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6 Neurophysiology of gaze orientation: 7 Core neuronal networks

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13 Summary

14 The appearance of an object in the visual field triggers a shift of gaze toward its location. This
15 orienting response consists of a rapid rotation of the eyes, the saccade, which can be
16 accompanied by a rotation of the head. If the target moves, the saccade is followed by a slow
17 movement of the eyes and a catch-up saccade. In this chapter, instead of describing the path
18 leading from the target-evoked retinal activity to the changes in muscle tension, we shall take
19 the reverse path. Starting from the muscle contractions, we shall proceed upstream and
20 describe the tremendous organization that, in the brainstem and cerebellum, enables us to
21 rapidly and accurately orient the foveae towards visual targets located at different
22 eccentricities and depths. This chapter is an attempt to synthesize the considerable
23 knowledge that neurophysiologists and neuroanatomists gathered in the monkey during the
24 last six decades.

25
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27

57 The situation is more complicated when gaze moves vertically. Vertical movements
58 involve not only steady tension of LR and MR muscles, but also a complex cooperation
59 between the four other muscles. The contraction of superior and inferior rectus muscles
60 elevate and depress each eye, respectively. These actions are stronger when the eye is in
61 abduction. The contraction of oblique muscles causes torsional movements but also elevate
62 or depress the eye, more strongly when the eye is in adduction. If we consider the movements
63 made when the eyes are centered in the orbit, in addition to elevating the optic axis (turquoise
64 arrows in Fig. 1B), the contraction of the superior rectus (SR) muscle fibers causes adduction
65 (black arrows) and intorsion (blue arrows) of the eyeball. Likewise, in addition to lowering the
66 optic axis (yellow arrows in Fig. 1B), the contraction of the inferior rectus (IR) muscle fibers
67 causes adduction and extorsion (green arrows). These secondary actions can be counteracted
68 by the contraction of oblique muscles, for the contraction of inferior oblique (IO) muscle fibers
69 causes elevation, abduction and extorsion of the eyeball, whereas the contraction of superior
70 oblique (SO) muscle fibers causes depression, abduction and intorsion.

71 Binocular conjugate movements are made when the head rotates while a visual target
72 is being fixated (vestibulo-ocular reflex), when the visual surround is moving (optokinetic
73 reflex) and whenever a target appears or is imagined in the peripheral visual field (saccades).
74 We shall first examine the neurophysiology of saccade generation when the head does not
75 move. Then, we shall study the case when a head rotation accompanies the saccade. During
76 these combined eye-head movements, two couplings can happen: the eyes and the head
77 move either in the same direction or in opposite directions. Next, we shall see the
78 neurophysiology of disconjugate movements of the eyes, which occur when gaze is shifted
79 between targets located at different depths (vergence eye movements). Finally, we shall have
80 an overview of the complex network that enables one to fixate and track a moving target, i.e.,
81 an object whose spatial coordinates keep changing. (smooth pursuit eye movements).

82 Binocular conjugate movements

83 Horizontal saccades

84 Figure 2 schematizes the current view of the premotor neurophysiology of horizontal
85 saccades in the pontine and mesencephalic reticular formation. During leftward saccades (Fig.
86 2A), the fast-twitch muscle fibers of the right eye's MR and of the left eye's LR contract while

87 those of antagonist muscles (right eye's LR and left eye's MR) relax. Motor neurons in the
88 abducens nucleus (ABD, located in the pontine reticular formation) and in the oculomotor
89 nucleus (OMN in the midbrain tegmentum) emit bursts of action potentials that respectively
90 cause the phasic contraction of muscle fibers. The burst discharge of cells in the OMN is
91 triggered and supported by spikes emitted by internuclear neurons (AIN) also located in the
92 abducens nucleus. In return, the bursts of abducens motor (MN) and internuclear (AIN)
93 neurons are driven by afferent input from excitatory burst neurons (EBN) located in the
94 ipsilateral paramedian pontine reticular formation (PPRF, synapses a). The abducens neurons
95 also receive excitatory input from internuclear burst-tonic neurons in the contralateral
96 oculomotor nucleus (not shown). Discharging during saccades and increasing their firing rate
97 during convergence, these cells are possibly involved in the motor drive for conjugate
98 saccades because in addition to cause exophoria, lidocaine injection in the medial rectus
99 subdivision of the oculomotor nucleus causes hypometria and slowing of abducting saccades
100 of the contralateral eye.

101 Otherwise silent, the EBN fire trains of action potentials whose interspike interval is
102 smaller for larger saccades. Contrary to statements found in numerous review articles, the
103 instantaneous firing rate of EBN is not a replica of instantaneous eye velocity. For each
104 saccade, the interspike interval is much more constant than expected if this claim were true
105 (i.e, that EBN rate equals instantaneous eye velocity). The suggestion that the firing rate of
106 motor neurons would alone determine the instantaneous eye velocity is also brought into
107 question by a study in the cat, which showed that a model factoring in muscle tension and its
108 first derivative accounted for the firing rate of motor neurons better than a model factoring
109 in eye position and its first and second derivatives (velocity and acceleration).

110 Regarding the relaxation of antagonist muscles, it results from a pause in the firing of
111 motor neurons innervating them. This pause is itself caused by inhibitory input from burst
112 neurons (IBN) located in the ipsilateral dorsal paragigantocellular reticular formation (dPGRF,
113 synapses b). In addition to bursting during ipsiversive horizontal saccades (so called "on-
114 direction" response), approximately half of these inhibitory burst neurons also emit spikes
115 during contralateral horizontal saccades (off-direction response). Thus, the agonist motor
116 drive is a combination of excitatory and inhibitory presynaptic input from the ipsilateral EBN
117 and contralateral IBN, respectively. The relative strength of these antagonist premotor inputs

118 is under the descending influence of saccade-related burst neurons located in regions involved
119 in other functions, such as the left and right caudal fastigial nuclei (located in the medial
120 cerebellum) and the contralateral deep superior colliculus (in the midbrain tectum). The
121 bilateral fastigial input exerts an influence that is more modulatory than the collicular
122 influence because, contrary to lesions in the superior colliculus, fastigial lesions do not
123 suppress or delay the generation of saccades.

124

Figure 2 about here

125 During rightward saccades (Fig. 2B), the active circuit is mirror reversed. The agonist
126 muscles are the right eye's LR and the left eye's MR, whereas the antagonist muscles are the
127 right eye's MR and the left eye's LR. IBN in the right dPGRF cause the relaxation of antagonist
128 muscles. Under the excitatory influence of EBN in the right PPRF and the inhibitory influence
129 of IBN in the left dPGRF, motor and internuclear neurons in the right abducens nucleus provide
130 the motor commands to the ipsilateral LR and contralateral MR, respectively. The circuits
131 producing rightward and leftward saccades are presumably not completely symmetric insofar
132 as the number of active neurons and the number of synapses and neuromuscular junctions
133 likely differ between them. By contrast, we shall see next that the networks involved in the
134 generation of downward and upward eye movements are not at all symmetrical with respect
135 to each other.

136 Vertical cardinal saccades

137 The neuronal network underlying the generation of vertical saccades is located in the
138 midbrain tegmentum. For upward saccades (Fig. 3A), the agonist muscles are the IO and the
139 SR and the antagonist muscles the IR and the SO. As reported above, in addition to elevating
140 the eye, the contraction of SR muscle fibers causes intorsion, whereas contraction of IO
141 muscle fibers causes extorsion. Thus, the intorsion caused by the motor commands to the SR
142 combines with the extorsion caused by the commands to the IO. The observation of negligible
143 torsional component during upward saccades suggests that the two torsions cancel each other
144 out. Such a balance of force likely involves bilateral activity in the midbrain because for each
145 eye, the motor neurons innervating the SR muscle are located in the contralateral OMN
146 whereas the motor neurons innervating the IO muscle are located in the ipsilateral OMN. The

147 two sets of commands during upward saccades must be adjusted in a timely manner, and any
148 asymmetry in the bilateral motor drive would engender a torsional component.

149 **Figure 3 about here**

150 The excitatory commands responsible for generating upward saccades are issued by
151 burst neurons located in the left and right rostral interstitial nucleus of the medial longitudinal
152 fasciculus (RIMLF). These commands are doubly bilateral. Indeed, on the one hand, the burst
153 emitted by premotor neurons (uEBN) in the left RIMLF excite the motoneurons innervating
154 the SR muscles of *both* eyes (black synapses a) and motor neurons innervating the IO muscles
155 of *both* eyes as well (black synapses b in Fig. 3). On the other hand, the burst emitted by uEBNs
156 in the opposite RIMLF excite the same motoneuronal group (blue synapses a and b).
157 Moreover, in addition to recruiting the motor neurons, the uEBN also excite neurons that
158 inhibit the motor neurons that innervate the antagonist muscles (IR and SO, synapses c).
159 Located in the interstitial nucleus of Cajal, these cells (uIBN) inhibit the motor neurons in the
160 contralateral oculomotor nucleus, i.e., cells responsible for the contraction of the IR of the
161 contralateral eye (synapses d) and motor neurons responsible for the contraction of the SO of
162 the ipsilateral eye (synapses e). However, contrary to uEBN, uIBN do not send bilateral
163 projections to the motor neurons innervating the SO muscle fibers. Their projection make
164 synaptic contacts only with motor neurons on the contralateral side.

165 As for the upward saccades, the discharge of neurons located in each side of the brain
166 is capable of causing a downward movement of *both* eyes (Fig. 3B). The premotor excitatory
167 burst neurons leading to downward saccades (dEBN) are also located in the RIMLF. However,
168 unlike the uEBN, the dEBN do not send bilateral projections to the motoneurons; their
169 projection is ipsilateral only. During downward saccades, the SO and IR muscle fibers of *both*
170 eyes contract because the dEBN excite 1) the motor neurons in the ipsilateral OMN, which
171 cause the contraction of IR muscle fibers of the *ipsilateral* eye (synapses a), and 2) the motor
172 neurons which, in the ipsilateral trochlear nucleus, cause the contraction of SO muscle fibers
173 of the *contralateral* eye (synapses b). Moreover, in addition to lowering the eyes, the
174 contraction of SO muscle fibers causes an intorsion of the eye while the contraction of IR
175 muscle fibers causes their extorsion. The commands from the ipsilateral OMN for extorsion
176 combine with commands from the contralateral trochlear nucleus for intorsion. Precisely how

177 these opposite torsional components cancel each other out during downward saccades
178 remains unexplained. A bilateral adjustment at the level of premotor burst neurons seems
179 inevitable. Moreover, the neural processes in charge of the relaxation of antagonist muscles
180 during downward saccades remain to be characterized.

181 Even though the number of cells and the number of synaptic boutons likely differ
182 between the left and right sides of the reticular formation, the connectivity patterns involved
183 in generating leftward and rightward eye movements are symmetrical with respect to the
184 brainstem midsagittal plane (see Fig. 2 and 5). By contrast, the networks involved in the
185 generation of downward and upward eye movements are not symmetrical with respect to the
186 midsagittal plane (Fig 3).

187 During vertical saccades, the EBN involved in the generation of horizontal saccades do
188 not fire. Some IBN in the dPGRF emit action potentials whose number increases with the
189 saccade size. For vertical saccades to remain straight while their size increases, one possibility
190 is that the motor and internuclear cells in the abducens nucleus emit additional spikes, thus
191 reducing the contrapulsive effect of IBN spikes. This does not seem to be the case because
192 MN and AIN in the abducens nucleus do not emit action potentials during vertical saccades. A
193 more likely possibility is that the contrapulsion exerted by IBN in the left and right dPGRF
194 cancel each other out. If no perfect symmetry exists between the set of active neural elements
195 (number of neurons and of synaptic boutons) located on each part of the reticular formation,
196 then the observation of strictly vertical saccades leads us to infer that a process adjusts the
197 bilateral activity of IBN during vertical saccades.

198 This bilateral control is not restricted to the group of IBNs, which are primarily involved
199 in the generation of horizontal saccades. In addition to elevating both eyes, the discharge of
200 motor neurons in the right OMN causes, as a secondary action and via the contraction of the
201 right eye's IO and the left eye's SR, a rightward deflection of both eyes during vertical saccades
202 while the discharge of motor neurons in the opposite side causes a leftward deflection (Fig.
203 3A, top row). Likewise, in addition to lowering both eyes, the dEBN in the right RIMLF lead to
204 the contraction of the left eye's SO and the right eye's IR, causing a leftward deflection of their
205 trajectory while dEBN in the left RIMLF cause a rightward deflection during vertical saccades
206 (Fig. 3B, top row). The observation of straight vertical saccades (with no horizontal deviation)

207 implies that the horizontal deflections caused by the secondary action of the muscles elevating
208 or depressing the eyes are also canceled in the motor drives.

209 Therefore, the generation of straight vertical saccades rests upon a balance of bilateral
210 motor activation, which itself depends upon an adjustment of premotor commands that takes
211 into account the structural (neurons and their connectivity) and functional (firing properties,
212 secondary and tertiary consequence of muscle contractions) asymmetries between the
213 oculomotor territories that are distributed on either side of the brain stem. The saccade-
214 related neurons in the left and right fastigial nuclei and in the oculomotor vermis regulate this
215 bilateral balance. Indeed, most of them burst during vertical saccades and their asymmetrical
216 perturbation horizontally deflects the trajectory of vertical saccades. Bilateral activity in the
217 two deep superior colliculi is also involved with their medial halves for driving upward
218 saccades and their lateral halves driving downward saccades. The contribution of the deep
219 superior colliculi and of the caudal fastigial nuclei differ insofar as horizontal saccades involve
220 activity of bursting cells in only the superior colliculus on the contralateral side, whereas
221 saccade-related neurons burst in the caudal fastigial nuclei on both sides.

