saccade generation. *J Neurophysiol* 107(7),1904-1916.

694 Hafed, Z.M., Krauzlis, R.J., 2008. Goal representations dominate superior colliculus activity
695 during extrafoveal tracking. *J Neurosci* 28(38), 9426-9439.

696 Hafed, Z.M., Goffart, L., Krauzlis, R.J., 2008. Superior colliculus inactivation causes stable
697 offsets in eye position during tracking. *J Neurosci* 28(32), 8124-8137.

698 Hall, W.E., Moschovakis, A.K., 2004. The superior colliculus: new approaches for studying
699 sensorimotor integration. Boca Raton, FL: CRC.

700 Hartwich-Young, R., Nelson, J.S., Sparks, D.L., 1990. The perihypoglossal projection to the
701 superior colliculus in the rhesus monkey. *Vis Neurosci* 4(1), 29-42.

702 Helmick, J.S., 1951. Pursuit learning as affected by size of target and speed of rotation. *J Exp*
703 *Psychol* 41(2),126-138.

704 Henn, V., Lang, W., Hepp, K., Reisine, H., 1984. Experimental gaze palsies in monkeys and
705 their relation to human pathology. *Brain* 107(2), 619–636.

706 Katnani, H.A., Gandhi, N.J., 2012. The relative impact of microstimulation parameters on
707 movement generation. *J Neurophysiol* 108(2), 528-538.

708 Keller, E.L., Gandhi, N.J., Weir, P., 1996. Discharge of superior collicular neurons during
709 saccades made to moving targets. *J Neurophysiol* 76(5), 3573–3577.

710 Keller, E.L., Johnsen, S.D., 1990. Velocity prediction in corrective saccades during smooth
711 pursuit eye movements in monkey. *Exp Brain Res* 80(3), 525–531.

712 Klam, F., Petit, J., Grantyn, A., Berthoz, A., 2001. Predictive elements in ocular interception
713 and tracking of a moving target by untrained cats. *Exp Brain Res* 139(2), 233–247.

714 Krauzlis, R.J., 2001. Extraretinal inputs to neurons in the rostral superior colliculus of the
715 monkey during smooth-pursuit eye movements. *J Neurophysiol* 86(5), 2629-2633.

716 Krauzlis, R.J., 2004. Recasting the smooth pursuit eye movement system. *J Neurophysiol*
717 91(2), 591–603.

718 Krauzlis, R.J., Basso, M.A., Wurtz, R.H., 2000. Discharge properties of neurons in the rostral
719 superior colliculus of the monkey during smooth-pursuit eye movements. *J Neurophysiol* 84(2),
720 876-891.

