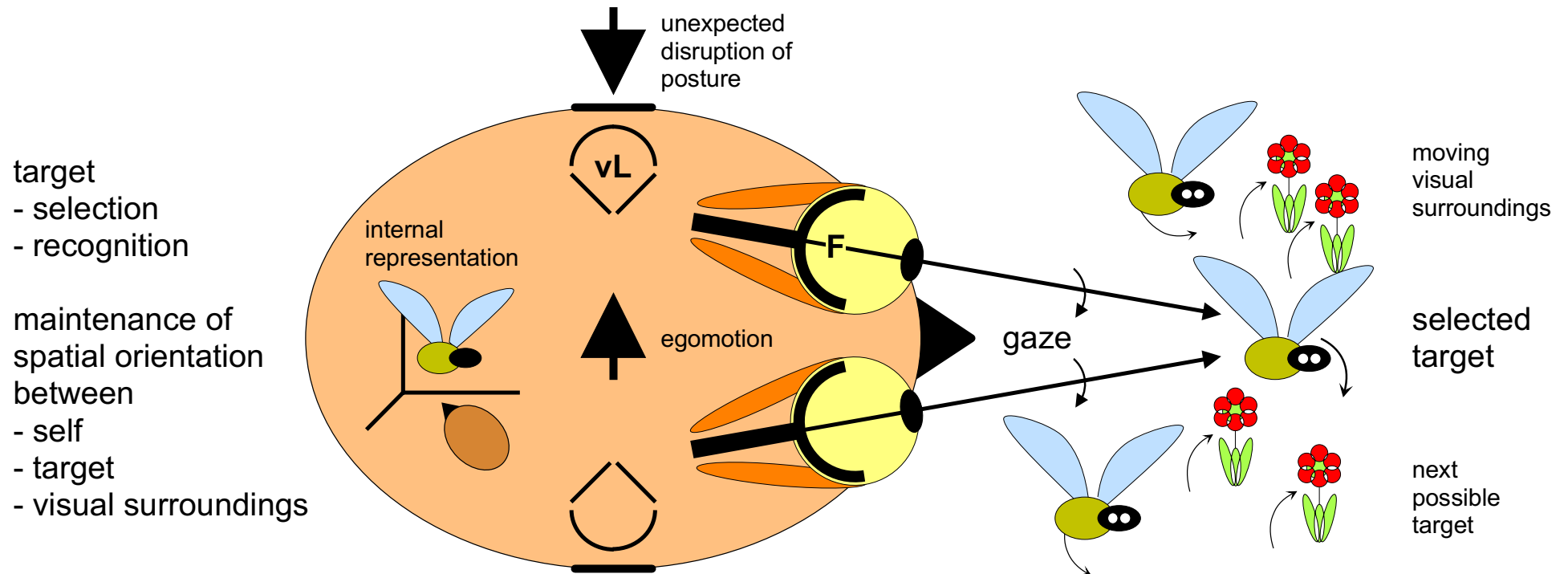


## vestibular tasks

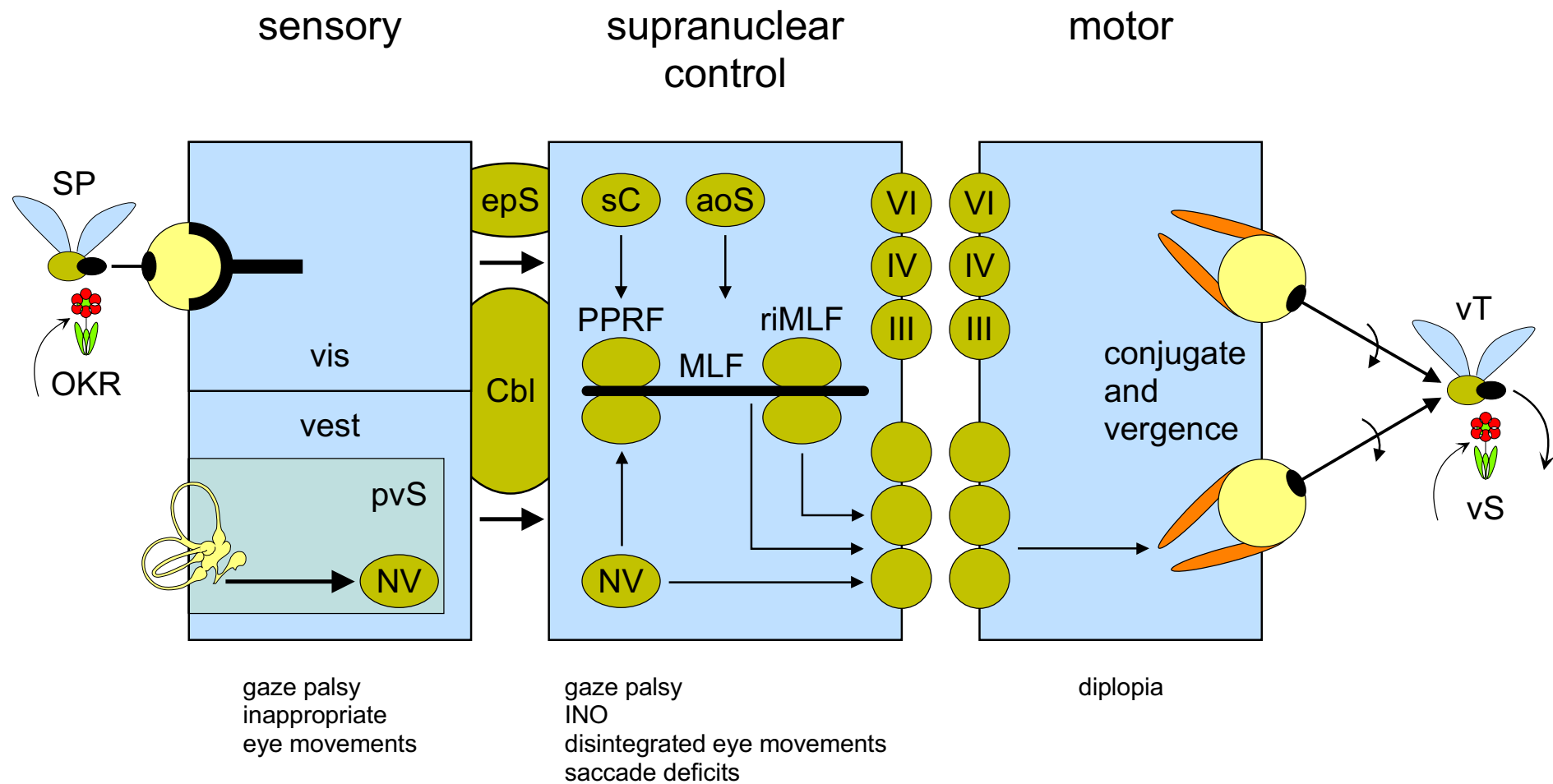
## visual tasks



**Figure 1**

Optomotor tasks. The visuo-, vestibulo-, and proprioceptive-optomotor systems ensure maintenance of orientation in space as well as target selection and recognition despite a host of sensory conflicts and adversary disturbances. Its main goals are to keep the target of interest on the fovea (stabilization of gaze) and to produce an accurate internal representation of spatial relations between the visual surroundings, the target, and the self.

vL = vestibular labyrinth.