222 Combined horizontal and vertical saccades

223 When a target appears off the cardinal visual axes, the orienting response does not
224 consist of horizontal and vertical saccades made in sequential order. Both horizontal and
225 vertical components are generated in such a manner that their onset and offset are relatively
226 simultaneous. These combined horizontal-vertical saccades are conventionally called
227 “oblique” saccades. Considering the muscle diversity (lengths, contractile properties and
228 orbital attachments) involved in the horizontal and vertical components and the fact that their
229 motor innervations are not located in nearby regions of the brainstem, their simultaneous
230 onsets and the limited curvature of their spatial trajectory are empirical observations
231 suggesting coupling mechanisms.

232 In the medial pontine reticular formation, the nucleus raphe interpositus (RIP) hosts a
233 population of cells that exhibit a sustained firing rate during intersaccadic intervals but pauses
234 during all saccades, regardless of their direction and amplitude. These cells are called
235 omnidirectional pause (or omnipause) neurons (OPN) and are thought to prevent the eyes
236 from moving during visual fixation through their inhibitory post-synaptic influence upon the

237 premotor burst neurons (Fig. 2). Moreover, with their pause, OPN could also be responsible
238 for the synchronous onsets of horizontal and vertical saccades, as they project to burst
239 neurons in both the horizontal and vertical gaze centers. So far, however, experimental
240 studies have failed to document onset asynchronies during inactivation or lesion of RIP. No
241 fixation instability was reported either. The absence of deficits in visual fixation may have
242 resulted from the particular testing conditions. Indeed, the consequence of suppressing OPN
243 sustained activity during delayed or memory-guided saccade tasks was not tested. Indeed, the
244 observation of irrepressible saccades to the peripheral target during the delay interval would
245 unambiguously confirm the role of OPN in visual fixation; a result that electrical
246 microstimulation studies have suggested. Unfortunately, these stimulation studies are not
247 sufficiently conclusive because it is possible that the interruption and the delaying of saccades
248 by electrical stimulation result from undesired retrograde recruitment of inhibitory burst
249 neurons.

250 Turning back to the generation of combined horizontal and vertical saccades, one
251 study reported crucial observations signaling a process that couples their time course during
252 oblique saccades. When the horizontal component is experimentally slowed by the local
253 injection of a pharmacological agent in the pontine reticular formation, the vertical
254 component was also slowed. In some of these experiments, the duration of both components
255 was prolonged and the accuracy of saccades was preserved, supporting further the
256 persistence and preservation of the target-related commands. The neural connectivity
257 underlying this “component stretching mechanism” have not yet been elucidated.

258 Combined eye and head movements

259 Saccades are frequently associated with a head movement when the target
260 eccentricity approaches and exceeds the limits of the oculomotor range. Moving the head
261 enable to look at targets located more eccentrically in the visual field, and to re-centers the
262 eyes in their orbit. The directions of the eyes in the orbit and of the head relative to the trunk
263 add together to determine the direction of gaze.

264 Two functional modes characterize orienting gaze movements toward a static target:
265 a mode during which both eyes and the head rotate in the same direction and a mode during
266 which they move in opposite directions. The second mode happens sometimes when the head

267 movement precedes the eye saccade, mostly when the target location is known or
268 foreseeable. More frequently, it happens later because the eyes move much faster than the
269 head. The equilibrium of bilateral activity that characterizes visual fixation has been reached
270 before the head has terminated its movement. Before describing how gaze is stabilized at the
271 end of orienting movements, we shall examine the first mode, i.e., how despite the vestibulo-
272 ocular reflex, the eyes and the head can move in the same direction during horizontal gaze
273 shifts (Figure 4).

274 Combining a head movement with a saccade

275 In this section, we limit our description to the horizontal eye movements that are made
276 while the head also moves horizontally. Whether the head is moving or not, behavioral studies
277 show that the gaze movements are equally accurate. In the monkey, around twenty muscles
278 are involved to change the orientation of the head. Among them are the muscles whose
279 contraction changes the orientation of the head relative to the trunk, the muscles that
280 stabilize the head during its rotation and the muscles that do not exhibit any change. The co-
281 contraction of the left and right *rectus capitis posterior minor* (RCPm) stabilize the atlas while
282 the contraction of the *rectus capitis posterior major* (RCPM) and *obliquus capitis inferior* (OCI)
283 produce an ipsilateral horizontal rotation of the head. The observation that the contralateral
284 muscles exhibit no electromyographic change indicates that stopping the head rotation is not
285 caused by muscle co-contraction. For movement amplitudes greater than 20 degrees, the
286 contraction of the *splenius capitis* muscle adds to that of the RCPM and OCI muscles. At the
287 end of the orienting movement, the co-contraction of the RCPm, RCPM, OCI and *obliquus*
288 *capitis superior* (OCS) muscles altogether stabilizes the head.

289 Thus, orienting gaze shifts mobilize several muscles in parallel when a movement of
290 the head accompanies the saccade. The synergy results from activities distributed within a
291 complex set of motor and premotor neurons located in the reticular and vestibular nuclei.
292 Contrary those involved in the cat, the premotor processes remain incompletely characterized
293 in the monkey. Contemporary knowledge is not sufficient to reach a synthetic understanding
294 that is comparable to the neurophysiology of saccades.

295 The recruitment of EBN and reticulo-spinal neurons (RSN) by descending commands
296 from bursting cells in the deep superior colliculus (grey-colored synapses a in Fig. 4) leads to

297 the excitation of the pools of extraocular motoneurons (ABD) in the abducens nucleus and
298 neck motoneurons (NMN) in the cervical spinal cord (green and blue synapses b), and thus, to
299 the contraction of the agonist extraocular and neck muscle fibers, respectively. Contrary to
300 the cat, collicular connections with EBN do not seem to be direct in the monkey. The EBN and
301 RSN also excite the IBN (synapse a'), thereby suppressing the activity of cells that otherwise
302 act to facilitate the contraction of antagonist extraocular (synapses c) and neck muscles
303 (synapse g), respectively. Finally, they also excite secondary vestibular neurons which are
304 inhibitory (IVN-2; blue and green colored synapses d) and located in the ipsilateral medial
305 vestibular nucleus. Within the vestibular nuclei, the discharge of IVN-2 inhibits the secondary
306 vestibular neurons, IVN-1 and EVN-1 (purple-colored synapse e). By inhibiting IVN-1, the
307 motor neurons innervating the agonist extraocular and neck muscles fibers (red synapses f
308 and f') are disinhibited, and the contraction of these muscles is facilitated. By inhibiting the
309 EVN-1, the IVN-2 prevent the primary vestibular neurons (PVN), whose firing is enhanced by
310 the head movement, from causing a counter-rotation of the eyes in the orbits (synapse h).
311 The contraction of antagonist neck muscles through vestibulospinal pathways is also
312 prevented (synapse h').

313 **Figure 4 about here**

314 Stopping gaze while the head terminates its motion

315 The second mode of combined eye head movements is reminiscent of the vestibulo-
316 ocular reflex recorded when the head is passively rotated while subjects maintain their gaze
317 directed toward a visual target. During active eye and head movements, the premotor input
318 to motor neurons makes a transition from commands fed by target-related (visual or auditory)
319 signals to commands fed by head movement-related signals. The latter consist of trains of
320 action potentials that originate in the three semicircular canals buried within the temporal
321 bone. Each semicircular canal consists of a ring within which a fluid (endolymph) flows and
322 mechanically deflects the stereocilia of multiple cells whenever the head rotation accelerates
323 or decelerates. This deflection either increases or decreases the discharge of primary
324 vestibular neurons (PVN) with a rate proportional to head velocity.

325 The two lateral canals are located in the left and right inner ears and lie roughly in a
326 "plane" which is tilted not only relative to the Reid plane, but also to the "plane" passing

327 through the medial and lateral rectus muscles. These canals are often called “horizontal”
328 because they are primarily activated during head rotations about the Earth gravity axis. During
329 such rotations, PVN on the side toward which the nose is rotating (ipsilateral side) increase
330 their firing rate while those on the contralateral side decrease their firing rate. These bilateral
331 changes modify the firing rate of post-synaptic neurons (secondary vestibular neurons)
332 located in the medial and superior vestibular nuclei. On either side of the brain’s midsagittal
333 plane, these nuclei are bilaterally organized and house two categories of neurons: type 1 and
334 type 2 neurons. Type 1 neurons increase their firing rate during head rotations toward the
335 side (left or right) containing the nucleus in which their discharge is recorded. During
336 contraversive head rotations, they decrease their discharge. In addition, they pause during
337 saccades. In the monkey, these neurons have been called Position Vestibular Pause (PVP)
338 neurons. Type 2 neurons exhibit the opposite pattern, increasing their firing rate during
339 contraversive head rotations and decreasing it during ipsiversive head rotations.

340 **Figure 5 about here**

341 Figure 5 schematizes the mechanism by which vestibular signals contribute to ending
342 a leftward movement of gaze toward a visual target. The end of the orienting movement is
343 characterized by a time interval during which the gaze direction remains stationary relative to
344 the trunk while the head slowly terminates its motion. The saccades by both eyes give way to
345 their rotation in the opposite direction. As the head rotates, the primary vestibular neurons
346 (PVN) excite the type I vestibular neurons (EVN-1) in the ipsilateral medial and ventrolateral
347 vestibular nuclei. In turn, the EVN-1 initiate and drive the counter-rotation of both eyes in the
348 orbit by exciting the motor (LRMN) and internuclear (AIN) neurons in the contralateral
349 abducens nucleus (red-colored synapses a). Thus, the abducens neurons can resume their
350 activity from the pause imposed by the inhibitory input from IBN in the left Med RF (see blue-
351 colored synapses b in Fig. 2). The LR muscle fibers of the right eye can contract, as well as the
352 MR muscle fibers of the left eye, which are activated via motoneurons located in the OMN.
353 The latter cells (MRMN) are also excited by neurons in the ipsilateral nucleus of the ascending
354 tract of Deiters (ATDN; green-colored synapse b). In parallel, the spikes emitted by other type
355 1 vestibular neurons (IVN-1) choke the activity the LRMN and AIN in the abducens nucleus
356 (red-colored synapses c), preventing them from responding to any residual descending
357 (target-related) commands. The recruitment of type 2 neurons (IVN-2) in the contralateral

388 In addition to elevating both eyes, the contraction of these fibers causes an intorsion
389 of the left eye and an extorsion of the right eye, as if both eyes were counteracting a tilt of the
390 head toward the left shoulder. This clockwise torsion of both eyes can be attenuated by the
391 torsion caused by the excitatory input from EVN-U in the right MVN. Because of their
392 excitation by the right anterior canal, PVN drive the firing rate of EVN-U, which in turn excite
393 the motor neurons that innervate the right eye's SR and the left eye's IO muscle fibers
394 (synapses b), causing the right eye's intorsion and left eye's extorsion. The absence of torsion
395 during strictly upward slow eye movements suggests that the output of the left and right
396 vestibulo-oculomotor channels have been adjusted so that the torsional signals balance out.

397 Regarding the antagonist muscles, their inhibition is promoted by IVN-U located in the
398 superior vestibular nuclei. These cells inhibit the motor neurons innervating the IR of the
399 ipsilateral eye (synapses c) and those innervating the SO muscle of the contralateral eye
400 (synapse d). Contrary to the network involved in horizontal eye and head movements (Fig. 5),
401 the neural mechanisms triggering the counter-rotation of the eyes when the head pitches
402 down are not yet elucidated. However, the inputs are necessarily bilateral and balanced since
403 the eyes move by the same amount and their torsion canceled.

404 Finally, figure 6B schematizes the neuronal network involved in stopping an upward
405 gaze shift while the head slowly terminates its upward motion. Both eyes rotate downward in
406 the orbits because of the contraction of IR and SO muscle fibers. This is driven by the increased
407 firing of primary vestibular neurons (PVN) connected with the left posterior canal. Excitatory
408 vestibular neurons (EVN-D) in the left medial vestibular and ventral lateral vestibular nuclei
409 activate the motor neurons innervating the fibers of the right eye's IR and the left eye's SO
410 muscles (synapses a).

411 As above, in addition to depressing both eyes, the contraction of these fibers cause an
412 extorsion of the right eye and an intorsion of the left eye, as if the eyes are counteracting a tilt
413 of the head toward the right shoulder. Once again, the binocular torsion is attenuated by a
414 torsion made in the opposite direction and caused by excitatory input from the right posterior
415 canal to the motor neurons innervating the left eye's IR and the right eye's SO muscle fibers
416 (synapses b). Inhibitory vestibular neurons (IVN-D) located in the superior vestibular nuclei
417 prevent the antagonist muscles from contracting by inhibiting the motor neurons innervating

418 the SR of the contralateral eye (synapses c) and possibly also the motor neurons innervating
419 the IO muscle of the ipsilateral eye (synapse d). As for the neural mechanisms ending
420 downward gaze shifts, the neural mechanisms triggering the counter-rotation of the eyes
421 when the head pitches up are not completely identified. Nevertheless, if the eyes do not
422 exhibit any torsional component, the motor commands are necessarily bilateral and balanced.

