

# Neurophysiology: Cerebral Carbon Copies

## Dispatch

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**Predicting the consequences of our actions is essential for sensorimotor control. A candidate neural pathway underlying the prediction of eye position during saccades has been reported.**

As your eyes scan this page, despite the constantly changing retinal images, your perception of the world is stable. If, however, the identical retinal images were induced by moving the visual scene, with eyes fixed, you would correctly perceive the world as moving. How can these two identical retinal inputs give such different percepts? René Descartes [1] first understood that if the visual scene is apparently stable during eye movements, this is because the brain takes into account the motor commands sent to move the eyes. This is easily demonstrable: close one eye and gently push on the open eye (through the lid) with your finger. The world appears to move, as this is the usual percept for a changing retinal image without an oculomotor command. Sperry [2] suggested that when a motor command is sent to the eyes, a ‘corollary discharge’ of that command is fed back to sensory centers to adjust perception. In parallel, von Holst and Mittelstaedt [3] developed the idea that a copy of the motor command is used to cancel out the effects of sensory changes induced by self-motion — the so-called ‘efference copy’ hypothesis. In this way, the brain is able to predict the sensory consequences of our actions and adjust our percepts appropriately.

Direct demonstrations of the existence and use of corollary discharge in mammals have proved difficult. The putative corollary discharge must meet four criteria. First, the signal must be correlated with the motor command, and not with sensory feedback. Second, to distinguish it from the actual motor command, the signal must not generate movement. Third, the signal must be used to update the estimated body state, for example eye position. Last, it must alter perception appropriately. Several studies have already found pathways which fulfill some of these criteria. For example, in a series of experiments in the cat, Arshavsky and colleagues [4] discovered fibers in the spinal cord that relay motor patterns to the cerebellum. Other motor signals that feed back to central structures have also been found. In the monkey, some neurons in the primary somatosensory area discharge before movement, at a time when their receptive field cannot have been stimulated [5]. In both cases, however, it is unclear how these internal feedback signals are processed, let alone

integrated with the ongoing motor program or the eventual proprioceptive feedback. Significant progress has recently been made by Sommer and Wurtz [6] in a study of eye movements in monkeys. Recording in the medio-dorsal thalamus, they found neurons that seem to pass the first three criteria. Their results suggest that these cells belong to a corollary discharge pathway necessary for rapid updating of the internal representation of eye position.

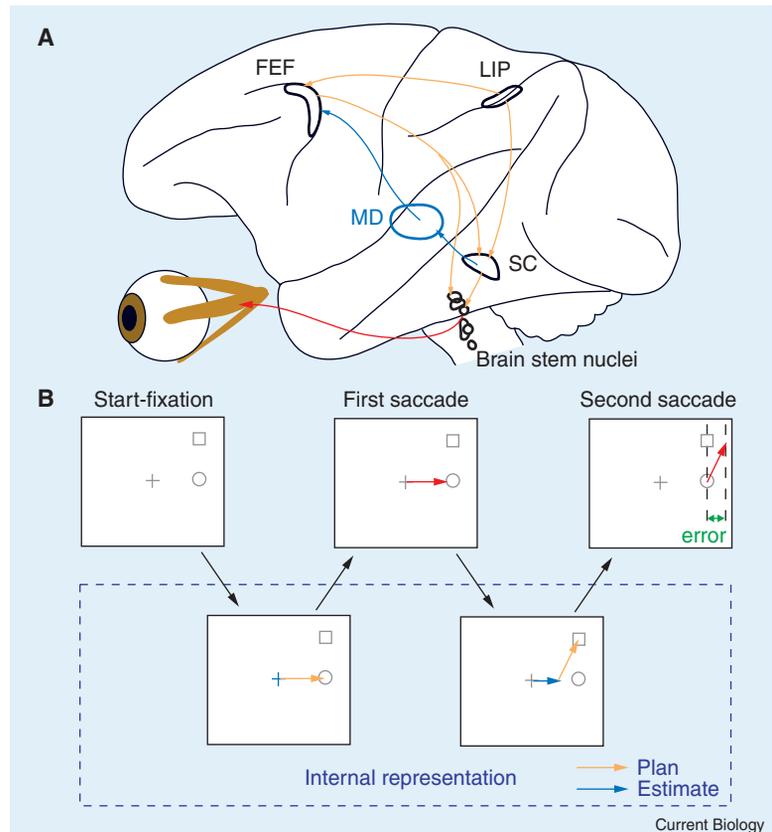
Sommer and Wurtz [6] examined the brisk eye movements, known as saccades, which primates make two to three times per second. Previous research had already established that saccades are planned as eye displacement vectors; there is no specification of a desired eye position. When making sequential eye movements to two remembered targets (a double-step saccade task), the brain cannot simply use the original retinal vectors for each movement: current eye position must be taken into account prior to the second movement [7]. The second saccade is still accurate after removal of proprioception, and therefore must be based on corollary discharge [8]. Sommer and Wurtz [6] reasoned that if the corollary discharge signal was disrupted, this would lead to an incorrect estimate of eye position after the first saccade, and hence an inaccurate second saccade. In contrast, the absence of corollary discharge should not affect the first saccade, as this can be planned based on the retinal vector experienced during the initial presentation of the targets.

Sommer and Wurtz [6] investigated the properties of medio-dorsal (MD) thalamic neurons which link the superior colliculus to the frontal eye fields (FEF), an area of the cerebral cortex involved in the planning of voluntary saccades (Figure 1A). They first established that MD neurons fire before saccade onset, demonstrating that their activity is linked to the motor command, not the sensory feedback. These neurons were then temporarily inactivated on one side of the brain by a local application of muscimol (a GABA<sub>A</sub> antagonist). This did not seem to affect the precision and velocity of a saccade to a single target. In contrast, monkeys were impaired in the second saccade of the double-step task. Their errors suggested that they had not fully updated their estimate of the eyes’ position (Figure 1B). These results fulfill the first three criteria that MD neurons carry corollary discharge signals.