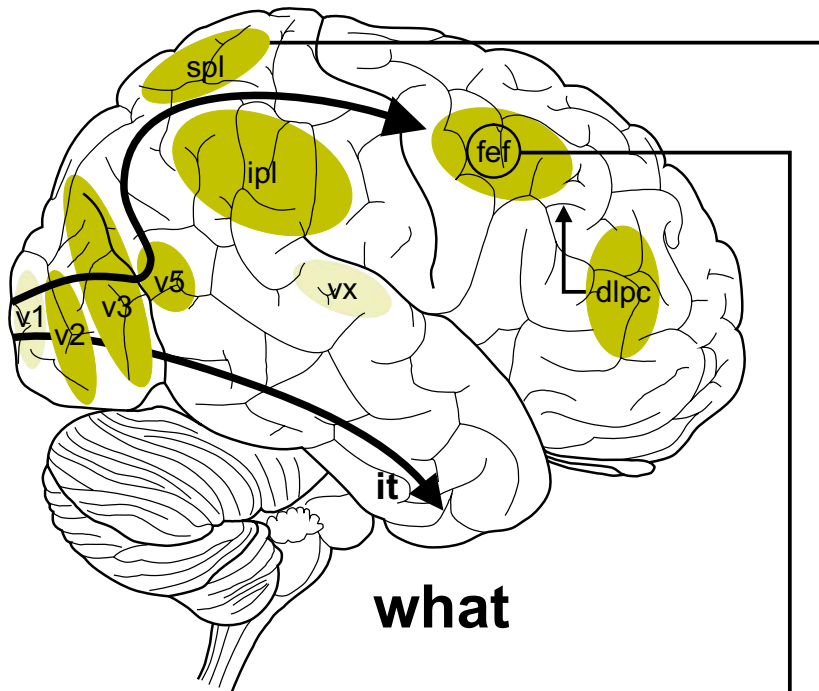


**Figure 2**

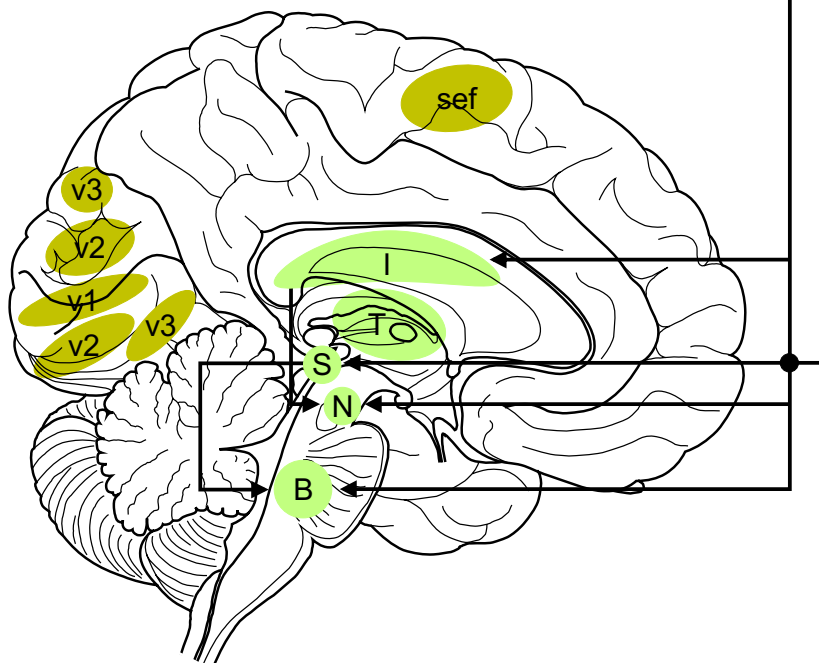
Synopsis of the optomotor system (modified after (Schwarz, Steurer et al., 2000)). Multisensory, visual, vestibular and proprioceptive (not shown) signals (afference) are cortically and subcortically integrated, and guided to the supranuclear optomotor control system, which computes appropriate conjugate and vergence signals for each eye muscle, and distributes them via the medial longitudinal fasciculus (MLF) to the individual oculomotor nuclei (efference). Therefore, the supranuclear control implements the final common pathway for any mechanism that requests eye movements. Typical eye movement patterns due to lesions of the afferences, supranuclear control, and efferences are shown at the bottom. The scene exemplary shows the complexity of the visual computation: While smoothly following a moving visual target (vT) with the eyes, the visual surrounding (vS) is shifted in the opposite direction (evoking full field stimulation), and, hence, elicits an optokinetic response (OKR). Sensory integration must solve the problem of these counteracting demands and generate appropriate signals to the supranuclear control for smooth pursuit eye movements (SP) only.

vT = visual target, vS = visual surroundings, SP = smooth pursuit eye movements, OKR = optokinetic reflex, pvS = peripheral vestibular system, epS = extrapyramidal system, aoS = accessory optic system, Cbl = cerebellum, NV = vestibular nucleus, PPRF = paramedian pontine reticular formation, MLF = medial longitudinal fasciculus, riMLF = rostral interstitial nucleus of the MLF, III = oculomotor nucleus, IV = trochlear nucleus, VI = abducens nucleus, INO = internuclear ophthalmoplegia.