423 In summary, by studying the networks underlying the generation of slow eye
424 movements, we discover a complexity that radically differs from the straightforward solutions
425 that human engineers would have designed. One puzzling question concerns the constraints
426 that led the torsional components caused by the contraction of elevator or depressor muscles
427 to cancel each other out. Moreover, the connectivity that we have described is not complete,
428 because new eye movements can be produced in response to “unusual” combinations of head
429 rotations and visual stimulation. Experiments in the cat have shown that the visual stimulation
430 exerts a significant influence on the functional connectivity yielding vestibulo-oculomotor
431 responses. Horizontal compensatory eye movements can be generated during vertical head
432 rotations in the dark after training sessions during which the visual field moved horizontally
433 whenever the head rotated vertically.

434 Fixating a static visual target

435 Considering the line of sight as the direction of gaze measured when a subject fixates
436 a visual target, the binocular fixation point designates the intersection between the two lines
437 of sight. Of course, the quantification of movements must be distinguished from their
438 neurophysiological correspondence. On the retinal side, looking at a visual target obviously
439 does not reduce to the excitation of one single photoreceptor on the fovea of each eye. On
440 the oculomotor side, the orientation of the eyes is maintained steady thanks to the discharge
441 of a tonic neurons distributed in the nucleus prepositus hypoglossi (NPH), the vestibular nuclei
442 (in the medullary reticular formation) and in the interstitial nucleus of Cajal. The more
443 deviated the eyes in the orbit, the higher their firing rate. In addition to connective tissues
444 that stabilize each eyeball relative to the orbit, two neuronal networks are involved in
445 maintaining the rotation axes of the eyes within Listing’s plane and deviating them
446 horizontally and vertically. These networks are relatively independent from each other insofar
447 as a lesion in the NPH primarily affects the ability to maintain gaze direction within the

448 horizontal plane, with marginal effects on vertical gaze direction. After the saccades, whose
449 amplitude is unaffected, the eyes exhibit an exponential drift toward their primary orientation
450 (roughly straight ahead). By contrast, lesion in the NIC causes a failure to hold vertical
451 deviations of the eyes (i.e. both upward and downward) but not horizontal deviations. A
452 torsional drift of the eyes is also observed when the lesion is unilateral.

453 Considering now the case when the foveation changes between targets or locations
454 situated at different depths in the three-dimensional physical space, three visuomotor
455 processes occur: 1) vergence, 2) accommodation and 3) variation of pupil diameter.
456 Convergence designates the symmetrical eye movements made when the MR muscle fibers
457 of both eyes contract, diminishing the distance of the binocular fixation zone relative to the
458 head. Divergence designates those movements made when the distance increases because of
459 a binocular relaxation of MR muscle fibers. The contraction level of intraocular muscles also
460 changes. During convergence, the contraction of ciliary muscles (CM) reduces the tension in
461 zonular fibers, changing the refractive power of the lens as its anterior surface bulges forward
462 (increase in convexity). Thus, the target images are brought into focus on the foveae. This
463 accommodation is associated with a myosis, i.e., the constriction of the iris and the reduction
464 of the pupil diameter, thereby increasing the depth of field. The myosis itself results from the
465 contraction of the sphincter pupillae (SP) combined with the relaxation of the dilator pupillae
466 (DP). Altogether, these three visuomotor processes constitute the so-called the near response
467 (or near triad).

468 Although these processes are generated jointly, clinical studies report pathological
469 cases in which they are dissociated and the neuroanatomy helps us to understand why. Figure
470 7 shows that the contraction of MR muscle fibers is controlled by the firing rate of motor
471 neurons (MRMN) located in the oculomotor nucleus whereas the intrinsic musculature of each
472 eye is controlled by motor neurons located in the ciliary ganglions (CG) and premotor neurons
473 in the Edinger-Westphal preganglionic nucleus (EWpg). In both cases, the innervation is
474 ipsilateral. The binocular control and the near triad starts with their afferent input from two
475 major regions of the midbrain tegmentum: the supraoculomotor area (SOA) and the central
476 mesencephalic reticular formation (cMRF).

477 **Figure 7 about here**

478 The SOA is primarily involved in the generation of the slow near response and its
479 sustained maintenance. Therein, we find burst neurons and tonic neurons, with separate
480 subgroups characterized by different discharge patterns during the generation of diverging
481 and converging eye movements. More common just lateral to the MLF, four categories of
482 neurons are found: convergence burst neurons, divergence burst neurons, convergence tonic
483 neurons and divergence tonic neurons. Whether divergence neurons exert an inhibitory
484 influence upon the firing rate of convergence neurons is not known yet. Neurons in SOA send
485 projections to the medial rectus MN that are ipsilateral, whereas the projections to the EWpg
486 are bilateral.

487 In the cMRF, we find neurons that emit a burst discharge whenever the near response
488 accompanies a saccadic eye movement: saccade convergence burst neurons and saccade
489 divergence burst neurons. The former fire during asymmetrical saccades associated with an
490 increase of the vergence angle and the latter fire during asymmetrical saccades associated
491 with a divergence. Each cMRF innervates the SOA and the EWpg bilaterally. It also sends
492 ipsilateral projections to the sites in the OMN in which the motor neurons that innervate the
493 singly-innervated muscle fibers are located.

494 The bilateral projections from SOA to the EWpg, and from the cMRF to both EWpg and
495 SOA, are completed by bilateral afferents from caudal fastigial nuclei (CFN) whose
496 contribution in converging eye movements has been reported by unit recording and lesion
497 studies. In addition to send bilateral projections to the midbrain tegmentum and contralateral
498 projections to the pontomedullary reticular formation (where EBN and IBN are located, Fig.
499 2), the CFN also project bilaterally to the rostral part of the deep superior colliculi, with a
500 contralateral predominance. Therein, some cells either increase (convergence neurons) or
501 decrease (divergence neurons) their firing rate during vergence eye movements.

502 In addition to this role in vergence, recording studies in the rostral superior colliculi
503 (SC) also revealed the presence of cells that burst during miniature saccades (also called
504 microsaccades), just like more caudal cells discharge during larger saccades. Local
505 pharmacological inactivation confirmed a causal role in the generation of microsaccades.
506 However, it also unraveled an implication of rostral SC in specifying the direction of gaze when
507 a target is presented (or even imagined) in the central visual field, static or moving.

508 Unbalanced activity between the two rostral SC causes a fixation offset: gaze direction is not
509 directed to the target center but toward an offset location. The same deficit happens after
510 unilateral pharmacological perturbation of CFN, suggesting that the sustained firing rate of its
511 neurons adjusts the balance of activity between the two rostral SC during visual fixation. Thus,
512 the direction of gaze would correspond to an equilibrium of commands that counterbalance
513 with each other, involving fastigial projections to the left and right rostral SC but also to the
514 left and right nuclei *reticularis tegmenti pontis* (NRTP). Through their projections to NRTP, the
515 two rostral SC and CFN have access to neurons which, in the flocculus and paraflocculus,
516 influence the firing rate of tonic neurons that innervate the motor and internuclear neurons
517 in the abducens nuclei.

518 In summary, the knowledge of the detailed neuronal circuitry underlying the
519 generation of disjunctive eye movements is not advanced as much as the circuitry for
520 conjugate saccades. However, significant progress has been made during the last decade,
521 helping to better understand the neurophysiology of vergence eye movements and
522 strabismus.

523 Tracking a moving visual target

524 A target drifting in the visual field often elicits a primary saccade (called interceptive
525 saccade) at the end of which gaze does *not* land ahead of the moving target. Interceptive
526 saccades either accurately capture (foveate) or fall behind the target. Then, a slow eye
527 movement follows with a velocity that rarely matches the target's. A textured background
528 (yielding visual motion in the direction opposite to the eye movement) does not seem to be
529 responsible for the pursuit slower than target velocity because the consequences of its
530 suppression are very weak. A subsequent correction saccade (called catch-up saccade)
531 restores the foveation. Thus, unless the target trajectory is already known and foreseeable,
532 gaze lags behind the target most of the time, especially when the target is small: the visual
533 tracking is mostly composed of catch-up saccades interspersed by intervals during which the
534 eyes drift roughly in the same direction as the target and with a lesser speed. In well-trained
535 subjects, the catch-up saccades can be eliminated. Moreover, increasing the target size
536 enhances the velocity of slow eye movements and reduces the size and number of catch-up

537 saccades. This point is important because most experimental studies use a small spot of light
538 as a target.

539 Contrary to a static target which yields a bounded activity, a moving spot evokes on
540 the retina a streak of activity the tail of which corresponds to past locations of the target and
541 the leading edge the most recent location. In the deep superior colliculus, the population of
542 saccade-related burst neurons is expanded as for a static target. However, it does not recruit
543 cells that fire during saccades to future target locations. The population consists of a
544 continuum of cells ranging from neurons issuing commands related to past locations of the
545 target to neurons issuing commands related to its current location. At the level of motor
546 neurons, other input must therefore complement the collicular signals. This input stems, at
547 least in part, from motion signals processed in area MT because its lesion leads to saccades
548 landing at locations that the target crossed earlier. Thus, the ability to capture the visual target
549 here and now (at the time of saccade landing) may consist of adding a “predictive” component
550 based on the integration of putative target-related “velocity” signals. However, an alternative
551 explanation is possible. Accurate saccades toward a moving target may result from
552 attenuating the synaptic weight of spikes emitted by cells that were the earliest to be excited
553 by the passage of the target across their response field combined with promoting the synaptic
554 weight of action potentials emitted by the cells that are more recently excited.

555 The dorsolateral pontine nucleus (DLPN) is one of the nuclei that relays signals from
556 motion-related areas of the cerebral cortex to the cerebellum. When a chemical lesion is
557 placed in the DLPN, saccades toward a moving target are hypometric whereas saccades to a
558 static target remain unchanged. The hypometria suggests that the saccades were directed
559 toward the past location of the target. Neurons in DLPN project to the floccular and medio-
560 posterior regions of the cerebellum. Ablation of the floccular region (flocculus and
561 paraflocculus) impairs the velocity of slow eye movements, seemingly without affecting catch-
562 up saccades. By contrast, unilateral inactivation of the output nucleus of the medio-posterior
563 cerebellum, the caudal fastigial nucleus, impairs both contralesional saccadic and pursuit eye
564 movements. Gaze direction always lags behind the moving target because the saccades are
565 hypometric and the pursuit velocity slowed. Unfortunately, the interpretation of the
566 hypometria is complicated by the fact that saccades toward a static target are also

567 hypometric. More experiments are required to refine the neuronal mechanisms underlying
568 the generation of these two saccade categories.

569 **Figure 8 about here**

570 Concerning the generation of slow pursuit eye movements, the figure 8 schematizes
571 the complex neuronal network involved in their generation when the movement direction is
572 horizontal. The schema is not complete because our current knowledge prevents from
573 explaining how neurons in the oculomotor vermis and the rostral superior colliculi are
574 recruited during the generation of tracking (saccadic and slow) eye movements.

575 Some cells firing tonically in the nucleus prepositus hypoglossi (NPH) and the nearby
576 medial vestibular nucleus (MVN) increase their firing rate during ipsilateral pursuit. Although
577 called “eye-head velocity” neurons in the monkey, we shall name them tonic neurons for
578 simplicity and for distinguishing them from the burst neurons and EVN-1 described in the
579 previous paragraphs. Some of the tonic neurons are believed to provide an excitatory input to
580 the abducens neurons for contracting the agonist muscle fibers during ipsilateral pursuit.
581 While documented in the cat, this ipsilateral excitatory tonic input (ETN) has been questioned
582 in the monkey. Most NPH/MVN neurons seem to be inhibitory and to project to the
583 contralateral side (synapses a and b). When the sustained firing rate of tonic neurons is
584 considered, we understand that the reciprocal commissural inhibition between the NPH/MVN
585 in the left and right sides yields a push-pull organization, such that a reduced firing rate on
586 one side enhances the firing rate on the opposite side. Thus, by suppressing the activity of the
587 neurons that innervate the antagonist muscle fibers (red synapses a), the inhibitory tonic
588 neurons (ITN) in the NPH/MVN contribute to the relaxation of these muscles, while
589 disinhibiting the ipsilateral abducens and internuclear neurons (blue synapses a) and
590 promoting an ipsiversive movement of both eyes.

591 Neurons in NPH/MVN are monosynaptically inhibited by Purkinje cells in the flocculus
592 and the ventral paraflocculus (synapse b), which receive excitatory input from the three major
593 pontine nuclei (synapses c) involved in relaying visual motion signals to the cerebellum: the
594 rostral part of nucleus reticularis tegmenti pontis (rNRTP), the dorsolateral pontine nucleus
595 (DLPN) and the dorsomedian pontine nucleus (DMPN). These pontine nuclei contribute to the
596 inhibition that Purkinje cells exert upon NPH/MVN neurons. After a chemical lesion in the

597 dorsolateral pontine nucleus (DLPN) or in the rostral nucleus reticularis tegmenti pontis
598 (rNRTP), ipsilesional pursuit eye movements are severely impaired. The suppression of
599 pontine input likely reduces the floccular inhibition of ITN neurons, which in turn impede the
600 recruitment of agonist motor and internuclear neurons. The consequences of suppressing the
601 input from DMPN have not been tested yet. However, an impairment of ipsilesional pursuit is
602 also expected because the DMPN and the contralateral caudal fastigial nucleus exhibit strong
603 reciprocal connections, and fastigial inactivation severely impairs the generation of
604 contralesional pursuit eye movements.