721 Langer, T., Fuchs, A.F., Scudder, C.A., Chubb, M.C., 1985. Afferents to the flocculus of the
 722 cerebellum in the rhesus macaque as revealed by retrograde transport of horseradish
 723 peroxidase. *J Comp Neurol* 235(1),1-25.
 724 Lee, C., Rohrer, W.H., Sparks, D.L., 1988. Population coding of saccadic eye movements by
 725 neurons in the superior colliculus. *Nature* 332(6162), 357–360.
 726 Lee, J., Kim, H.R., Lee, C., 2010. Trial-to-trial variability of spike response of V1 and saccadic
 727 response time. *J Neurophysiol* 104(5), 2556-2572.
 728 Lisberger, S.G., 1998. Post-saccadic enhancement of the initiation of smooth pursuit eye
 729 movements in monkeys. *J Neurophysiol* 79(4), 1918-1930.
 730 Lisberger, S.G., Westbrook, L.E., 1985. Properties of visual inputs that initiate horizontal
 731 smooth pursuit eye movements in monkeys. *J Neurosci* 5(6), 1662-1673.
 732 Lisi, M., Cavanagh P., 2015. Dissociation between the perceptual and saccadic localization of
 733 moving objects. *Curr Biol* 25(19), 2535-2540.
 734 Lynch, J.C., 2009. Oculomotor control: anatomical pathways. In: *Encyclopedia of*
 735 *Neuroscience*, edited by Squire LR. Oxford, UK: Academic, p. 17–23.
 736 May, P.J., Hartwich-Young, R., Nelson, J., Sparks, D.L., Porter, J.D., 1990. Cerebellotectal
 737 pathways in the macaque: implications for collicular generation of saccades. *Neuroscience*
 738 36(2), 305–324.
 739 Mays, L.E., Sparks, D.L., 1980. Dissociation of visual and saccade-related responses in
 740 superior colliculus neurons. *J Neurophysiol* 43(1), 207-232.
 741 McIlwain, J.T., 1976. Large receptive fields and spatial transformations in the visual system.
 742 *Int Rev Physiol* 10, 223–248.
 743 McIlwain, J.T., 1991. Distributed spatial coding in the superior colliculus: a review. *Vis Neurosci*
 744 6(1), 3-13.
 745 Miall, R.C., Weir, D.J., Stein, J.F., 1986. Manual tracking of visual targets by trained monkeys.
 746 *Behav Brain Res* 20(2): 185-201.
 747 Michael, J.A., Melvill-Jones, G., 1966. Dependence of visual tracking capability upon stimulus
 748 predictability. *Vision Res* 6(12), 707-716.
 749 Missal, M., Keller, E.L., 2002. Common inhibitory mechanism for saccades and smooth-pursuit
 750 eye movements. *J Neurophysiol* 88(4),1880-1892.
 751 Mitrani, L., Dimitrov, G., 1978. Pursuit eye movements of a disappearing moving target. *Vision*
 752 *Res* 18(5), 537-539.
 753 Morrow, M.J., Sharpe, J.A., 1995. Deficits of smooth-pursuit eye movement after unilateral
 754 frontal lobe lesions. *Ann Neurol* 37(4), 443–451.
 755 Moschovakis, A.K., Scudder, C.A., Highstein, S.M., 1996. The microscopic anatomy and
 756 physiology of the mammalian saccadic system. *Prog Neurobiol* 50(2-3), 133-254.

757 Mrotek, L.A., Flanders, M., Soechting, J.F., 2006. Oculomotor responses to gradual changes
 758 in target direction. *Exp Brain Res* 172(2), 175–192.

759 Mustari, M.J., Ono, S., Das, V.E., 2009. Signal processing and distribution in cortical brainstem
 760 pathways for smooth pursuit eye movements. *Ann N Y Acad Sci* 1164, 147-154.

761 Nichols, M.J. and Sparks, D.L., 1995. Nonstationary properties of the saccadic system: new
 762 constraints on models of saccadic control. *J Neurophysiol* 73(1), 431-435.

763 Nichols, M.J. and Sparks, D.L., 1996. Independent feedback control of horizontal and vertical
 764 amplitude during oblique saccades evoked by electrical stimulation of the superior colliculus.
 765 *J Neurophysiol* 76(6), 4080-4093.

766 Noda, H., Mikami, A., 1986. Discharges of neurons in the dorsal paraflocculus of monkeys
 767 during eye movements and visual stimulation 56(4), 1129-1146.

768 Noda H., Sugita S. and Ikeda Y., Afferent and efferent connections of the oculomotor region
 769 of the fastigial nucleus in the macaque monkey, *J. Comp. Neurol.* 302(2), 1990, 330–348.

770 Noda, H., Suzuki, D.A., 1979. The role of the flocculus of the monkey in fixation and smooth
 771 pursuit eye movements. *J Physiol* 294, 335-348.

772 Nowak, L.G., Bullier, J., 1997. The timing of information transfer in the visual system. In
 773 *Extrastriate Cortex* (eds J. Kaas, et al.) pp 205-241. Plenum Press, Vol. 12.

774 Ohtsuka, K., Igarashi, Y., Chiba, S., 1992. Cerebellar peduncle lesion without saccadic
 775 abnormalities. *Int J Ophthalmol* 204(1), 44–48.

776 Optican, L.M., 2009. Oculomotor system: models. In: *Encyclopedia of neuroscience* (Squire
 777 LR, ed.), pp. 25–34. Oxford: Academic.