Can this deficit be explained differently? It seems unlikely to arise from an impairment of movement planning, as the monkey could not guess where the second target would appear when preparing the first movement. Sommer and Wurtz [6] also demonstrated that the variability in both the first and second saccade end points is not increased by the inactivation. From this, they can rule out that the results arise from an accumulation of errors along a sequence of vectorially planned movements. The same argument excludes a degradation of perception or working memory.

Figure 1.

(A) Schematic organization of cerebral saccadic control. The goal of the eye movement is defined by parietal area LIP. The saccade is then triggered by activity in the superior colliculus (SC) through the brain stem nuclei. A feedback pathway (blue) from SC through medio-dorsal thalamus (MD) to the frontal eye fields (FEF) exhibits properties of a corollary discharge. (B) The double-step saccade task during MD inactivation. Upper row shows actual movements (red) and lower row shows the internal estimates of the planned movement vectors (orange) and estimates of current eye position (blue). A first target (circle) is briefly flashed. Just before movement initiation, a second target (square) is flashed and the monkey must make a saccade to this after its first saccade. Stimulus durations are tailored so that the animal cannot pre-plan the second saccade. Based on the retinal error, the first saccade is correctly planned (lower left panel, orange) and executed (upper middle panel, red). But because of inactivation of corollary discharge, the estimate of eye position is not fully updated (lower right, blue) and hence the next eye movement is planned incorrectly (lower right, orange). When executed as a vector (top right, red) this leads, as observed, to an inaccurate second saccade.



As with every exciting experiment, this one generates several predictions which can be tested. If MD activity is indeed a corollary discharge, electrical microstimulation in MD should not trigger eye movements, but should induce errors in subsequent eye movements. Also, to rule out any explanation related to deficits of movement planning, an MD-inactivated monkey could be asked to make a single saccade to a remembered target following a saccade triggered by electrical stimulation of the superior colliculus [9]. Similar deficits should be seen in this situation. Interestingly, in humans, FEF lesions do not impair double-step saccade tasks [10,11], whereas fronto-parietal lesions [12] induce precisely the errors reported here. It will be important to reconcile the new view of FEF with the clinical data.

Finally, it remains to be demonstrated whether MD inactivation alters the monkey's visual percept. Prediction of incoming sensory feedback, using corollary discharge, has been demonstrated in the primate parietal cortex. Parietal neurons become active when a stimulus is about to be brought into their receptive field by an impending saccade, even though the eye has not yet moved [13]. Such a predictive remapping could underlie the apparent stability of the visual world. Do Sommer and Wurtz's [6] MD neurons play a role in this sensory anticipation? Our understanding of the interplay between structures involved in oculomotor control is still embryonic. Nevertheless, the long-awaited discovery of a possible corollary discharge in the primate brain is very welcome news to anybody interested in the neural control of movement.

## References

1. Descartes, R. (1664). *Traité de l'homme*. In *L'homme* de René Descartes. L. de la Forge. (Paris: Fayard [1999]).
2. Sperry, R.W. (1950). Neural basis of the spontaneous optokinetic response. *J. Comp. Physiol. Psychol.* 43, 482–489.
3. von Holst, E. and Mittelstaedt, H. (1950). Das Refferenzprinzip. Wechselwirkungen zwischen Zentralnervensystem und Peripherie. *Naturwissenschaften* 37, 464–476.
4. Arshavsky, Y.I., Gelfand, I.M., Orlovsky, G.N. and Pavlova, G.A. (1978). Messages conveyed by descending tracts during scratching in the cat. I. Activity of vestibulospinal neurons. *Brain Res.* 159, 99–110.
5. Soso, M.J. and Fetz, E.E. (1980). Responses of identified cells in postcentral cortex of awake monkeys during comparable active and passive joint movements. *J. Neurophysiol.* 43, 1090–1110.
6. Sommer, M.A. and Wurtz, R.H. (2002). A pathway in primate brain for internal monitoring of movements. *Science* 296, 1480–1482.
7. Becker, W. and Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Res.* 19, 967–983.
8. Guthrie, B.L., Porter, J.D. and Sparks, D.L. (1983). Corollary discharge provides accurate eye positional information to the oculomotor system. *Science* 221, 1193–1195.
9. Sparks, D.L. and Mays, L.E. (1983). Spatial localization of saccade targets. I. Compensation for stimulation-induced perturbations in eye position. *J. Neurophysiol.* 49, 45–63.
10. Rivaud, S., Muri, R.M., Gaymard, B., Vermersch, A.I. and Pierrot-Deseilligny, C. (1994). Eye movement disorders after frontal eye field lesions in humans. *Exp. Brain Res.* 102, 110–120.
11. Heide, W., Blankenburg, M., Zimmermann, E. and Kompf, D. (1995). Cortical control of double-step saccades: implications for spatial orientation. *Ann. Neurol.* 38, 739–748.
12. Duhamel, J.R., Goldberg, M.E., Fitzgibbon, E.J., Sirigu, A. and Grafman, J. (1992). Saccadic dysmetria in a patient with a right frontoparietal lesion. *Brain* 115, 1387–1402.
13. Duhamel, J.R., Colby, C.L. and Goldberg, M.E. (1992). The updating of the representation of visual space in parietal cortex by intended eye movements. *Science* 255, 90–92.