605 The NPH/MVN are also the target of signals from neurons in the pretectal nucleus of
606 the optic tract (NOT; synapse d) some of which are sensitive to the motion of a small visual
607 target. These neurons fire during ipsilateral target motions and their loss severely impairs the
608 ability to generate ipsilesional slow pursuit eye movements. NOT receives visual signals from
609 the retina and from the middle temporal (MT) and medial superior temporal (MST) areas of
610 cerebral cortex (synapses e and f) wherein numerous cells are sensitive to target motion as
611 well. Projections of the frontal eye field (FEF) to NOT and to NPH have been documented
612 (synapses e and e'). This access of frontal cortex to premotor neurons does not indicate a
613 voluntary control of pursuit eye movements since the presence of a target is required for
614 initiating a smooth pursuit. The NOT contributes to the maintenance of ipsilateral pursuit eye
615 movements by its direct projections to tonic neurons in the ipsilateral NPH/MVN (synapse d),
616 but also to the ipsilateral pontine nuclei (synapses g).

617 Through their projections to the ipsilateral rostral SC (synapse j), Gaba-ergic cells in
618 NOT may contribute to suppression of the generation of saccades made in the direction
619 opposite to the target motion. Simultaneously, they may depress the excitatory drive that
620 NRTP exerts upon the ipsilateral paraflocculus (synapse k).

621 Finally, the secondary excitatory vestibular neurons (EVN-1 or PVP cells) that are
622 involved in moving the eyes in the direction opposite to the head movement (Fig. 5) increase
623 their firing rate during contraversive pursuit eye movements. However, as they do not seem
624 to be inhibited by Purkinje cells located in the floccular region, the origin of the discharge
625 modulation during contraversive pursuit remains to be identified. Direct projections from the
626 frontal eye fields to the NPH/MVN might support this influence.

628 Conclusion

629 Studying orienting movements of gaze is a convenient means for investigating how
630 intertwined networks of neurons in the central nervous system transforms sensory signals into
631 motor commands, but also, how it enables an entire animal to visually locate and capture an
632 object in the physical environment and to adapt when intrinsic damage or contextual changes
633 alter their execution.

634 During the last decades, technical developments offered the possibility to measure
635 precisely the time course of these movements and to study correlations between the firing
636 rate of neurons and kinematic parameters such as movement amplitude, velocity,
637 acceleration and various differences (e.g., gaze error, velocity error, etc.). However, these
638 correlation studies should not lead us to believe that a one-to-one correspondence exists
639 between the multiple neuronal networks within which activities propagate, and the extrinsic
640 and homogeneous medium (mathematical space) with which we quantify the motion of rigid
641 objects such as the eyeballs, the head and targets. Such a mapping is not at all obvious; it is
642 even quite questionable. Contrary to the physical space, the medium of neuronal activity is
643 neither homogeneous nor passive. Unlike most objects at which we look and that we
644 manipulate, the corresponding brain activity is not rigid. Even the mere spot of activity that a
645 small static object evokes on the retina yields multiple parallel flows of activity that make its
646 correspondence in the brain spatially distributed, temporally extended and context-
647 dependent. Moreover, reducing neurons or neuronal chains to units encoding geometric or
648 kinematic relations between gaze and target conceals the muscle forces and the multiple
649 antagonisms that we have described between muscles. Furthermore, the velocity profile of
650 the movement and the time course of force development do not match. During horizontal
651 saccades for example, the duration of the interval during which the muscle force increases is
652 on average 60% shorter than the duration of the total change in eye orientation. A force decay
653 happens well before the change in eye position ends and the larger the saccade, the longer its
654 lead-time relative to saccade arrest. Finally, the temporal series of numerical values
655 quantifying the changes during eye reorientation hides the antagonisms between those
656 multiple channels that cause each movement. To our knowledge, no study has reported
657 identical time courses between the kinematic and neurophysiological recordings that would
658 support the assumption of an isomorphism.

659 In the majority of models proposed during the last decades, the movements of the
660 eyes and the head were considered as driven by (intrinsic) error signals encoding displacement
661 vectors in physical space. These models have definitely been useful to communicate concepts
662 and to bring a comprehensive picture of the complexity underlying the generation of
663 movements. However, embedding geometric and kinematic notions within the inner
664 functioning of the brain (i.e., mapping intrinsic neuronal signals with extrinsic behavioral
665 measurements) may be neurophysiologically misleading because different constraints
666 characterize the neurophysiological and kinematic descriptions. In fact, rather than outcomes
667 of processes reducing geometric or kinematic errors, the saccade and pursuit acceleration
668 may resume merely to transitions between equilibria opposing populations of neurons whose
669 activity leads to mutually antagonist movement tendencies.

670 Further empirical investigation is still required to determine and explain several other
671 issues: i.e., whether and how the networks underlying orienting movements of the eyes and
672 head interact with those generating other types of goal-directed action such as reaching
673 movements of the hand or locomotion; whether and how they interact with the networks
674 involved in the navigation and the memory of locations; and whether and how they support
675 the learning of new skills and possibly the acquisition of more abstract knowledge such as
676 geometry or counting. With the recent multiplication of cognitive studies that use eye-tracking
677 techniques to explore the so-called “inner space” with quantitative methods, more effort is
678 required to characterize what exactly are those covert processes that eye movements would
679 express. At the same time, neurophysiological and neuroanatomical works must continue to
680 reveal the fine structure of the brain connectivity and to unravel the multiplicity of channels
681 and networks that enable a living organism to connect with its natural and cultural
682 environments as well as to reactivate the memory of past events.

683 By studying the simple and seemingly straightforward problem of orienting the eyes
684 toward the location of a physical object, we see how the neurophysiological and
685 neuroanatomical studies performed with animals enables us to understand the symptoms
686 exhibited by patients suffering from eye movement disorders. They also show that
687 evolutionary and embryological developments led to patterns that are different from the
688 strategies of human engineers. Contrary to the case where a design precedes the realization
689 of a machine for solving a specific problem, the physiology teaches us that any behavioral

690 observation is the outcome of a complex network of multiple and parallel chains of neurons.
691 It also teaches us how the multiplicity and the diversity of elements enable an organism to
692 solve several problems in parallel and even take up new challenges.

693

694 Bibliography

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696 Barton EJ, Nelson JS, Gandhi NJ, Sparks DL. Effects of partial lidocaine inactivation of the
697 paramedian pontine reticular formation on saccades of macaques. *J Neurophysiol* 90: 372–
698 386, 2003.

699 Basso MA, Krauzlis RJ, Wurtz RH. Activation and inactivation of rostral superior colliculus
700 neurons during smooth-pursuit eye movements in monkeys. *J Neurophysiol* 84: 892-908,
701 2000.

702 Belton T, McCrea RA. Role of the cerebellar flocculus region in the coordination of eye and
703 head movements during gaze pursuit. *J Neurophysiol* 84: 1614-1626, 2000.

704 Berthoz A, Droulez J, Vidal PP, Yoshida K. Neural correlates of horizontal vestibulo-ocular reflex
705 cancellation during rapid eye movements in the cat. *J Physiol* 419: 717-751, 1989.

706 Blazquez PM, Kim G, Yakusheva TA. Searching for an internal representation of stimulus
707 kinematics in the response of ventral paraflocculus Purkinje cells. *Cerebellum* 16: 817-826,
708 2017.

709 Bohlen M, Gamlin PD, Warren S, May PJ. Cerebellar projections to the macaque midbrain
710 tegmentum: possible near response connections. *Visual Neurosc* 38: E007, 2021.

711 Bourrelly C, Quinet J, Goffart L. The caudal fastigial nucleus and the steering of saccades
712 toward a moving visual target. *J Neurophysiol* 120: 421-438, 2018.

713 Bourrelly C, Quinet J, Goffart L. Pursuit disorder and saccade dysmetria after caudal fastigial
714 inactivation in the monkey. *J Neurophysiol* 120: 1640-1654, 2018.

715 Bourrelly C, Quinet J, Goffart L. Bilateral control of interceptive saccades: evidence from the
716 ipsipulsion of vertical saccades after caudal fastigial inactivation. *J Neurophysiol* 125: 2068-
717 2083, 2021.

718 Broussard DM, DeCharms RC, Lisberger SG. Inputs from the ipsilateral and contralateral
719 vestibular apparatus to behaviorally characterized abducens neurons in rhesus monkeys. *J*
720 *Neurophysiol* 74: 2445-2459, 1995.

721 Büttner U, Büttner-Ennever JA. Present concepts of oculomotor organization. *Prog Brain Res*
722 151: 1-42, 2006.

723 Büttner, U, Büttner-Ennever J, Henn V. Vertical eye movement related unit activity in the
724 rostral mesencephalic reticular formation of the alert monkey. *Brain Res* 130: 239–252, 1977.

725 Clendaniel RA, Mays LE. Characteristics of antidromically identified oculomotor internuclear
726 neurons during vergence and versional eye movements. *J Neurophysiol* 71:1111–1127, 1994.

727 Corneil BD, Olivier E, Richmond FJ, Loeb GE, Munoz DP. Neck muscles in the rhesus monkey.
728 II. Electromyographic patterns of activation underlying postures and movements. *J*
729 *Neurophysiol* 86: 1729-1749, 2001.

730 Cox PG, Jeffery N. Geometry of the semicircular canals and extraocular muscles in rodents,
731 lagomorphs, felids and modern humans. *J Anat* 213: 583-596, 2008.

732 Cromer JA, Waitzman DM. Comparison of saccade-associated neuronal activity in the primate
733 central mesencephalic and paramedian pontine reticular formations. *J Neurophysiol* 98: 835–
734 850, 2007.

735 Cullen KE. Eye and head movements. *Encyclopedia of neuroscience*, 157-167, 2009.

736 Cullen KE, Guitton D. Analysis of primate IBN spike trains using system identification
737 techniques. I. Relationship to eye movement dynamics during head-fixed saccades. *J*
738 *Neurophysiol* 78: 3259-3282, 1997.

739 Cullen KE, Roy JE. Signal processing in the vestibular system during active versus passive head
740 movements. *J Neurophysiol* 91: 1919-1933, 2004.

741 Das VE. Strabismus and the oculomotor system: insights from macaque models. *Annu Rev Vis*
742 *Sci* 2: 37-59, 2016.

743 Davis-López de Carrizosa MA, Morado-Díaz CJ, Miller JM, de la Cruz RR, Pastor AM.. Dual
744 encoding of muscle tension and eye position by abducens motoneurons. *J Neurosci* 31: 2271–
745 2279, 2011.

746 Distler C, Mustari M, Hoffmann KP. Cortical projections to the nucleus of the optic tract and
747 dorsal terminal nucleus and to the dorsolateral pontine nucleus in macaques: a dual
748 retrograde tracing study. *J Comp Neurol* 444: 144-158, 2002.

749 Freedman EG, Stanford TR, Sparks DL. Combined eye-head gaze shifts produced by electrical
750 stimulation of the superior colliculus in rhesus monkeys. *J Neurophysiol* 76: 927-952, 1996.

751 Fuchs AF, Kaneko CR, Scudder CA. Brainstem control of saccadic eye movements. *Annu Rev*
752 *Neurosci* 8: 307–337, 1985.

753 Fuchs AF, Ling L, Phillips JO. Behavior of the position vestibular pause (PVP) interneurons of
754 the vestibuloocular reflex during head-free gaze shifts in the monkey. *J Neurophysiol* 94: 4481-
755 4490, 2005.

756 Fuchs AF, Luschei ES. Firing patterns of abducens neurons of alert monkeys in relationship to
757 horizontal eye movement. *J Neurophysiol* 33: 382–392, 1970.

758 Fuchs AF, Mustari MJ, Robinson FR, Kaneko CR. Visual signals in the nucleus of the optic tract
759 and their brain stem destinations. *Ann N Y Acad Sci* 656: 266-276, 1992.

760 Fukushima K, Kaneko CRS, Fuchs AF. The neuronal substrate of integration in the oculomotor
761 system. *Progr Neurobiol* 39: 609-639, 1992.

762 Gamlin PD. Subcortical neural circuits for ocular accommodation and vergence in primates.
763 *Ophthalmic Physiol Opt* 19: 81-89, 1999.

764 Gamlin PD. Neural mechanisms for the control of vergence eye movements. *Ann N Y Acad Sci*
765 956: 264-272, 2002.

766 Gamlin PD. The pretectum: connections and oculomotor-related roles. *Prog Brain Res* 151:
767 379-405, 2006.

768 Gamlin PD, Yoon K, Zhang H. The role of cerebro-ponto-cerebellar pathways in the control of
769 vergence eye movements. *Eye (London)* 10 : 167-171, 1996.

770 Gandhi NJ, Barton EJ, Sparks DL. Coordination of eye and head components of movements
771 evoked by stimulation of the paramedian pontine reticular formation. *Exp Brain Res* 189: 35-
772 47, 2008.

773 Gandhi NJ, Katnani HA. Motor functions of the superior colliculus. *Annu Rev Neurosci* 34: 205-
774 231, 2011.

775 Gandhi NJ, Sparks DL. Dissociation of eye and head components of gaze shifts by stimulation
776 of the omnipause neuron region. *J Neurophysiol* 98: 360-373, 2007.

777 Goffart L. Saccadic eye movements: basic neural processes. Reference Module in
778 Neuroscience and Biobehavioral Psychology, 2017.

779 Goffart L. Kinematics and the neurophysiological study of visually-guided eye movements.
780 *Prog Brain Res* 249: 375–384, 2019.

781 Goffart L, Burreilly C, Quinton JC. Neurophysiology of visually-guided eye movements: critical
782 review and alternative viewpoint. *J Neurophysiol* 120: 3234–3245, 2018.

