A number of terrestrial arthropods have the capability to balance their water budget by actively absorbing water from highly unsaturated atmospheres. These truly terrestrial arthropods achieve this balance by a combination of a cuticle with very low permeability and locally creating extremely low water activity in specialized tissues (*3*). In common with most soil arthropods, *F. candida* has a highly permeable integument, making localized active water absorption inappropriate. This animal is therefore forced to maintain all its body fluids hyperosmotic to its surroundings to allow net water uptake from the atmosphere by passive diffusion along the gradient in water potential. We have shown that glucose and myoinositol account for a large portion of the measured increase in osmotic pressure. This type of water vapor absorption confers the capability of meeting the water requirements of a terrestrial arthropod under prolonged drought stress (*14*). The adaptive importance of this mechanism is obvious, allowing *F. candida* to remain active in the same range of drought intensities that plants are capable of surviving and that must therefore occur throughout the root zone (*15*). Hitherto, experimental designs in studies of hygrophilic soil arthropods have masked the discovery of such water-regulating abilities. The physiological adaptations of these animals to desiccation require reevaluation.

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14. *Folsomia candida* is adapted to the range of humidities it will encounter in the soil. The water vapor absorption by *F. candida* at 98% RH is therefore of equal ecological importance as the water uptake of a desert insect at 50% RH.
15. We did not investigate the process at lower RH, but we expect it to work at even lower humidities because increasing mortality only occurs at RH below 97%. The soil is a very buffered environment, and drying of the soil is a rather slow process. This implies that SP accumulation in *F. candida* will be induced well before the lethal limit is reached.
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18. One- to two-month-old adult *F. candida* were placed in food-free Petri dishes containing a 5-mm-thick layer of water-saturated active charcoal and plaster of Paris for 48 hours to void their gut before the experiment. In the two groups of animals without access to free water, animals were randomly removed from the Petri dish at time zero and placed in small plastic containers (replicate), where the relative humidity of the air was precisely controlled at 99.6 or 98.2% RH with 7 and 31.6 g of NaCl liter^{-1} of water, respectively, as described (*6*). Each of these replicates contained 10 animals for measurement of water content and SPs and 20 for the measurement of body fluid osmotic pressure. The animals with access to free water were kept on the Petri dishes until sampling, when the appropriate numbers were randomly chosen for analyses. During the following 7 days, water content, osmotic pressure of body fluids, and the concentration of SPs were measured at the intervals shown in figures. At each sampling time, three replicates were removed for measurement of osmotic pressure and five for measurement of water content and SP concentration. Total water content was determined gravimetrically (grams per gram of dry weight) and converted to OAW by use of the relation given by (*16*).
19. After measurement of water content, animals were placed in 600-μl Eppendorf tubes. One hundred microliters of 40% ethanol containing the sorbitol internal standard was added (undetectable in crude extracts of both drought-stressed and control animals), and the animals were homogenized with a rotating glass rod. The rod was rinsed into the Eppendorf tubes with 2× 100 μl of 40% ethanol and the homogenate placed in an ultrasonic bath (Branson 5200; Branson Cleaning Equipment Company, Shelton, CT) for 30 min. The tubes were warmed to 80°C for 5 min and subsequently centrifuged at 20,000*g* for 10 min. The supernatant was removed to a 1.5-ml Eppendorf tube, and the pellet was rinsed twice with 100 μl of warm 40% ethanol and once with 100 μl of warm 20% ethanol. These extracts were left in a heat block at 60°C for about 15 hours until dry. SPs were redissolved in 500 μl of H_2O and filtered through a 0.2-μl filter (Nylon acrodisc; Gelman Sciences, Ann Arbor, MI) ready for high-performance liquid chromatography (HPLC) analysis. Samples of 25 μl were run in triplicate on a Shimadzu (Tokyo, Japan) HPLC system with a LC-6A pump, a SIL-6B auto-injector, and a C-R4AX integrator. SPs were separated by ion exchange chromatography with a Supelcogel-Ca column (30 mm by 7.8 mm) and a Supelcogel-Ca guard column maintained at 55°C with pure water as the mobile phase. SPs were detected with an evaporative light scattering detector (Sedex 55). Concentrations were calculated from a standard curve with SP standards including trehalose, myoinositol, glucose, mannitol, and sorbitol. Recovery of internal standard averaged 75% (SD 5%). The colligative contribution of SPs to the animals' osmotic pressure was calculated with the conversion table in (*17*). A supplementary gas chromatography analysis showed that glycerol content was not elevated in drought-stressed animals and that no traces of erythritol, ribitol, fructose, or sucrose were found.

20. This study received financial support from the Danish Natural Science Research Council. We are indebted to M. H. Petersen for technical assistance in chemical analyses and to H. Ravn for advice concerning the HPLC analysis.

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Coincident Induction of Long-Term Facilitation in *Aplysia*: Cooperativity Between Cell Bodies and Remote Synapses

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Induction of long-term synaptic changes at one synapse can facilitate the induction of long-term plasticity at another synapse. Evidence is presented here that if *Aplysia* sensory neuron somata and their remote motor neuron synapses are simultaneously exposed to serotonin pulses insufficient to induce long-term facilitation (LTF) at either site alone, processes activated at these sites interact to induce LTF. This coincident induction of LTF requires that (i) the synaptic pulse occur within a brief temporal window of the somatic pulse, and (ii) local protein synthesis occur immediately at the synapse, followed by delayed protein synthesis at the soma.