**where**



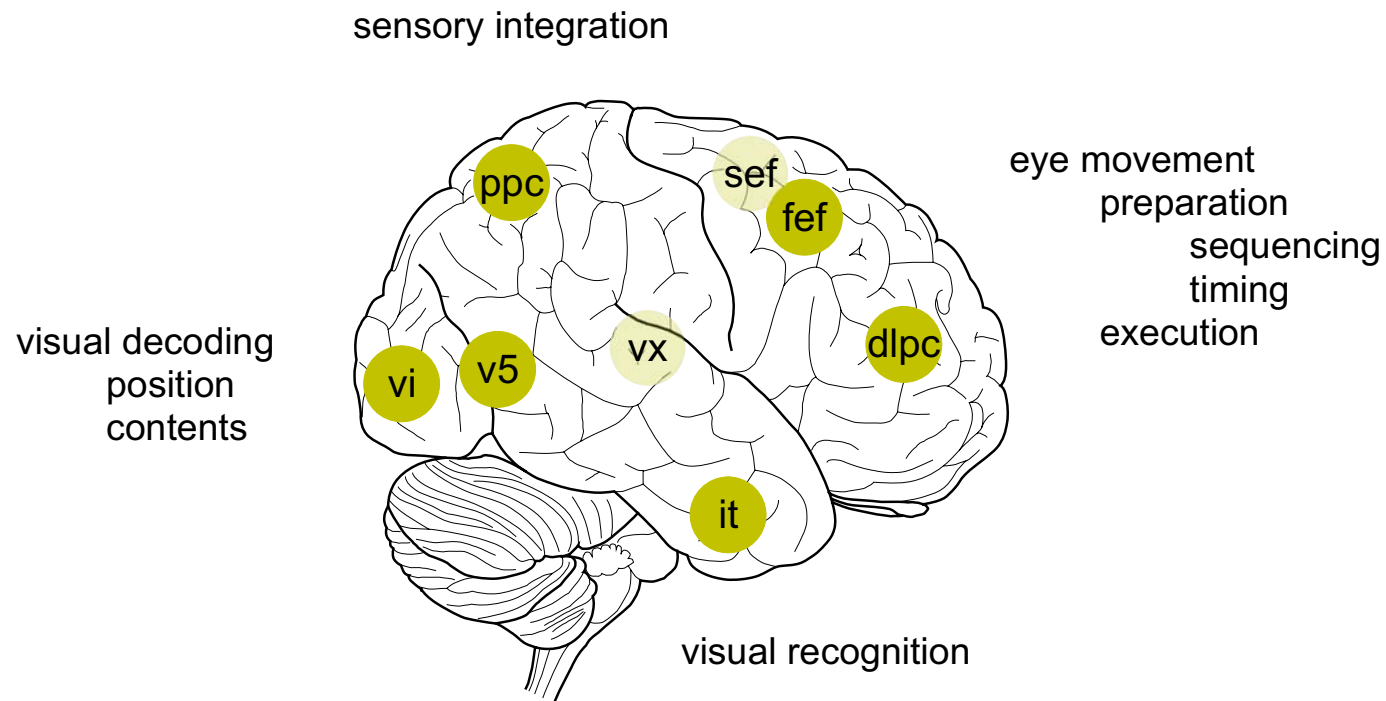
**what**



#### Figure 4

Cortical and subcortical control of visually induced or volitional eye movements (modified after (Schwarz, Steurer, and Candinas, 2000)). Note: Due to considerable variability, cortical areas are shown patchy and approximately. After primordial analysis of the visual scene in the striate cortex (v1, BA 17) and the first relay in the extrastriate cortex (v2, BA 18), signals are forwarded in two distinctly different pathways: The ventral **what** stream transmits object properties, such as shape and color, to the inferior temporal cortex (it). The dorsal **where** stream routes position and velocity signals via the polysensory posterior parietal cortex (spl, ipl), which adds additional information, in particular, from the primary vestibular cortex (vx), and projects to the frontal eye fields (fef), supplementary eye fields (sef), and dorsolateral prefrontal cortex (dlpc) where cortical eye movement commands are generated. The frontal eye field, directly or indirectly via the superior colliculus (S), activates the brain stem optomotor centers. In addition, signals are routed to the substantia nigra (N), which projects back to striatum (I) via the thalamus (T). Therefore, each eye movement also activates the extrapyramidal system. (See Figure 39).

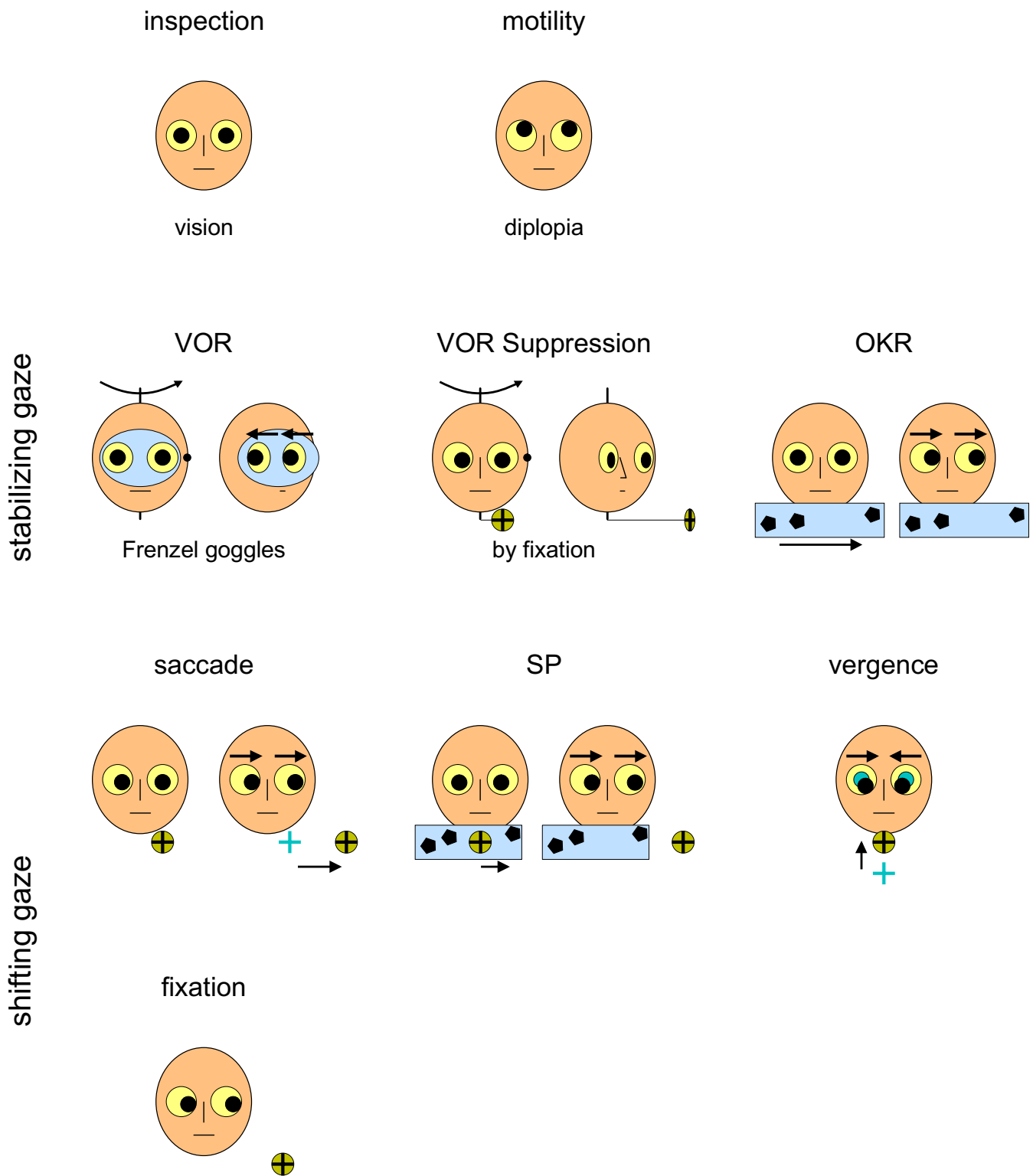
BA = Brodmann area, v1 = primary visual cortex, v2-v5 = extrastriate visual areas, it = inferior temporal areas, spl = superior parietal lobule (BA 5, BA 7), ipl = inferior parietal lobule (BA 39, BA 40), vx = primary vestibular cortex (BA 41, BA 42), fef = frontal eye field (BA 6 in humans), sef = supplementary eye field (BA 6), dlpc = dorsolateral prefrontal cortex (BA 46), I = striatum, T = thalamus, S = superior colliculus, N = substantia nigra, B = brain stem optomotor centers.



**Figure 14**

Contributions of important cortical areas to the generation of visually guided reflexive and volitional saccades and smooth pursuit eye movements. vi = striate and extrastriate visual cortex, v5 = motion processing part of the extrastriate visual cortex (junction of Brodmann areas 19, 37, and 39, including middle temporal area MT and medial superior temporal area MST), it = inferior temporal areas, ppc = posterior parietal cortex, vx = primary vestibular cortex (Brodmann areas 41 and 42, fef = frontal eye field (Brodmann area 6 in humans), sef = supplementary eye field (Brodmann area 6), dlpc = dorsolateral prefrontal cortex (Brodmann area 46).