778 Optican, L.M., Pretegeiani, E., 2017. What stops a saccade? *Philos Trans R Soc Lond B Biol*
 779 *Sci* 372(1718), 20160194.

780 Pellionisz, A., Llinas, R., 1982. Space-time representation in the brain: the cerebellum as a
 781 predictive space-time metric tensor. *Neuroscience* 7(12), 2949–2970.

782 Pierrot-Deseilligny, C., Amarenco, P., Roullet, E., Marteau, R., 1990. Vermal infarct with pursuit
 783 eye movement disorders. *J Neurol Neurosurg Psychiatry* 53(6), 519-521.

784 Pitts, W., McCulloch, W.S., 1947. How we know universals; the perception of auditory and
 785 visual forms. *Bull Math Biophys* 9(3), 127-147.

786 Pola, J., Wyatt, H.J., 1985. Active and passive smooth eye movements: effects of stimulus
 787 size and location. *Vision Res* 25(8), 1063-1076.

788 Quinet, J., Goffart, L., 2015a. Does the brain extrapolate the position of a transient moving
 789 target? *J Neurosci* 35(34), 11780–11790.

790 Quinet, J., Goffart, L., 2015b. Cerebellar control of saccade dynamics: contribution of the
 791 fastigial oculomotor region. *J Neurophysiol* 113(9), 3323-3336.

792 Robinson, D.A., 1965. The mechanics of human smooth pursuit eye movement. *J Physiol*
 793 180(3), 569-591.

794 Robinson, D.A., 1972. Eye movements evoked by collicular stimulation in the alert monkey.
795 Vision Res 12(11), 1795-1808.

796 Robinson, F.R., Fuchs, A.F., 2001. The role of the cerebellum in voluntary eye movements.
797 Annu Rev Neurosci 24, 981-1004.

798 Robinson, F.R., Straube, A., Fuchs, A.F., 1997. Participation of caudal fastigial nucleus in
799 smooth pursuit eye movements. II. Effects of muscimol inactivation. J Neurophysiol 78(2), 848-
800 859.

801 Sato, H., Noda, H., 1992. Posterior vermal Purkinje cells in macaques responding during
802 saccades, smooth pursuit, chair rotation and/or optokinetic stimulation. Neurosci Res 12(5),
803 583-595.

804 Schiller, P.H., 1970. The discharge characteristics of single units in the oculomotor and
805 abducens nuclei of the unanesthetized monkey. Exp Brain Res 10(4), 347-62.

806 Schiller, P.H., Koerner, F., 1971. Discharge characteristics of single units in superior colliculus
807 of the alert rhesus monkey. J Neurophysiol 34(5), 920-936.

808 Schiller, P.H., Stryker, M., 1972. Single-unit recording and stimulation in superior colliculus of
809 the alert rhesus monkey. J Neurophysiol 35(6), 915-924.

810 Schlag, J., Pouget, A., Sadeghpour, S., Schlag-Rey, M., 1998. Interactions between natural
811 and electrically evoked saccades. III. Is the nonstationarity the result of an integrator not
812 instantaneously reset? J Neurophysiol 79(2), 903-910.

813 Schmolesky, M.T., Wang, Y., Hanes, D.P., Thompson, K.G., Leutgeb, S., Schall, J.D.,
814 Leventhal, A.G., 1998. Signal timing across the macaque visual system. J Neurophysiol 79,
815 3272-3278.

816 Sharpe, J.A., 2008. Neurophysiology and neuroanatomy of smooth pursuit: Lesion studies.
817 Brain and Cognition 68(3), 241-254.

818 Sparks, D.L., Holland, R., Guthrie, B.L., 1976. Size and distribution of movement fields in the
819 monkey superior colliculus. Brain Res 113(1), 21-34.

820 Sparks, D.L., Kristan, W.B., Shaw, B.K., 1997. The role of population coding in the control of
821 movement. In: Stein, Grillner, Selverston, and Stuart (eds) Neurons, Networks, and Motor
822 Behavior. MIT Press, pp. 21-32.