783 Goffart L, Burreilly C, Quinet J. Synchronizing the tracking eye movements with the motion of
784 a visual target: Basic neural processes. *Prog Brain Res* 236: 243–268, 2017.

785 Goffart L, Cecala AL, Gandhi NJ. The superior colliculus and the steering of saccades toward a
786 moving visual target. *J Neurophysiol* 118: 2890-2901, 2017.

787 Goffart L, Haged ZM, Krauzlis RJ. Visual fixation as equilibrium: evidence from superior
788 colliculus inactivation. *J Neurosci* 32: 10627–10636, 2012.

789 Goossens HH, Van Opstal AJ. Dynamic ensemble coding of saccades in the monkey superior
790 colliculus. *J Neurophysiol* 95: 2326-2341, 2006.

791 Grandin A, Brandi AM, Dubayle D, Graf W, Ugolini G, Hadjidimitrakis K, Moschovakis A. Density
792 gradients of trans-synaptically labeled collicular neurons after injections of rabies virus in the
793 lateral rectus muscle of the rhesus monkey. *J Comp Neurol* 451: 346-361, 2002.

794 Haged ZM, Goffart L, Krauzlis RJ. A neural mechanism for microsaccade generation in the
795 primate superior colliculus. *Science* 323: 940-943, 2009.

796 Haged ZM, Goffart L, Krauzlis RJ. Superior colliculus inactivation causes stable offsets in eye
797 position during tracking. *J Neurosci* 28: 8124-8137, 2008.

798 Haged ZM, Krauzlis RJ. Similarity of superior colliculus involvement in microsaccade and
799 saccade generation. *J Neurophysiol* 107: 1904–1916, 2012.

800 Henn V, Lang W, Hepp K, Reisine H. Experimental gaze palsies in monkeys and their relation
801 to human pathology. *Brain* 107: 619–636, 1984.

802 Hepp K, Henn V, Vilis T, Cohen B. Brainstem regions related to saccade generation. In: The
803 neurobiology of saccadic eye movements, edited by Wurtz RH, Goldberg ME. Amsterdam, The
804 Netherlands: Elsevier, 1989, pp 105–212.

805 Highstein SM, Holstein GR. The anatomy of the vestibular nuclei. *Prog Brain Res* 151: 157-203,
806 2006.

807 Horn AK. The reticular formation. *Progr Brain Res* 151: 127–155, 2006.

808 Horn AKE & Leigh RJ (2011) The anatomy and physiology of the ocular motor system.
809 *Handbook of clinical neurology* 102: 21-69.

810 Horn AK, Helmchen C, Wahle P. GABAergic neurons in the rostral mesencephalon of the
811 macaque monkey that control vertical eye movements. *Annals of the New York Academy of*
812 *Sciences* 1004: 19-28, 2003.

813 Hu X, Jiang H, Gu C, Li C, Sparks DL. Reliability of oculomotor command signals carried by
814 individual neurons. *Proc Nat Acad Sci* 104: 8137–8142, 2007.

815 Ilg UJ. Slow eye movements. *Prog Neurobiol* 53: 293-329, 1997.

816 Johansson R, Holsanova J, Holmqvist K. Using eye movements and spoken discourse as
817 windows to inner space. In *The construal of spatial meaning: Windows into conceptual space*
818 (pp. 9-28). Oxford University Press, 2013.

819 Kaneko CR. Effect of ibotenic acid lesions of the omnipause neurons on saccadic eye
820 movements in rhesus macaques. *J Neurophysiol* 75: 2229–2242, 1996.

821 Kaneko CR. Eye movement deficits after ibotenic acid lesions of the nucleus prepositus
822 hypoglossi in monkeys. I. Saccades and fixation. *J Neurophysiol* 78: 1753-1768, 1997.

823 Kaneko CR. Eye movement deficits following ibotenic acid lesions of the nucleus prepositus
824 hypoglossi in monkeys II. Pursuit, vestibular, and optokinetic responses. *J Neurophysiol* 81:
825 668-681, 1999.

826 Keller EL. Participation of medial pontine reticular formation in eye movement generation in
827 monkey. *J Neurophysiol* 37: 316–332, 1974.

828 Keller EL, Gandhi NJ, Weir PT. Discharge of superior collicular neurons during saccades made
829 to moving targets. *J Neurophysiol* 76: 3573–3577, 1996.

830 Keller EL, Heinen SJ. Generation of smooth-pursuit eye movements: neuronal mechanisms and
831 pathways. *Neurosc Res* 11: 79-107, 1991.

832 Keller EL, Khan NS. Smooth pursuit initiation in the presence of a textured background in
833 monkey. *Vision Res* 26: 943-955, 1986.

834 Keller EL, McPeck RM, Salz T. Evidence against direct connections to PPRF EBNs from SC in the
835 monkey. *J Neurophysiol*. 84: 1303-1313, 2000.

836 Kojima Y, Iwamoto Y, Robinson FR, Noto CT, Yoshida K. Premotor inhibitory neurons carry
837 signals related to saccade adaptation in the monkey. *J Neurophysiol* 99: 220–230, 2008.

838 Krauzlis RJ. Recasting the smooth pursuit eye movement system. *J Neurophysiol* 91: 591-603,
839 2004.

840 Krauzlis RJ, Basso MA, Wurtz RH. Discharge properties of neurons in the rostral superior
841 colliculus of the monkey during smooth-pursuit eye movements. *J Neurophysiol* 84: 876-891,
842 2000.

843 Krauzlis RJ, Goffart L, Hafed ZM. Neuronal control of fixation and fixational eye movements.
844 *Philos Trans R Soc Lond B Biol Sci* 372: 20160205, 2017.

845 Langer T, Kaneko CRS, Scudder CA, Fuchs AF. Afferents to the abducens nucleus in the monkey
846 and cat. *J Comp Neurol* 245:379-400, 1986.

847 Leigh RJ, Zee DS. *The Neurology of Eye Movements*. Oxford, UK: Oxford University Press, 2006.

848 Lennerstrand (2007) Strabismus and eye muscle function. *Acta Ophthalmologica Scandinavia*
849 85: 711-723.

850 Lennerstrand G, Tian S, Zhao TX. Force development and velocity of human saccadic eye
851 movements. I: Abduction and adduction. *Clin Vision Sci* 8: 295-305, 1993.

852 Lestienne FG, Le Goff B, Liverneaux PA. Head movement trajectory in three-dimensional space
853 during orienting behavior toward visual targets in rhesus monkeys. *Exp Brain Res* 102: 393-
854 406, 1995.

855 Lisberger SG, Morris EJ, Tychsen L. Visual motion processing and sensory-motor integration
856 for smooth pursuit eye movements. *Annu Rev Neurosci* 10: 97-129, 1987.

857 Lisberger SG, Pavelko TA, Broussard DM. Responses during eye movements of brain stem
858 neurons that receive monosynaptic inhibition from the flocculus and ventral paraflocculus in
859 monkeys. *J Neurophysiol* 72: 909-927, 1994.

860 Luschei ES, Fuchs AF. Activity of brain stem neurons during eye movements of alert monkeys.
861 *J Neurophysiol* 35: 445-461, 1972.

862 May JG, Keller EL, Suzuki DA. Smooth-pursuit eye movement deficits with chemical lesions in
863 the dorsolateral pontine nucleus of the monkey. *J Neurophysiol* 59: 952-77, 1988.

864 May PJ, Hartwich-Young R, Nelson J, Sparks DL, Porter JD. Cerebellotectal pathways in the
865 macaque: implications for collicular generation of saccades. *Neuroscience* 36: 305-324, 1990.

866 May PJ, Porter JD, Gamlin PD. Interconnections between the primate cerebellum and midbrain
867 near-response regions. *J Comp Neurol* 315: 98-116, 1992.

868 May PJ, Warren S, Gamlin PDR, Billig I. An anatomic characterization of the midbrain near
869 response neurons in the macaque monkey. *Invest Ophthalmol Vis Sci* 59: 1486-1502, 2018.

870 McCrea RA, Horn AK. Nucleus prepositus. *Prog Brain Res* 151: 205-230, 2006.

871 McCrea RA, Strassman A, May E, Highstein SM. Anatomical and physiological characteristics
872 of vestibular neurons mediating the horizontal vestibulo-ocular reflex of the squirrel monkey.
873 *J Comp Neurol* 264:547-570, 1987.

874 McCrea RA, Strassman A, Highstein SM. Anatomical and physiological characteristics of
875 vestibular neurons mediating the vertical vestibulo-ocular reflexes of the squirrel monkey. *J*
876 *Comp Neurol* 264: 571–594, 1987.

877 McDougal DH, Gamlin PD. Autonomic control of the eye. *Compr Physiol* 5: 439-473, 2015.

878 McFarland JL, Fuchs AF. Discharge patterns in nucleus prepositus hypoglossi and adjacent
879 medial vestibular nucleus during horizontal eye movement in behaving macaques. *J*
880 *Neurophysiol* 68: 319–332, 1992.

881 Mays LE. Neural control of vergence eye movements: convergence and divergence neurons in
882 midbrain. *J Neurophysiol* 51: 1091–1108, 1984.

883 Mays LE, Porter JD, Gamlin PD, Tello CA. Neural control of vergence eye movements: neurons
884 encoding vergence velocity. *J Neurophysiol* 56: 1007-1021, 1986.

885 Mays LE, Gamlin PDR. A neural mechanism subserving saccade-vergence interactions. In: *Eye*
886 *movement research: Mechanisms, processes and applications*, edited by Findlay J, Walker R,
887 and Kentridge RW. Amsterdam, The Netherlands: Elsevier, 1995, p. 215–223.

888 Mays LE, Gamlin PD. Neuronal circuitry controlling the near response. *Curr Opin Neurobiol* 5:
889 763-768, 1995.

890 Miller JM. Understanding and misunderstanding extraocular muscle pulleys. *J Vis* 7: 10.1-15,
891 2007.

892 Miller JM, Robins D. Extraocular muscle forces in alert monkey. *Vis Res* 32: 1099–1113, 1992.

893 Miller JM, Bockisch CJ, Pavlovski DS. Missing lateral rectus force and absence of medial rectus
894 co-contraction in ocular convergence. *J Neurophysiol* 87: 2421-2433, 2002.

895 Moschovakis AK. Are laws that govern behavior embedded in the structure of the CNS? The
896 case of Hering's law. *Vision Res* 35: 3207-3216, 1995.

897 Moschovakis AK. The neural integrators of the mammalian saccadic system. *Front Biosci* 2:
898 d552-577, 1997.

899 Moschovakis AK, Highstein SM. The anatomy and physiology of primate neurons that control
900 rapid eye movements. *Annu Rev Neurosci* 17: 465-488, 1994.

901 Moschovakis AK, Kitama T, Dalezios Y, Petit J, Brandi AM, Grantyn AA. An anatomical substrate
902 for the spatiotemporal transformation. *J Neurosci* 18: 10219-10229, 1998.

903 Moschovakis AK, Scudder CA, Highstein SM. The microscopic anatomy and physiology of the
904 mammalian saccadic system. *Prog Neurobiol* 50: 133–254, 1996.

905 Moschovakis AK, Scudder CA, Highstein SM. The structure of the primate oculomotor burst
906 generator. I. Medium-lead burst neurons with upward on-directions. *J. Neurophysiol* 65: 203-
907 217, 1991.

908 Moschovakis AK, Scudder CA, Highstein SM, Warren JDM. The structure of the primate
909 oculomotor burst generator. II. Medium-lead burst neurons with downward on-directions. *J*
910 *Neurophysiol* 65: 218-229, 1991.

911 Mustari MJ, Fuchs AF Discharge patterns of neurons in the pretectal nucleus of the optic tract
912 (NOT) in the behaving macaque. *J Neurophysiol* 64:77-90, 1990.

913 Mustari MJ, Fuchs AF, Wallman J. Response properties of dorsolateral pontine units during
914 smooth pursuit in the rhesus macaque. *J Neurophysiol* 60: 664-686, 1988.

915 Mustari MJ, Fuchs AF, Kaneko CR, Robinson FR. Anatomical connections of the primate
916 pretectal nucleus of the optic tract. *J Comp Neurol* 349: 111-128, 1994.

917 Mustari MJ, Ono S, Das VE. Signal processing and distribution in cortical-brainstem pathways
918 for smooth pursuit eye movements. *Ann N Y Acad Sci* 1164: 147-154, 2009.

919 Noda H, Mikami A. Discharges of neurons in the dorsal paraflocculus of monkeys during eye
920 movements and visual stimulation. *J Neurophysiol* 56: 1129–1146, 1986

921 Noda H, Suzuki DA. The role of the flocculus of the monkey in fixation and smooth pursuit eye
922 movements. *J Physiol* 294: 335–348, 1979.

923 Noda H, Sugita S, Ikeda Y. Afferent and efferent connections of the oculomotor region of the
924 fastigial nucleus in the macaque monkey. *J Comp Neurol* 302: 330–348, 1990.

925 Núñez R. Numbers and arithmetic: Neither hardwired nor out there. *Biol Theory* 4: 68-83,
926 2009.

927 Ohgaki T, Markham CH, Schneider JS, Curthoys IS. Anatomical evidence of the projection of
928 pontine omnipause neurons to midbrain regions controlling vertical eye movements. *J Comp*
929 *Neurol* 289: 610-625, 1989.

930 Ono S, Das VE, Mustari MJ. Role of the dorsolateral pontine nucleus in short-term adaptation
931 of the horizontal vestibuloocular reflex. *J Neurophysiol* 89: 2879-2885, 2003.