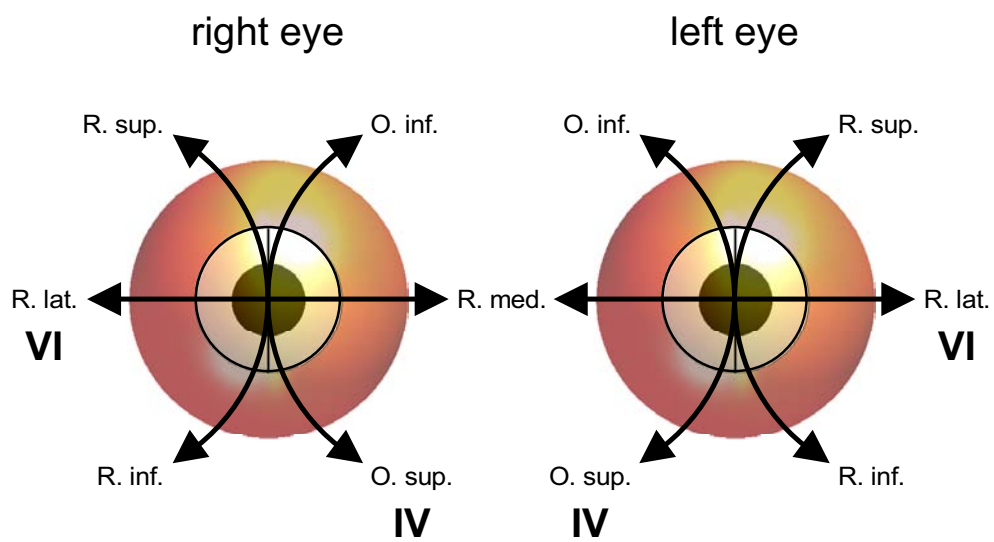




### Figure 15

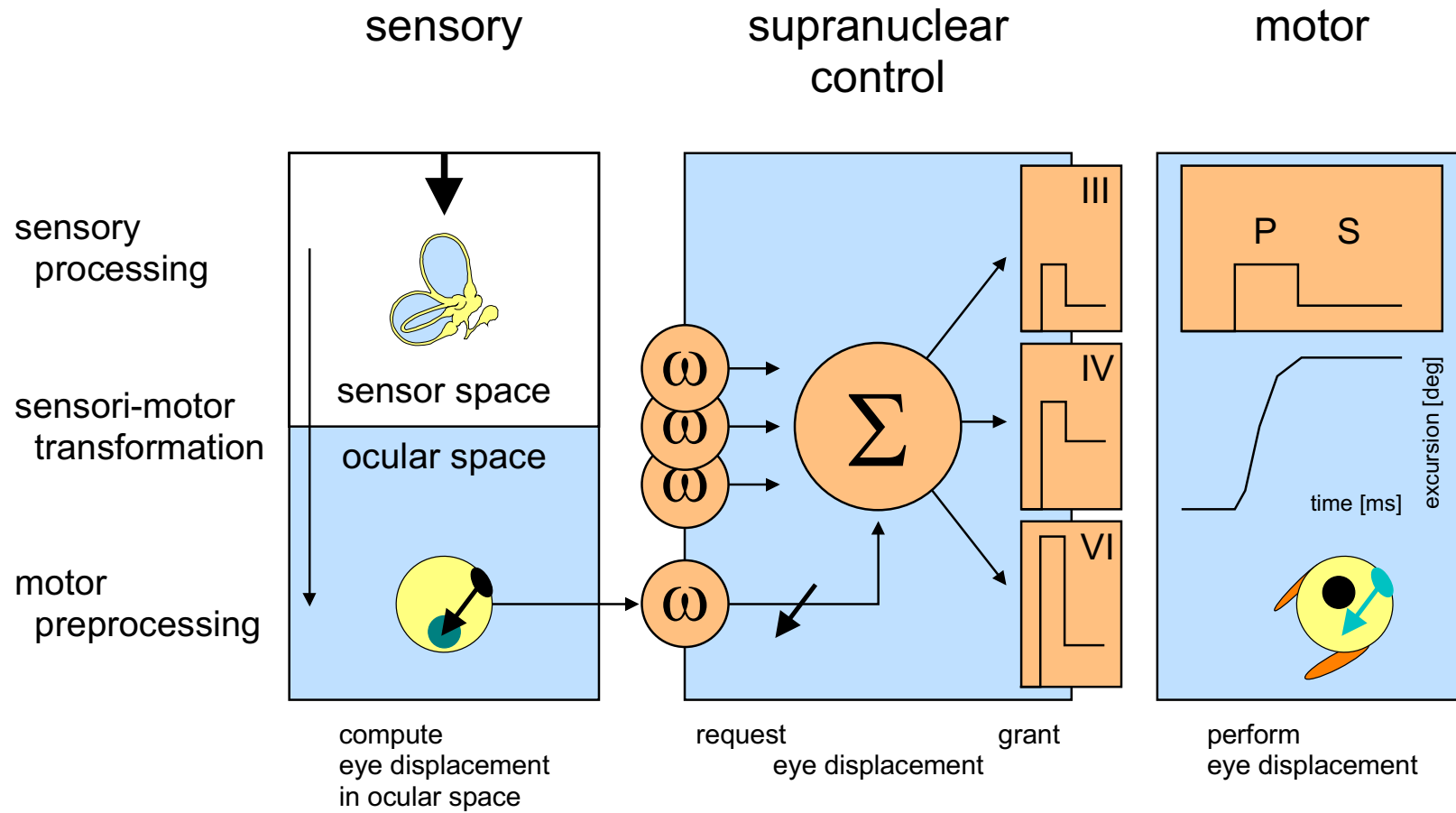
Clinical examination of the optomotor system (modified after (Schwarz, Steurer, and Candinas, 2000)). The investigation comprises both visually and vestibularly induced eye movements.

**Inspection:** reveals misalignment of the eyes and spontaneous nystagmus. Visual acuity must be sufficient and visual fields normal to proceed with examination of visually induced eye movements. **Motility:** eyes should move freely and painlessly in all directions without diplopia. **Gaze-holding mechanisms. VOR:** the peripheral vestibular system is examined by rotating the patient while he/she is wearing Frenzel-goggles (to remove visual input). A normal physiological vestibulo-ocular nystagmus must appear. **OKR:** a large visual pattern evokes a normal physiological optokinetic nystagmus when quickly moved in front of the patient. Note this test also engages the smooth pursuit system. Lack of response may be due to a lesion in the cortical and/or the accessory, subcortical visual system. Note both nystagmus patterns must evoke conjugate reflex eye movements and resetting saccades. These tests are particularly suitable to reveal even a minor unilateral INO due to the continuous generation of saccades. **Gaze-shifting mechanisms. Saccade:** the patient must quickly switch gaze from one small eccentric target to another. Note latency, velocity, and precision of the eye movements. A difference in performance between resetting saccades (during nystagmus) and intentional saccades most likely is due to a cortical, extrapyramidal, collicular, or cerebellar lesion and requires further investigations. **SP:** a small target is slowly moved back and forth in front of a stationary visual background (note difference to OKR). Conspicuously jerking movements may be due to lack of cooperation or concentration (catch-up saccades), or a structural or functional (intoxication) lesion, particularly in the striate or extrastriate visual cortex, the parietal lobe, or the cerebellum. **Vergence:** changing the point of fixation in depth (straight ahead of the patient) examines solely the oculomotor nuclei and nerves. This is of great importance in the diagnosis of an INO (lack of conjugate adduction, preserved adduction during vergence). **Fixation:** the eyes must remain motionless in the resting position and on eccentric targets. Possible pathologies include saccadic intrusions or gaze-evoked nystagmus (quick phase directed away from central position), which is often caused by cerebellar lesions (intoxication). **VOR suppression by fixation:** the patient is asked to fixate a spot that is rotated together with the head (cross on a fingernail). Alternatively, the patient is asked to read out loud a text while walking around. In this test, the VOR must be suppressed by fixation (and probably also by the SP system). Lack of gaze stabilization is mostly due to cerebellar lesions. VOR = vestibulo-ocular reflex, OKR = optokinetic reflex, SP = smooth pursuit.