823 Sparks, D.L., Lee, C., Rohrer, W.H., 1990. Population coding of the direction, amplitude, and
824 velocity of saccadic eye movements by neurons in the superior colliculus. Cold Spring Harb
825 Symp Quant Biol 55, 805-811.

826 Sparks, D.L., Mays, L.E., 1983. Spatial localization of saccade targets. I. Compensation for
827 stimulation-induced perturbations in eye position. J Neurophysiol 49(1), 45-63.

828 Sparks, D.L. and Mays, L.E., Porter, J.D., 1987. Eye movements induced by pontine
829 stimulation: interaction with visually triggered saccades. J Neurophysiol 58(2), 300-318.

Stanford, T.R., Freedman, E.G., Sparks, D.L., 1996. Site and parameters of microstimulation: evidence for independent effects on the properties of saccades evoked from the primate superior colliculus. *J Neurophysiol* 76(5), 3360–3381.

St-Cyr, G.J., Fender, D.H., 1969 Nonlinearities of the human oculomotor system: time delays. *Vision Res* 9(12), 1491–1503.

Stryker, M.P., Schiller, P.H., 1975. Eye and head movements evoked by electrical stimulation of monkey superior colliculus. *Exp Brain Res* 23(1), 103-112.

Sugita, S., Noda, H., 1991. Pathways and terminations of axons arising in the fastigial oculomotor region of macaque monkeys. *Neurosci Res* 10(2), 118-136.

Sun, Z., Smilgin, A., Junker, M., Dicke, P.W., Their, P., 2017. The same oculomotor vermal Purkinje cells encode the different kinematics of saccades and of smooth pursuit eye movements. *Sci Rep* 7, 40613.

Suzuki, D.A., Keller, E.L., 1988. The role of the posterior vermis of monkey cerebellum in smooth-pursuit eye movement control. II. Target velocity-related Purkinje cell activity. *J Neurophysiol* 59(1),19-40.

Suzuki, D.A., Noda, H., Kase, M., 1981. Visual and pursuit eye movement-related activity in posterior vermis of monkey cerebellum. *J Neurophysiol* 46(5), 1120-1139.

Takagi, M., Zee, D.S., Tamargo, R.J., 1998. Effects of lesions of the oculomotor vermis on eye movements in primate: saccades. *J Neurophysiol* 80(4),1911-1931.

Takagi, M., Zee, D.S., Tamargo, R.J., 2000 Effects of lesions of the oculomotor cerebellar vermis on eye movements in primate: smooth pursuit. *J Neurophysiol* 83(4), 2047-2062.

Van Rullen, R., Guyonneau, R., Thorpe S.J., 2005. Spike times make sense. *Trends Neurosci* 28(1), 1-4.

Wurtz, R.H., Goldberg, M.E., 1972. Activity of superior colliculus in behaving monkey. 3. Cells discharging before eye movements. *J Neurophysiol* 35(4), 575-586.

Wurtz, R.H., Goldberg, M.E., 1989. The neurobiology of saccadic eye movements. Volume 3 of *Reviews of oculomotor research*. Elsevier.

Zee, D.S., Yamazaki, A., Butler, P.H., Gücer, G., 1981. Effects of ablation of flocculus and paraflocculus of eye movements in primate. *J Neurophysiol* 46(4), 878-899.

FURTHER READING

Cavanagh P. and Alvarez G.A., Tracking multiple targets with multifocal attention. *Trends Cogn. Sci.* 9(7), 2005, 349-354.

Cavanagh P., Labianca A.T. and Thornton I.M., Attention-based visual routines: sprites, *Cognition* 80 (1–2), 2001, 47–60.

FIGURE LEGENDS

Figure 1: Effect of target contrast on the latency of saccades. Time course of the horizontal component of saccades aimed at a static target LED located 8 to the right in a dimly illuminated room. A gap interval separated the fixation of a central target from the onset of the brief peripheral target (50 ms duration). Additional methodological information can be found in Goffart et al., (2006).