932 Optican LM. Oculomotor system: models. In: *Encyclopedia of Neuroscience*, edited by Squire
933 LR. Oxford, UK: Academic, 2009.

934 Ostriker G, Pellionisz A, Llinás R. Tensorial computer model of gaze--I. Oculomotor activity is
935 expressed in non-orthogonal natural coordinates. *Neuroscience* 14: 483-500, 1985.

936 Pellionisz AJ. Tensor network theory of the central nervous system and sensorimotor
937 modeling. In : *Brain theory*. Springer, Berlin, Heidelberg, 1986. p. 121-145.

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

940 Phillips JO, Ling I, Siebold C, Fuchs AF. Behavior of primate vestibulo-ocular reflex neurons and
941 vestibular neurons during head-free gaze shifts. *Ann N Y Acad Sci* 781: 276-291, 1996.

942 Phillips JO, Ling L, Fuchs AF. Action of the brain stem saccade generator during horizontal gaze
943 shifts. I. Discharge patterns of omnidirectional pause neurons. *J Neurophysiol* 81: 1284-1295,
944 1999.

945 Quinet J, Goffart L. Head-unrestrained gaze shifts after muscimol injection in the caudal
946 fastigial nucleus of the monkey. *J Neurophysiol* 98: 3269-3283, 2007.

947 Quinet J, Schultz K, May PJ, Gamlin PD. Neural control of rapid binocular eye movements:
948 Saccade-vergence burst neurons. *Proc Natl Acad Sci USA* 117: 29123-29132, 2020.

949 Raphan T, Cohen B. Brainstem mechanisms for rapid and slow eye movements. *Annu Rev*
950 *Physiol* 40: 527-552, 1978.

951 Richmond FJ, Singh K, Corneil BD. Neck muscles in the rhesus monkey. I. Muscle morphometry
952 and histochemistry. *J Neurophysiol* 86: 1717-1728, 2001.

953 Roy JE, Cullen KE. Vestibuloocular reflex signal modulation during voluntary and passive head
954 movements. *J Neurophysiol* 87: 2337-2357, 2002.

955 Roy JE, Cullen KE. Brain stem pursuit pathways: dissociating visual, vestibular, and
956 proprioceptive inputs during combined eye-head gaze tracking. *J Neurophysiol* 90: 271-290,
957 2003.

958 Robinson DA. Implications of neural networks for how we think about brain function. *Behav*
959 *Brain Sci* 15: 644–655, 1992.

960 Robinson DA. A quantitative analysis of extraocular muscle cooperation and squint. *Invest*
961 *Ophthalmol* 14: 801–825, 1975.

962 Robinson DA. Oculomotor unit behavior in the monkey. *J Neurophysiol* 33: 393–403, 1970.

963 Roy JE, Cullen KE. Brain stem pursuit pathways: dissociating visual, vestibular, and
964 proprioceptive inputs during combined eye-head gaze tracking. *J Neurophysiol* 90: 271-290,
965 2003.

966 Scudder CA, Fuchs AF. Physiological and behavioral identification of vestibular nucleus
967 neurons mediating the horizontal vestibuloocular reflex in trained rhesus monkeys. *J*
968 *Neurophysiol* 68:244–264, 1992.

969 Scudder CA, Fuchs AF, Langer TP. Characteristics and functional identification of saccadic
970 inhibitory burst neurons in the alert monkey. *J Neurophysiol* 59:1430–1454, 1988.

971 Scudder CA, Kaneko CRS, Fuchs AF. The brainstem burst generator for saccadic eye
972 movements: a modern synthesis. *Exp Brain Res* 142: 439–462, 2002.

973 Sharpe JA. Neurophysiology and neuroanatomy of smooth pursuit: lesion studies. *Brain Cogn*
974 68: 241–254, 2008.

975 Sharpe J, Wong AM. Anatomy and physiology of ocular motor systems. *Walsh and Hoyt's*
976 *Clinical Neuro-Ophthalmology* 16: 809-885, 2005.

- 977 Soetedjo R, Kaneko CR, Fuchs AF. Evidence that the superior colliculus participates in the
978 feedback control of saccadic eye movements. *J Neurophysiol* 87: 679–695, 2002.
- 979 Soetedjo R, Kojima Y, Fuchs AF. How cerebellar motor learning keeps saccades accurate. *J*
980 *Neurophysiol* 121: 2153-2162, 2019.
- 981 Sparks DL. The brainstem control of saccadic eye movements. *Nat Rev Neurosci* 3: 952–964,
982 2002.
- 983 Sparks DL, Barton EJ, Gandhi NJ, Nelson J. Studies of the role of the paramedian pontine
984 reticular formation in the control of headrestrained and head-unrestrained gaze shifts. *Ann*
985 *NY Acad Sci* 956: 85–98, 2002.
- 986 Sparks DL, Freedman EG, Chen LL, Gandhi NJ. Cortical and subcortical contributions to
987 coordinated eye and head movements. *Vision Res* 41: 3295-3305, 2001.
- 988 Sparks DL, Gandhi NJ. Single cell signals: an oculomotor perspective. *Prog Brain Res* 142: 35-
989 53, 2003.
- 990 Sparks DL, Mays LE. Signal transformations required for the generation of saccadic eye
991 movements. *Annu Rev Neurosci* 13: 309–336, 1990.
- 992 Strassman A, Evinger C, McCrea RA, Baker RG, Highstein SM. Anatomy and physiology of
993 intracellularly labelled omnipause neurons in the cat and squirrel monkey. *Exp Brain Res* 67:
994 436-440, 1987.
- 995 Strassman A, Highstein SM, McCrea RA. Anatomy and physiology of saccadic burst neurons in
996 the alert squirrel monkey. I. Excitatory burst neurons. *J Comp Neurol* 249: 337–357, 1986a.
- 997 Strassman A, Highstein SM, McCrea RA. Anatomy and physiology of saccadic burst neurons in
998 the alert squirrel monkey. II. Inhibitory burst neurons. *J Comp Neurol* 249: 358–380, 1986b.
- 999 Straumann D, Zee DS, Solomon D, Lasker AG, Roberts DC. Transient torsion during and after
1000 saccades. *Vision Res* 35: 3321-3334, 1995.
- 1001 Strohmaier AR, MacKay KJ, Obersteiner A, Reiss KM. Eye-tracking methodology in
1002 mathematics education research: A systematic literature review. *Educational Studies in*
1003 *Mathematics* 104: 147-200, 2020.
- 1004 Suzuki DA, May JG, Keller EL, Yee RD. Visual motion response properties of neurons in
1005 dorsolateral pontine nucleus of alert monkey. *J Neurophysiol* 63: 37-59, 1990.
- 1006 Suzuki DA, Yamada T, Yee RD. Smooth-pursuit eye-movement-related neuronal activity in
1007 macaque nucleus reticularis tegmenti pontis. *J Neurophysiol* 89: 2146-2158, 2003.
- 1008 Sylvestre PA, Cullen KE. Quantitative analysis of abducens neuron discharge dynamics during
1009 saccadic and slow eye movements. *J Neurophysiol* 82: 2612–2632, 1999
- 1010 Tanaka M. Involvement of the central thalamus in the control of smooth pursuit eye
1011 movements. *J Neurosci* 25: 5866-5876, 2005.

- 1012 Takahashi M, Sugiuchi Y, Na J, Shinoda Y. Brainstem circuits triggering saccades and fixation. J
1013 Neurosci in press 2021
- 1014 Thier P, Möck M. The oculomotor role of the pontine nuclei and the nucleus reticularis
1015 tegmenti pontis. Prog Brain Res 151: 293-320, 2006.
- 1016 Ugolini G, Klam F, Doldan Dans M, Dubayle D, Brandi AM, Büttner-Ennever J, Graf W.
1017 Horizontal eye movement networks in primates as revealed by retrograde transneuronal
1018 transfer of rabies virus: differences in monosynaptic input to "slow" and "fast" abducens
1019 motoneurons. J Comp Neurol 498: 762-785, 2006.
- 1020 Van Gisbergen JAM, Robinson DA, Gielen S. A quantitative analysis of generation of saccadic
1021 eye movements by burst neurons. J Neurophysiol 45: 417-442, 1981.
- 1022 Van Gisbergen JA, Van Opstal AJ. The neurobiology of saccadic eye movements. Models. Rev
1023 Oculomot Res 3: 69-101, 1989.
- 1024 Van Horn MR, Waitzman DM, Cullen KE. Vergence neurons identified in the rostral superior
1025 colliculus code smooth eye movements in 3D space. J Neurosci 33: 7274-7284.
- 1026 Yakushin SB, Gizzi M, Reisine H, Raphan T, Büttner-Ennever J, Cohen B. Functions of the
1027 nucleus of the optic tract (NOT). II. Control of ocular pursuit. Exp Brain Res 131: 433-447, 2000.
- 1028 Zee DS, Yamazaki A, Butler PH, Gücer G. Effects of ablation of flocculus and paraflocculus of
1029 eye movements in primate. J. Neurophysiol 46: 878-899, 1981.
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1032

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1038

1039 Figure captions

1040

1041 **Figure 1:** Schematic representation of the extraocular muscles (A) and pulling directions
1042 engaged by the contraction of their fibers when the eyes are centered in the orbit (B). LR:
1043 lateral rectus, MR: medial rectus, SR: superior rectus, IR: inferior rectus, SO: superior oblique,
1044 IO: inferior oblique, tr: trochlea. The red arrows indicate the muscles whose contraction
1045 abducts the eye, the black arrows the muscles whose contraction adducts the eye. The
1046 turquoise arrows indicate the muscles whose contraction elevates the eye, the yellow arrows
1047 those whose contraction lowers the eye. The blue arrows indicate the muscles whose
1048 contraction causes an intorsion of the eye, the green arrows those whose contraction causes
1049 an extorsion.

1050

1051 **Figure 2:** Neuronal network involved during horizontal saccades toward the left (A) and the
1052 right (B). Connecting lines ended by an arrow indicate excitatory connections; those ended by
1053 a circle indicate inhibitory synaptic connections. Blue color indicates the agonist neuronal
1054 elements, red color the antagonist ones. The thickness of connecting lines schematizes the
1055 strength with which the neurons fire. OPN: omnipause neurons, EBN: excitatory burst
1056 neurons, IBN: inhibitory burst neurons, MN: abducens motoneurons, AIN: abducens
1057 internuclear neurons. In the bottom, the thickness of arrows attached to the eyeballs
1058 schematizes the strength of muscle contraction. LR: lateral rectus, MR: medial rectus, SR:
1059 superior rectus, IR: inferior rectus, SO: superior oblique, IO: inferior oblique.

1060

1061 **Figure 3:** Neuronal network involved during vertical saccades toward the top (A) and the
1062 bottom (B). Connecting lines ended by an arrow indicate excitatory connections; those ended
1063 by a circle indicate inhibitory synaptic connections. Blue color indicates the agonist neuronal
1064 elements, red color the antagonist ones. The thickness of connecting lines schematizes the
1065 strength with which the neurons fire. uEBN: upward excitatory burst neurons, dEBN:
1066 downward excitatory burst neurons, uIBN: upward inhibitory burst neurons, MN:
1067 motoneurons. In the top, the thickness of arrows attached to the eyeballs schematizes the
1068 strength of muscle contraction. LR: lateral rectus, MR: medial rectus, SR: superior rectus, IR:
1069 inferior rectus, SO: superior oblique, IO: inferior oblique.

1070

1071 **Figure 4:** Neuronal network involved during combined horizontal eye and head movements
1072 toward the left. Connecting lines ended by an arrow indicate excitatory connections; those
1073 ended by a circle indicate inhibitory synaptic connections. Blue color indicates the agonist
1074 neuronal oculomotor elements, red color the antagonist ones. Green color indicates the
1075 cephalomotor elements. The thickness of connecting lines schematizes the strength with
1076 which the neurons fire. dSC: deep superior colliculus, RSN: reticulospinal neurons, EBN:
1077 excitatory burst neurons, IBN: inhibitory burst neurons, ABD: abducens motor and
1078 internuclear neurons, NMN: neck motoneurons, PVN: primary vestibular neurons, IVN:
1079 inhibitory vestibular neurons, EVN: excitatory vestibular neurons, VIII: eight cranial nerve.

1080

1081 **Figure 5:** Neuronal network involved in ending a leftward gaze shift while the head terminates
1082 its rotation (stabilized gaze direction). Connecting lines ended by an arrow indicate excitatory
1083 connections; those ended by a circle indicate inhibitory synaptic connections. Blue color
1084 indicates the agonist neuronal oculomotor elements, red color the antagonist ones. Green
1085 color indicates the neurons of the ascending tract of Deiters (ATDN). The thickness of
1086 connecting lines schematizes the strength with which the neurons fire. LR: lateral rectus, MR:
1087 medial rectus, VI, abducens nerve, MRMN: motor neurons innervating the medial rectus
1088 muscle, LRMN: motor neurons innervating the lateral rectus muscle, AIN: abducens
1089 internuclear neurons, NMN: neck motoneurons, PVN: primary vestibular neurons, IVN:
1090 inhibitory vestibular neurons, EVN: excitatory vestibular neurons, VIII: eight cranial nerve.