**Figure 16**

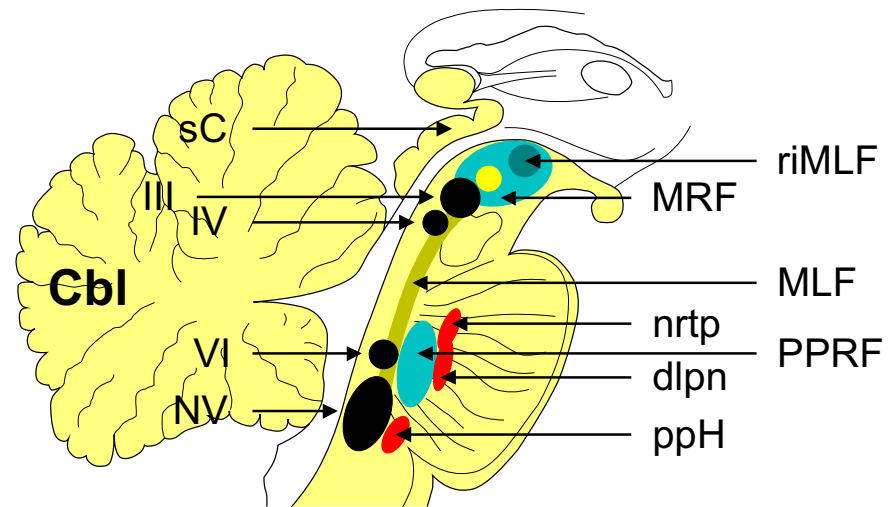
Primary pulling direction of the extraocular muscles. Together, the superior rectus and inferior oblique muscles elevate the eyes from their mid-position, whereas the inferior rectus and superior oblique muscles lower them. In addition, the oblique muscles rotate the eyes in- and outward (torsion). R = rectus muscles, O = oblique muscles.



### Figure 17

Important computational steps from sensory input to motor action. The motor command signals must comprise both a dynamic and a static component to move and hold the eye in an eccentric position since extraocular muscles act like a system of springs that tend to keep the eyeball in a central position in its socket. Characteristically, each motor signal consists of a brief, transient burst of spikes (pulse), to overcome viscous resistance and accelerate the eye, and a sustained discharge level (step) that is linearly dependent on the eccentricity and maintained as long as the eye is kept in its new position. **Left panel.** Eye movement requests resulting from primary sensory processing, which takes place entirely in its own frame of reference, e.g., a retinal frame of reference within the retino-geniculo-cortical system, first undergo sensori-motor transformation, e.g., into an oculocentric frame of reference, in order to become comparable with those from other sources (black arrow indicates desired eye movement). **Middle panel.** The supranuclear optomotor control sums weighted ( $\omega$ ), e.g., by attention, request and, finally, generates a solution consisting of a distinctly different pulse/step signal to each oculomotor nucleus. **Right panel.** Supranuclear pulse/step signals are converted by the efference system (ocular plant) into signals that are appropriate for the respective eye muscles. The pulse component moves the eye into a new position, whereas the step component keeps it there. The step is produced by summation of the puls in the 'neural integrator'. Note the final eye position (position of the pupil) does not fully comply with the requested movement (gray arrow) in this example.

P = pulse, S = step, III = oculomotor nuclei, IV = trochlear nuclei, VI = abducens nuclei.



**Figure 18**

Diagram of important supranuclear and nuclear brain stem structures that control eye movements. Afferent, visual and vestibular signals from the superior colliculus (cS) and the vestibular nuclei (NV), respectively, as well as signals from the paramedian pontine reticular formation (PPRF) and mesencephalic reticular formation (MRF) are distributed via the medial longitudinal fasciculus (MLF), which ends in the rostral interstitial nucleus (riMLF). Together with portions of the nucleus reticularis tegmenti pontis (nrtp), the PPRF generates ipsilateral, horizontal saccades, while the riMLF generates vertical and torsional saccades. In addition, the interstitial nucleus of Cajal (yellow circle in the MRF) plays an important role in maintaining the eccentric (vertical) eye position after saccade. Other structures mediate cortical signals for smooth pursuit eye movements to the cerebellum (dorsolateral pontine nucleus, DLPN), or are part of the 'neural integrator', in particular, the prepositus hypoglossi nucleus (PPH), which provides the step component of the final signal to the oculomotor nuclei.

Cbl = cerebellum, III = oculomotor nucleus, IV = trochlear nucleus, VI = abducens nucleus.

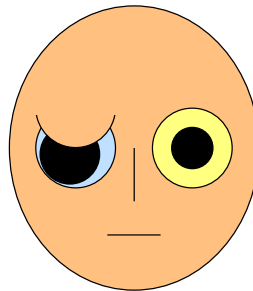
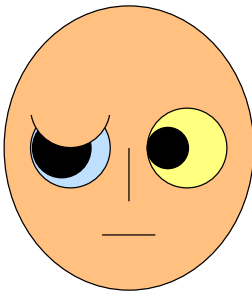


to the right

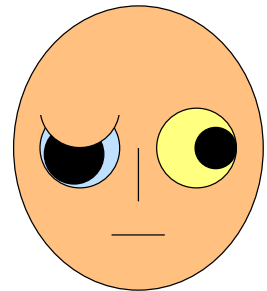
straight ahead

to the left

III

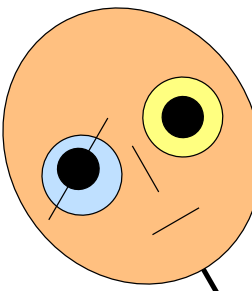


ptosis and mydriasis

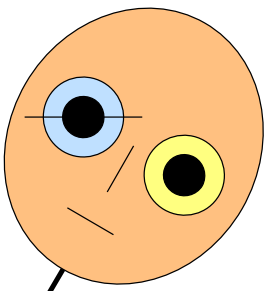
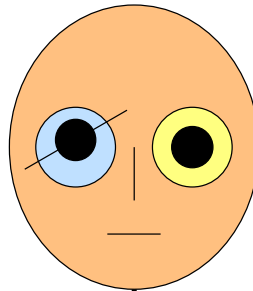


crossed diplopia

IV

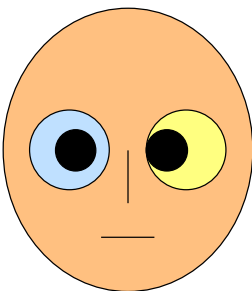


Bielschowsky test

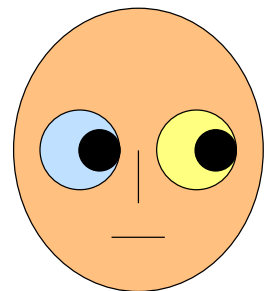
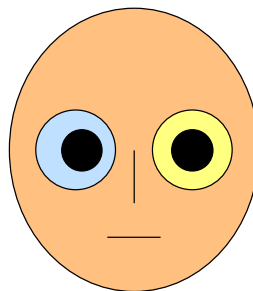


spontaneous

VI



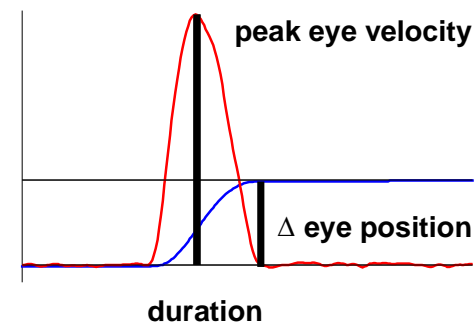
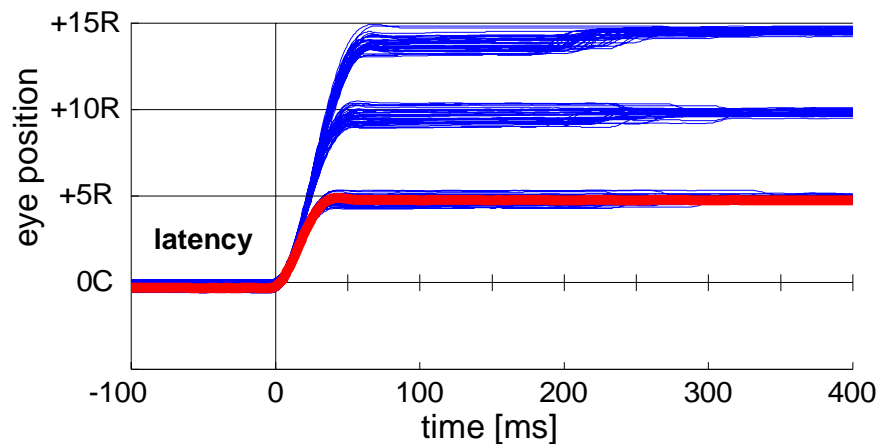
uncrossed diplopia