Figure 2: Saccades evoked by electrical microstimulation of one site in the deep superior colliculus. A: Reducing the rate of stimulation pulses (from 500 to 300 pulses per second) increases the latency of evoked saccades. B: The saccades (same as in A) have identical velocity profiles. C: Reducing further the rate of stimulation pulses (from 300 to 200 pulses per second) made the latencies of evoked saccades even longer and more variable. D: Increasing the current of stimulation reduces the latency of saccades.

Figure 3: Comparison of targeting errors between saccades toward a static versus a moving target. During the static target trials, the target appeared at locations comparable to those travelled by the moving target. The error is plotted as a function of the duration of the largest saccade component, i.e., the component orthogonal to the motion (when the target is moving). In A, the target moved horizontally toward the left or the right, from locations situated 8 or 16 degrees along the vertical meridian. In B, the target moved vertically upward or downward, from locations situated 8 or 16 degrees along the horizontal meridian. Negative values correspond to a hypometria (undershoot). Data collected in one monkey (N). Additional information can be found in Fleuriet et al., (2011).

Figure 4: Time course of horizontal and vertical eye movements toward a temporarily invisible target. The target moved horizontally away from the vertical meridian, to the left (A,C) or to the right (B,D), in the upper (top) or lower (bottom) visual field, and with a constant speed (20°/s). After a short interval of 150 ms, the target disappeared during 300 ms (grey zone) and reappeared at the location where it would have been if always visible, moving at the same speed. The black traces correspond to control trials, the blue traces to perturbed trials. During these trials, the trajectory of interceptive saccades was perturbed by a brief electrical microstimulation (30 ms, 12μA, 400 pps) in the deep superior colliculus. The black arrows indicate the electrically-evoked saccade (perturbation). The green and blue arrows indicate catch-up saccades made while the target is invisible during control and perturbed trials, respectively. Additional methodological information can be found in Fleuriet and Goffart (2012).

903

904 Figure 5: Typical oculomotor behaviour of a monkey tracking a visual target moving horizontally
905 with a constant speed. The horizontal eye position is plotted as a function of time after the
906 target motion onset for three trials recorded during the first (left column: Beginning) and last
907 training sessions (right column: End). The time course of horizontal target position is illustrated
908 by the red line. The selected trials were recorded in 5 monkeys (A, B, C, M and G: from top to
909 bottom, respectively) when the target moved in the upper right quadrant with a constant speed
910 ($20^\circ/\text{s}$). During the other randomly interleaved trials, the target moved similarly, horizontally
911 and away from the vertical meridian, but in the lower right, the lower left or the upper left
912 quadrant. Additional methodological information can be found in Bourrelly et al. (2016a).

913

914 Figure 6: Typical oculomotor behaviour of a monkey tracking an accelerating visual target. The
915 horizontal eye position is plotted as a function of time after the target motion onset for three
916 trials recorded during the first (left column: Beginning) and last training sessions (right column:
917 End). The time course of horizontal target position is illustrated by the red line. The selected
918 trials were recorded in 5 monkeys (A, B, C, M and Bi: from top to bottom, respectively) when
919 the target moved horizontally in the upper right quadrant with a speed which increased from 0
920 to $40^\circ/\text{s}$ during 800ms. During the other randomly interleaved trials, the target moved similarly,
921 horizontally and away from the vertical meridian, but in the lower right, the lower left or the
922 upper left quadrant. The experimental protocol is identical to that described in Bourrelly et al.
923 (2016a).

Figure 1
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Figure 2
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Figure 3
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Figure 4
Goffart, Bourelly and Quinet *Prog Brain Res* 2017

Beginning

Figure 5

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End

Monkey A

Monkey B

Monkey C

Monkey M

Monkey G

Time (ms)

Time (ms)

Beginning

Figure 6

Goffart, Burreilly and Quinet Prog Brain Res 2017

End

Monkey A

Monkey B

Monkey C

Monkey M

Monkey Bi

Time (ms)

Time (ms)