1091

1092 **Figure 6:** Neuronal network involved in ending a downward (A) and upward (B) gaze shift while
1093 the head terminates its movement (stabilized gaze direction). Connecting lines ended by an
1094 arrow indicate excitatory connections; those ended by a circle indicate inhibitory synaptic
1095 connections. Blue color indicates the agonist neuronal oculomotor elements, red color the
1096 antagonist ones. IOMN: motor neurons innervating the inferior oblique muscle, IRMN: motor
1097 neurons innervating the inferior rectus muscle, SRMN: motor neurons innervating the
1098 superior rectus muscle, SOMN: motor neurons innervating the superior oblique muscle, PVN:
1099 primary vestibular neurons, IVN: inhibitory vestibular neurons, EVN: excitatory vestibular
1100 neurons, VIII: eight cranial nerve.

1101

1102 **Figure 7:** Neuronal network involved in the near response. LR: lateral rectus, MR: medial
1103 rectus, SP: sphincter pupillae, DP: dilator pupillae, CM: ciliary muscle, CG: ciliary ganglion,
1104 MRMN: motor neurons innervating the medial rectus muscle, EWpg: Edinger-Westphal
1105 parasympathetic nucleus, cMRF: central mesencephalic reticular formation, SOA:
1106 supraoculomotor area, cFN: caudal fastigial nucleus, SC: superior colliculus.

1107

1108 **Figure 8:** Neuronal network involved in the generation of horizontal slow pursuit eye
1109 movements. LR: lateral rectus, MR: medial rectus, MN: motor neurons, AIN: abducens
1110 internuclear neurons, NHP/MV: complex nucleus prepositus hypoglossi-medial vestibular
1111 nucleus, ETN: excitatory tonic neurons, ITN: inhibitory tonic neurons, cFN: caudal fastigial
1112 nucleus, NOT: nucleus of the optic tract, rSC: rostral superior colliculus, rNRTP: rostral part of
1113 nucleus reticularis tegmenti pontis, DMPN: dorsomedian pontine nucleus, DLPN: dorsolateral
1114 pontine nucleus, VPL-Th: ventroposterolateral part of thalamus, FEF: frontal eye field, MST:
1115 medial superior temporal area of cerebral cortex.

Figure 1

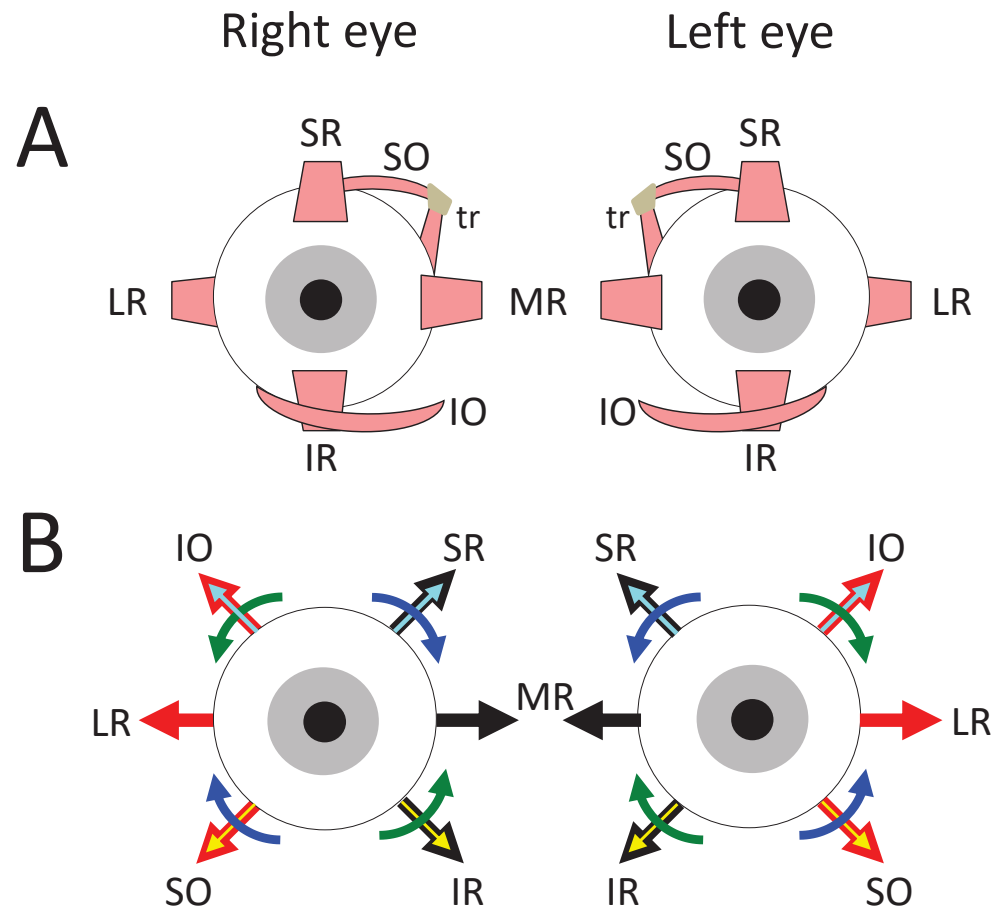
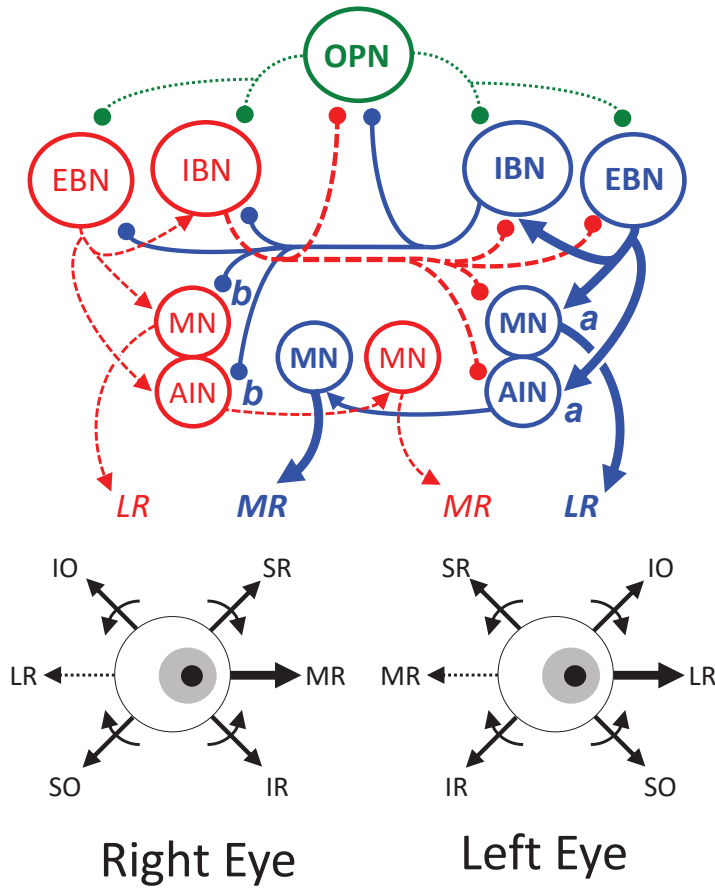


Figure 2

A

LEFTWARD



B

RIGHTWARD

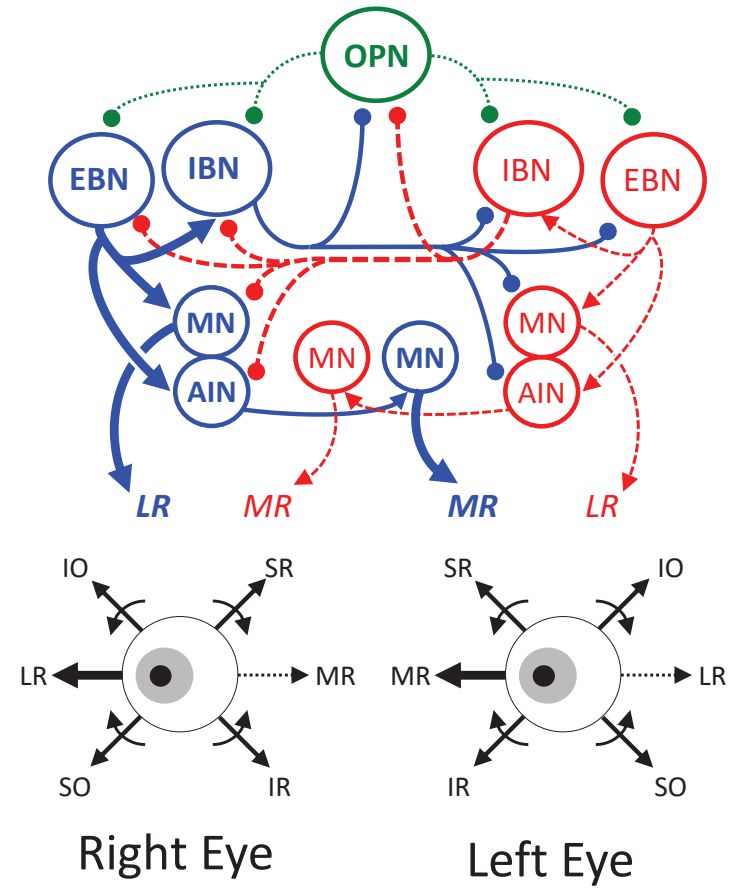


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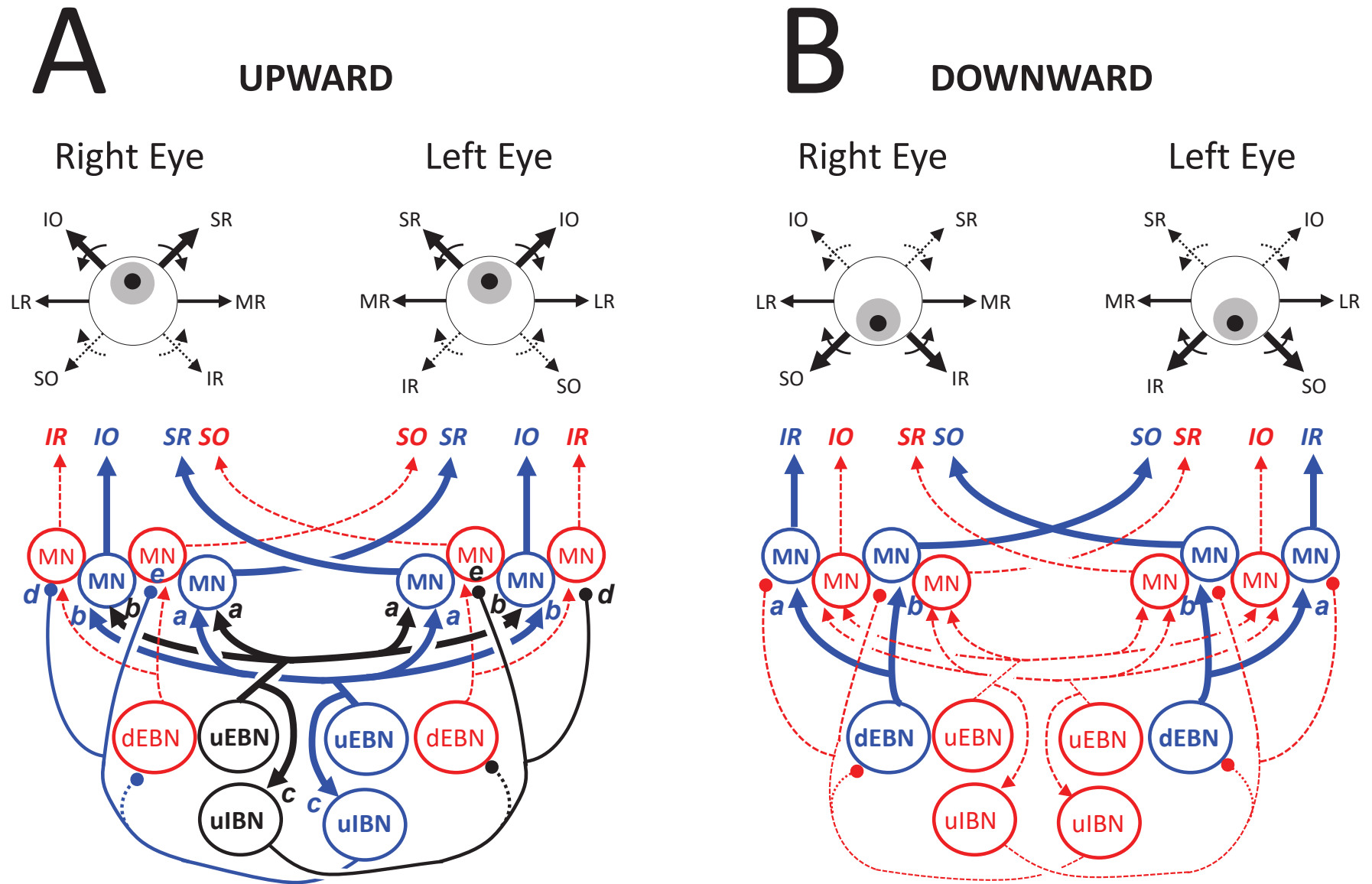