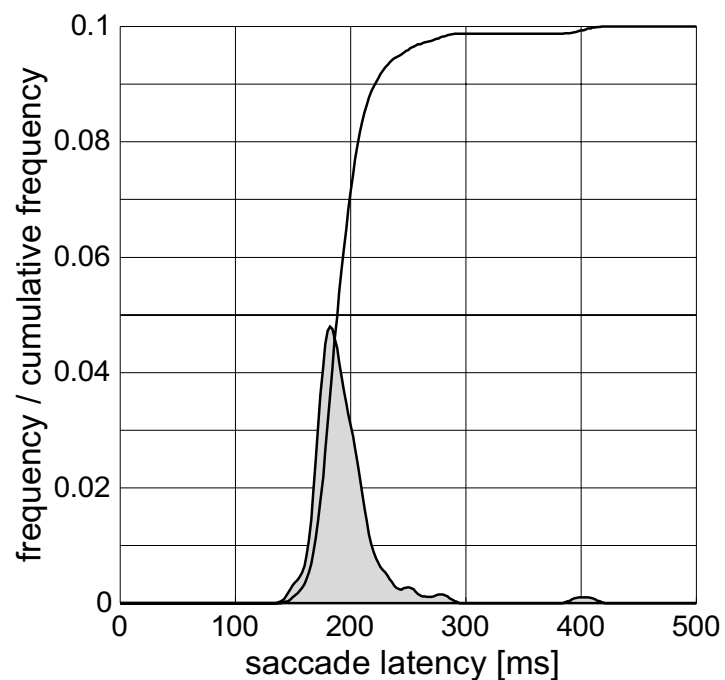
**Figure 19**

Eye position and direction of diplopia due to isolated palsies of the right oculomotor, trochlear, and abducens nerve (modified after (Schwarz, Steurer, and Candinas, 2000)). A complete, internal and external palsy of the oculomotor nerve causes additional ptosis and mydriasis. A trochlear palsy causes a conspicuous head tilt towards the unaffected side to compensate for the lack of inversion by the superior oblique muscle. Note the position of the horizontal eye axis shown for each head position. Diplopia is worse after tilting the head in the opposite direction (positive Bielschowsky test). See text for further explanations.  
III = oculomotor nerve, IV = trochlear nerve, VI = abducens nerve.

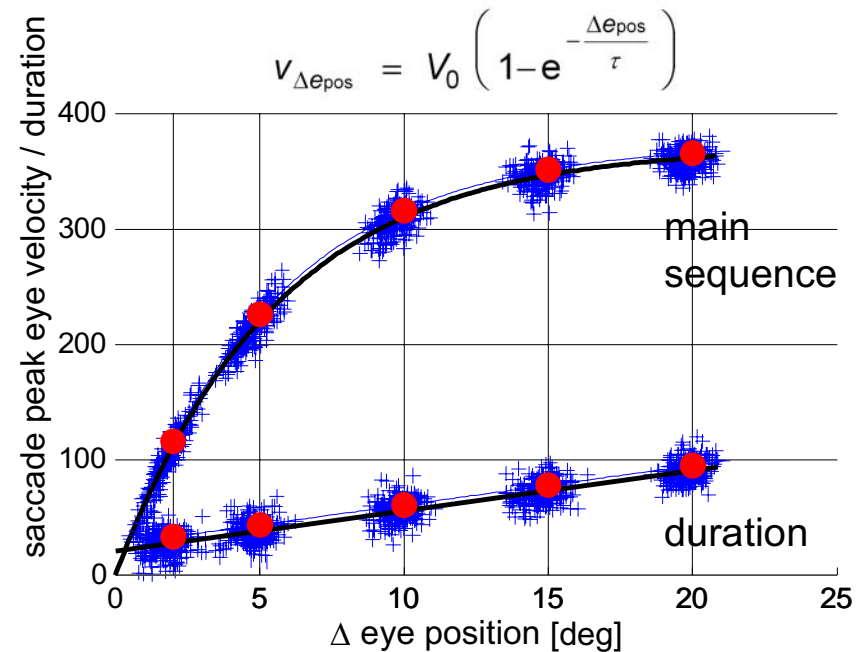
## Female, 62y normal visually guided saccades: raw data (n = 800)