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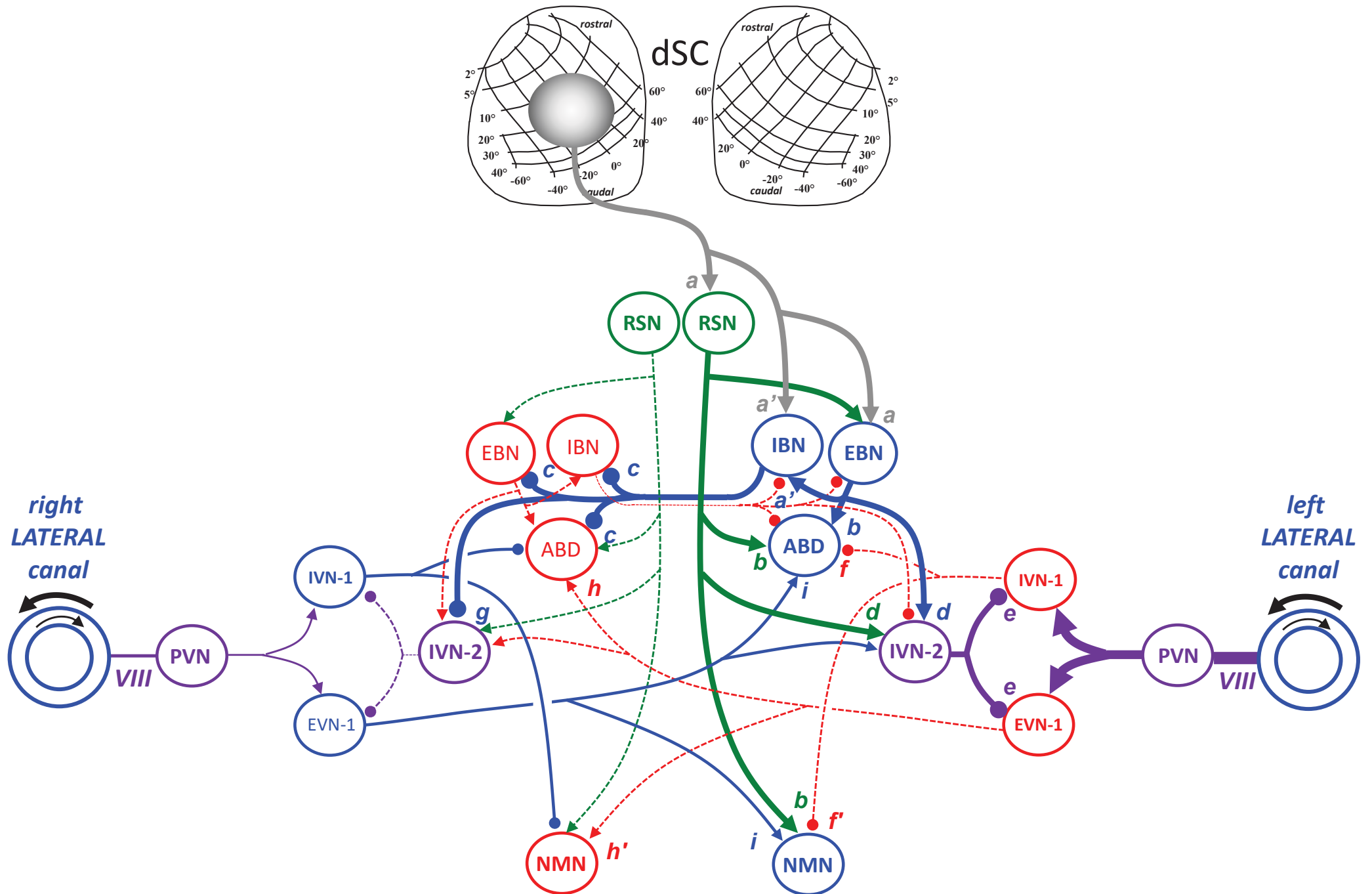


Figure 5

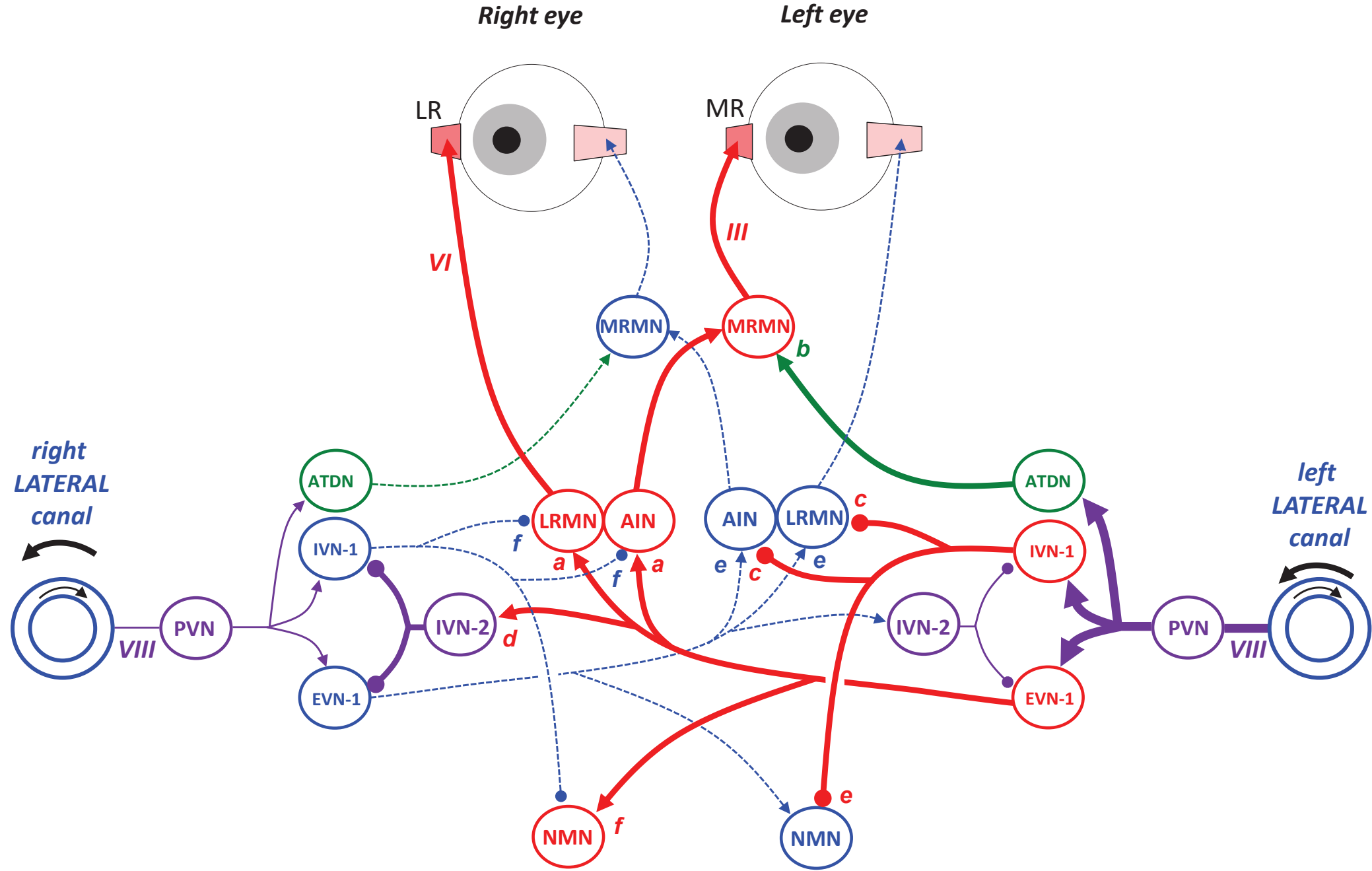


Figure 6

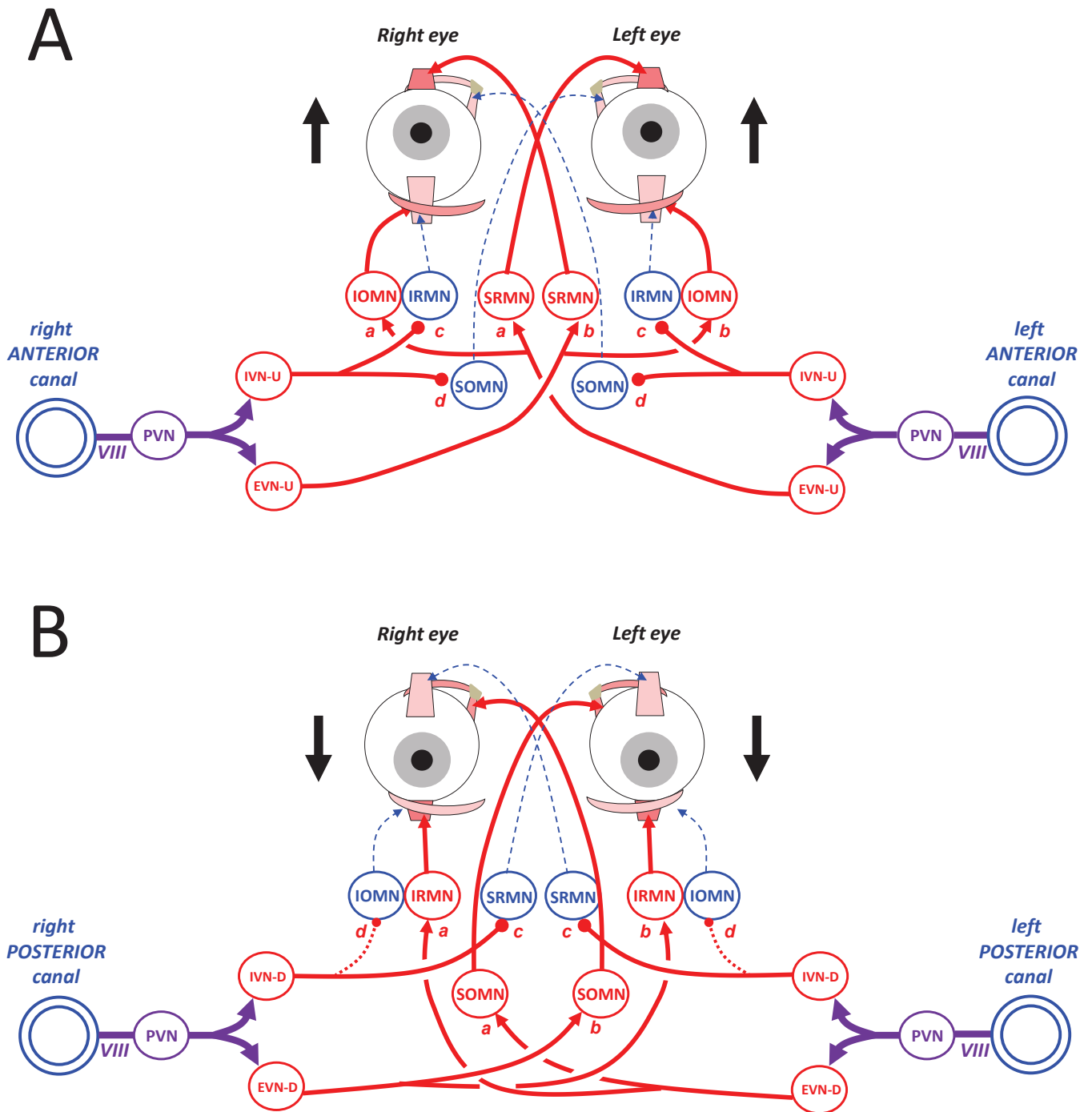


Figure 7

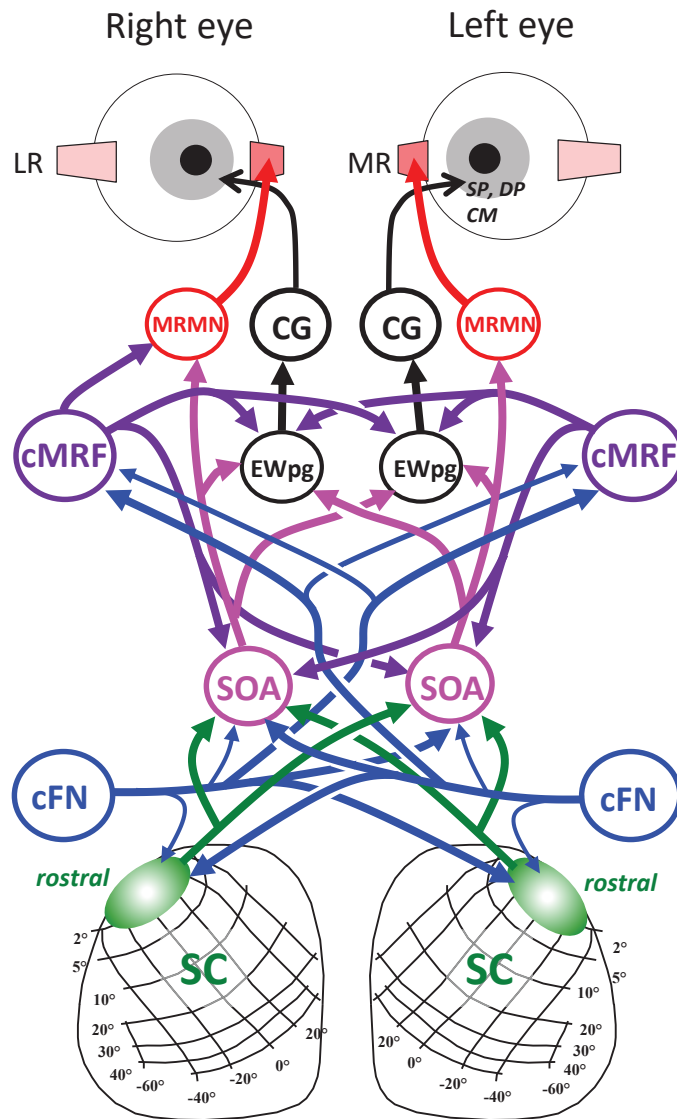


Figure 8