### latency

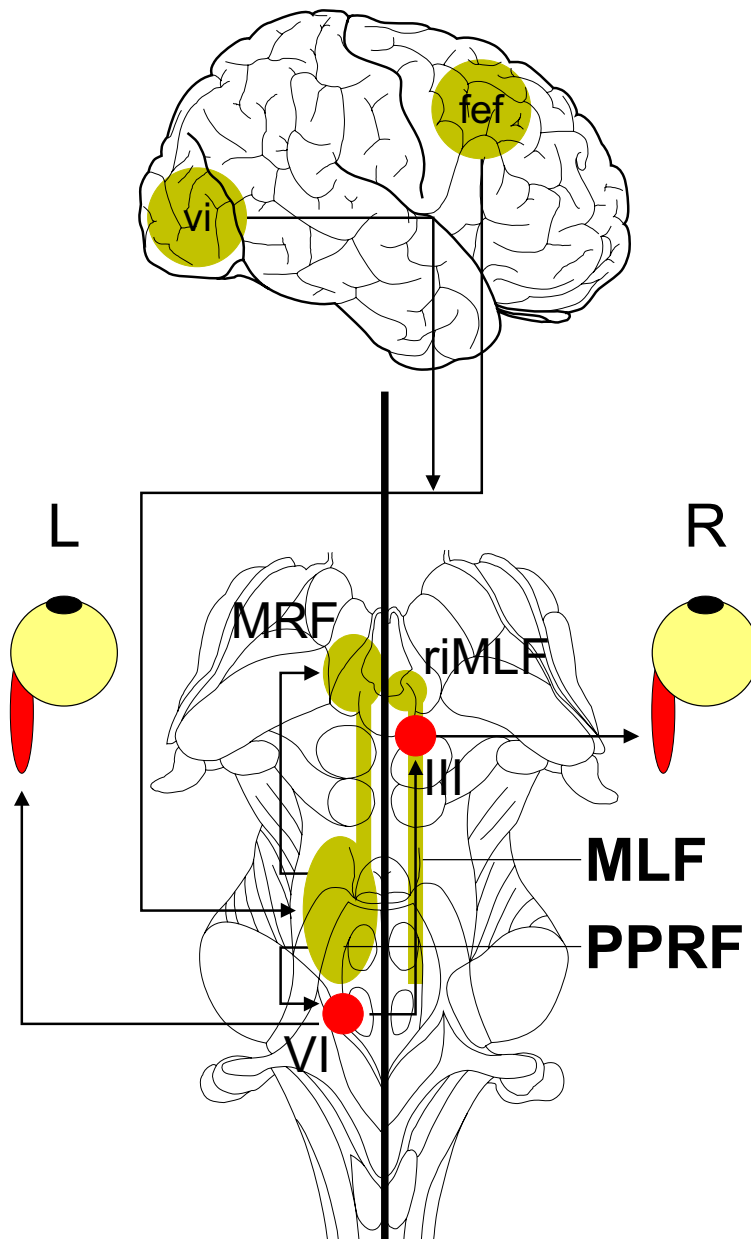


### main sequence / duration



**Figure 28**

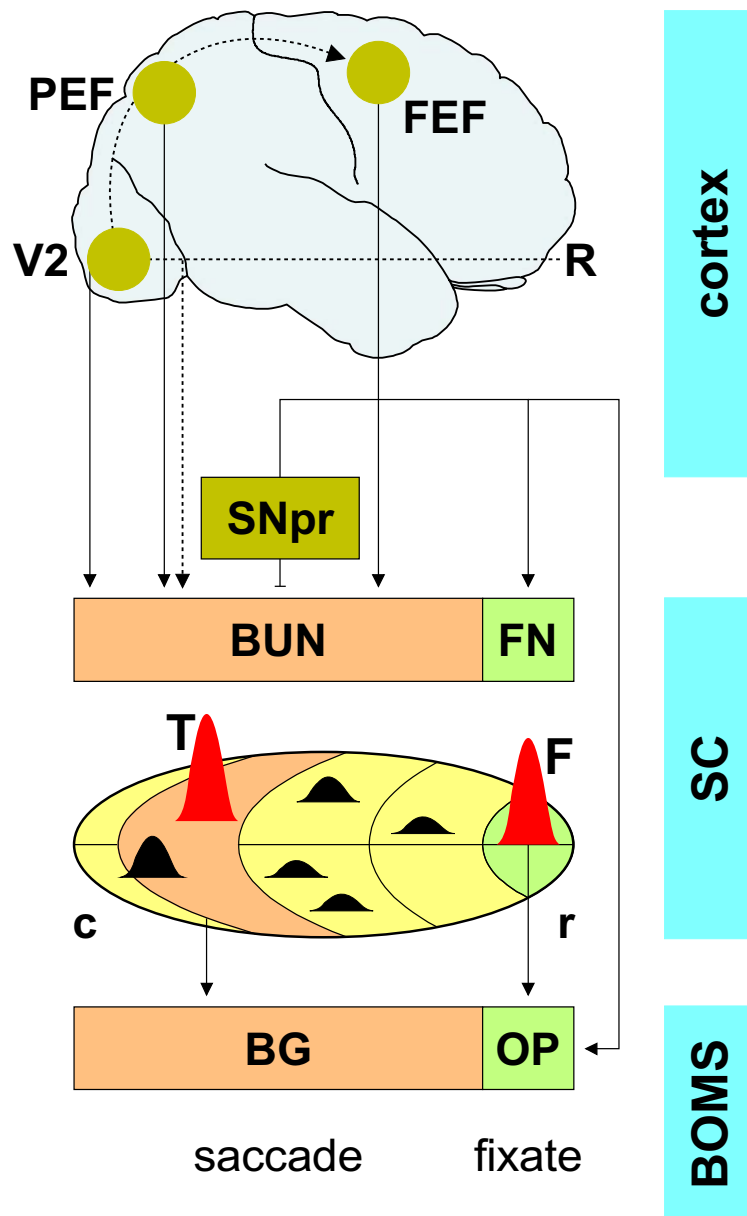
Typical saccade parameters obtained from a 62-year-old healthy female. **Left upper panel.** Exemplary original eye position traces sampled from visually guided saccades 5, 10 and 15° to the right (upward deflection). Saccades are aligned with respect to their onset; hence, the latency distribution will be reflected at negative points on the time axis. Note the machine like feature of saccade performance. **Right upper panel.** The main sequence is computed from the ratio of the eye excursion and the peak eye velocity from each individual trace (red trace in upper left panel). **Lower right panel.** Shows the main sequence (black line) obtained from all eye movements including excursions to 20° to the right (original traces not shown for simplicity) as well as saccade durations for this subject. The main sequence typically is parametrized by an exponential function with two variables (see equation). **Lower left panel.** Latency distribution for the same data. Note the narrow range with a characteristic peak around 200 ms.



**Figure 29**

Control of volitional saccades by the paramedian pontine reticular formation (PPRF) (after (Schwarz, Steurer, and Candinas, 2000)). First, signals from the frontal eye field (fef) and, to a lesser degree from the visual areas (vi), reach the contralateral PPRF. The PPRF, in turn, routes frontal eye field signals to the mesencephalic reticular formation (MRF) for vertical and torsional saccade components. More importantly, it computes the final pulse/step parameters for the horizontal saccadic displacement and sends these requests to the ipsilateral abducens nucleus (VI), which innervates the ipsilateral lateral rectus muscle. In addition, it generates supranuclear eye movement commands with travel to the contralateral oculomotor (III) and trochlear (not shown) nucleus via the medial longitudinal fasciculus (MLF). In this example, the oculomotor nucleus simply innervates the ipsilateral medial rectus muscle generating a purely horizontal saccade. Lesions of the PPRF or any higher order structure result in a conjugate gaze palsy without diplopia. Lesions of the MLF, on the other hand, result in an internuclear ophthalmoplegia (INO) with a dissociation of conjugate eye movements (see Figure 26).

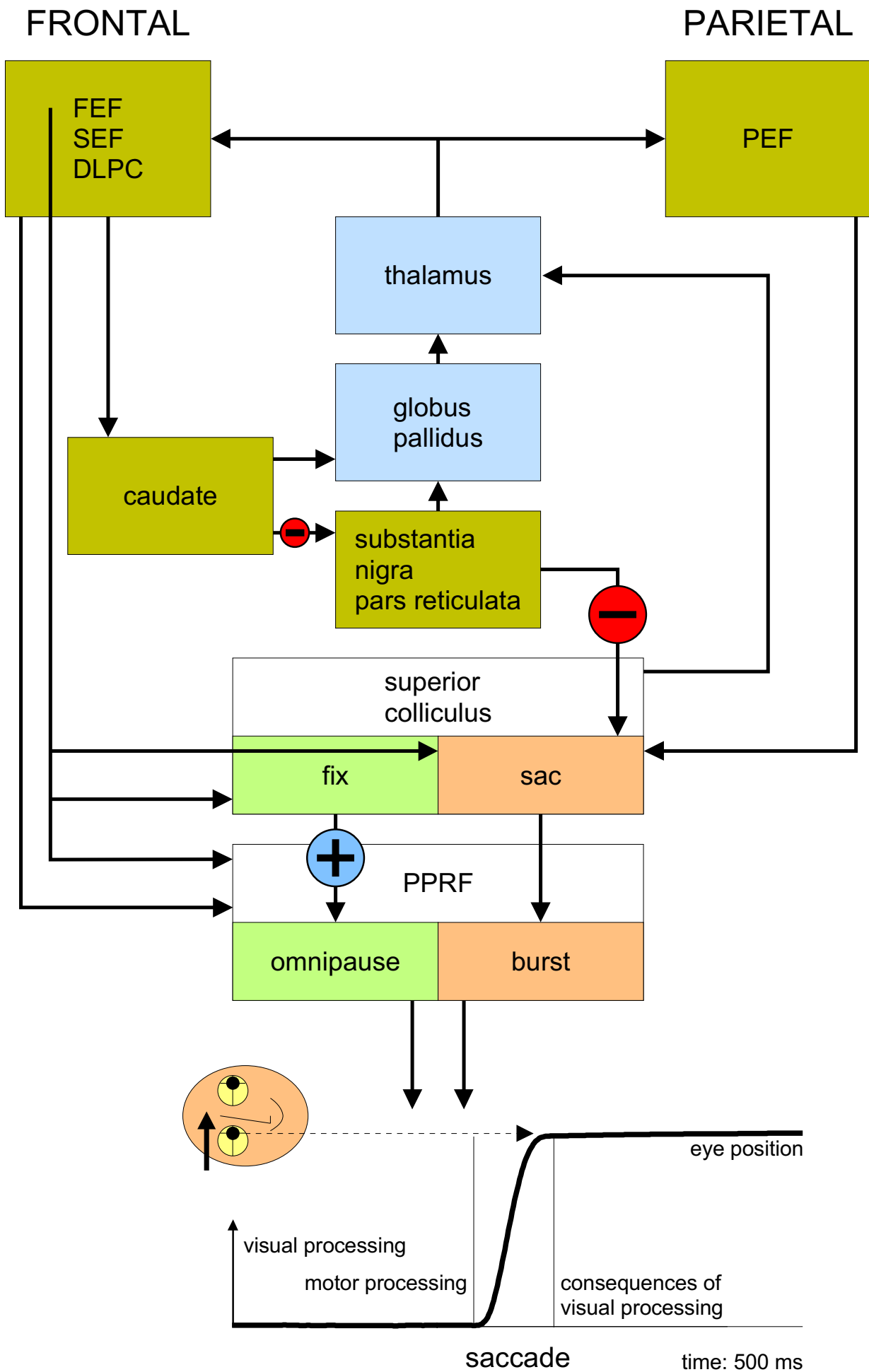
R = right side, L = left side, PPRF = paramedian pontine reticular formation, MRF = mesencephalic reticular formation, III = oculomotor nucleus, VI = abducens nucleus, MLF = medial longitudinal fasciculus, riMLF = rostral interstitial nucleus of the MLF,



**Figure 30**

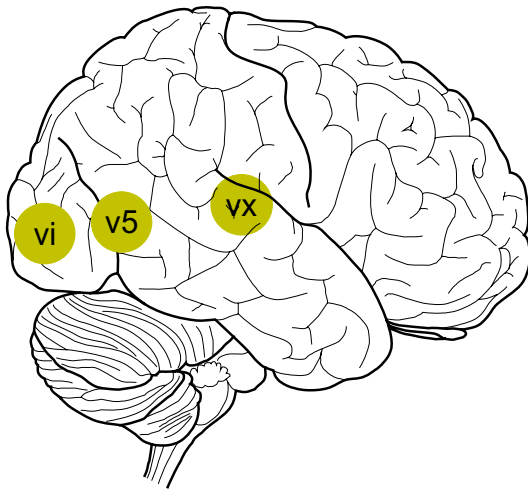
Simplified diagram of oculomotor behavior during an intended saccade, which would result in a gaze shift from the current point of fixation (F) to a novel target (T) (modified after (Weber, Schwarz et al., 2000)). See chapter 3.2.4.1 for details. The retinotopic superior colliculus (SC) consists of a sensory, intermediate and motor layer and is an important computational relay between various cortical and subcortical structures that require access to the brain stem saccade generator. It is able to prepare and maintain a map of many possible saccades, one of which may be released employing a very efficient and elegant push-pull mechanism between its fixation neurons and the corresponding omnipause neurons, which are located in the nucleus raphe interpositus close to the pontine midline, as well as its peripheral buildup neurons and their corresponding burst neurons, which are located in the paramedian pontine reticular formation (PPRF) and mesencephalic reticular formation (MRF) (Figure 19, Figure 37). Hence, shifting the focus of attention is either overt and produces a saccade, or it is covert, in which case the saccade is computed but not executed and fixation is maintained. Furthermore, it indicates that both the network for generating saccades and the network subserving attentional mechanisms at least in part share the same pathways. T = novel visual target, F = current point of fixation, PEF = parietal eye field, FEF = frontal eye field, R = retinal input, SNpr = substantia nigra pars reticulata, BUN = buildup neuron, FN = fixation neuron, SC = superior colliculus (all layers merged), c = caudal, r = rostral, BOMS = brain stem oculomotor system, BG = burst-generator neuron, OP = omnipause neuron. Heights of Gaussians indicate discharge activity of a cell cluster.





**Figure 31**

Simplified diagram of the involvement of the extrapyramidal system in the generation of saccadic eye movements (see also Figure 38). **Top panel.** During visual processing and visuo-motor transformation, fixation is maintained by the omnipause neurons, which are directly controlled by fixation neurons (fix) in the superior colliculus. In addition, the pars reticulata of the substantia nigra inhibits peripheral buildup neurons (sac), albeit not in a very clear way and profoundly influenced by the behavioral context. It is controlled by the frontal cortical eye movement system via the caudate nucleus, which, in turn, inhibits the substantia nigra pars reticulata. Depending on the site of an extrapyramidal lesion, it may cause a) incapacitating saccadic intrusions as well as b) the inability to launch a new saccade. **Bottom panel.** Eye position during execution of a saccade. Shown are the various epochs of supranuclear control. Shortly before the eyes are moved into a new position, the omnipause neurons are inhibited. Subsequently, the brain stem burst neurons are activated by the peripheral buildup neurons (sac) of the superior colliculus.



## **v1**

anopsias

defects of perception

*acutely*: unable to make sac or generate smooth pursuit to visual stimuli presented into the blind field

*chronically*: strategies develop to scan the environment and place the target into intact field

## **v5 (MT)**

retinotopic defect of motion vision causing sac and smooth pursuit to be impaired when visual stimuli fall into affected visual field

## **v5 (MST)**

directional defect of smooth pursuit for ipsilateral target motion

## **VX**

contralateral tilt of subjective visual vertical

circularvection abolished during optokinetic stimulation

**Figure 32**

Characteristic deficits of saccades and smooth pursuit eye movements after lesions of various visual cortical areas. (See Figure 15 for labels).

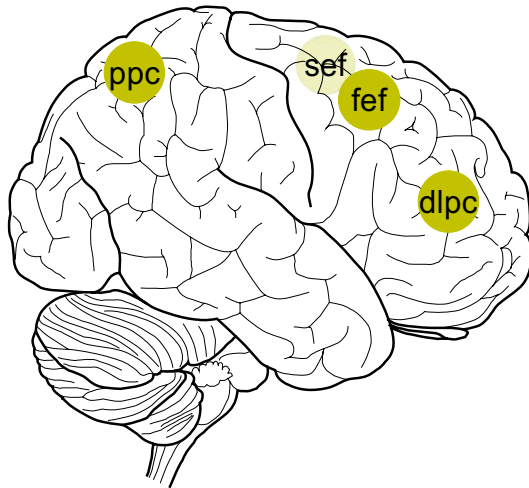
## **ppc**

contralateral inattention  
ipsilateral gaze deviation / preference  
increased latency for visually guided sac  
errors on response to double-step sac  
impaired smooth pursuit  
if target moves across background

## **ppc bilateral**

*Balint's syndrome*

peripheral visual inattention (simultanagnosia)  
inaccurate arm pointing (optic ataxia)  
difficulties in making visually guided sac



## **sef**

does not affect visually guided sac  
inaccuracy of memory guided sac  
if gaze shifts during memory period  
impaired ability to make remembered sequence of sac  
especially with left-sided lesions

## **fef**

increase in reaction time of sac  
visual target in overlap task  
remembered target location  
imagined target in antisac task  
hypometria of sac  
visual / remembered target contralateral  
reduced ability to make sac  
in anticipation of predictable target stepping contralaterally  
impaired ability to inhibit inappropriate sac to novel target  
impairment of smooth pursuit and okr moving ipsilaterally

## **dlpc**

inaccuracy of sac made to  
remembered target locations contralaterally  
defects of  
predictive sac  
memory guided sac  
antisac

**Figure 33**

Characteristic deficits of saccades and smooth pursuit eye movements after lesions of various parietal and frontal cortical areas. (See Figure 15 for labels).

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