Synaptic plasticity, commonly thought to be a neuronal substrate for learning and memory, can exist in several temporal phases. In both hippocampus (*1*) and *Aplysia* (*2–6*), temporal phases of plasticity range from short term (minutes) to long term (hours to days). Recent evidence from both systems has shown that long-term changes in synaptic strength induced at one synaptic site can facilitate the induction of long-term changes at another site (*7, 8*). We examined induction of long-term synaptic plasticity in the intact central nervous system of *Aplysia* by exploring the temporal and spatial constraints on interactions between two structurally remote cellular compartments: (i) the cell bodies of tail sensory neurons (SNs) and their proximal synapses onto interneurons (*9*), located in the pleural ganglion, and (ii) their distal synapses onto tail motor neurons (MNs) (2 to 3 mm

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away) in the pedal ganglion. We found that these two sites can cooperate in inducing long-term facilitation (LTF). Moreover, there is a narrow temporal window within which this cooperation must occur. Finally, this form of coincident LTF requires local protein synthesis immediately at the synapse followed by a delayed wave of protein synthesis at the soma.

We applied serotonin (5HT) to the somatic region and the distal synaptic terminals of the SNs by using a two-compartment chamber (*3*) (Fig. 1A). First, we determined durations of 5HT that alone were below threshold for induction of LTF (>24 hours) in either compartment (*10*). A 25-min perfusion of 5HT restricted to the soma did not induce LTF; excitatory postsynaptic potential (EPSP) amplitudes at the long-term test (20 to 22 hours after administration of 5HT) were not significantly different from baseline [+17.3 ± 8.2%; not significant (NS)] (Fig. 1B) (*11*). Synapses were also tested for short-term facilitation (STF), which lasts <15 min, after the first 5 min (T1) and at the end (T2) of 5HT perfusion. The lack of facilitation at T1 (−9.0 ± 6.3%; NS) and T2 (−11.5 ± 8.4%; NS) confirms that STF is not induced by 5HT at the soma (*3*). At the synapse, a 5-min pulse of 5HT induced STF immediately (T2, +117.0 ± 22.6%; $P = 0.004$) (Fig. 1C), but LTF was not observed 20 to 22 hours later (+5.2 ± 13.4%; NS) (Fig. 1C) [see also (*2, 3*)]. However, when the 5HT pulse in the synaptic compartment overlapped with the final 5 min of somatic 5HT, significant LTF was induced (+212.2 ± 60.5%; $P = 0.017$) (Fig. 1D). As before, no facilitation was observed at the T1 test (−8.0 ± 8.6%; NS), and STF was induced at the T2 test (+159.6 ± 51.5%; $P = 0.013$). Because neither somatic nor synaptic 5HT treatment alone was capable of inducing LTF, these results indicate that events in the two distant compartments must somehow interact for LTF induction to occur.

We next delivered the brief synaptic 5HT pulse either 20 min before or 15 min after somatic 5HT treatment (Fig. 2A). Both groups expressed STF after synaptic exposure (before, +169.0 ± 22.6%; after, +101.1 ± 22.8%; $P < 0.01$ in both cases). When the synaptic pulse of 5HT preceded somatic 5HT, reduced but significant LTF was induced (+57.5 ± 20.6%; $P = 0.038$) (Fig. 2A1). However, LTF was not induced when the synaptic pulse followed somatic 5HT (+9.3 ± 22.9%; NS) (Fig. 2A2). In both cases, EPSP amplitudes at the LTF test were significantly reduced compared with those expressed when the somatic and synaptic 5HT applications overlapped (*11*). Thus, within a surprisingly stringent time window, coincident 5HT exposure to both compartments induced significantly greater LTF than in all other groups ($P < 0.04$ for all pairs) (Fig. 2B). Interestingly, the time window may be somewhat asymmetric. When the synaptic pulse preceded the somatic pulse, some (reduced) LTF was still induced, but when the synaptic pulse followed the somatic pulse by only 15 min, the window was completely closed; no LTF was induced.

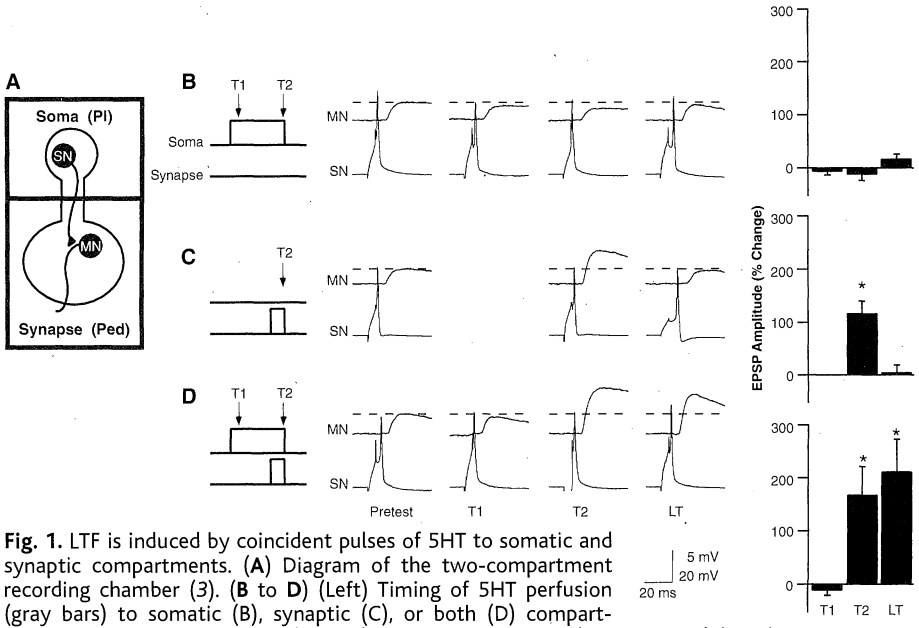

Fig. 1. LTF is induced by coincident pulses of 5HT to somatic and synaptic compartments. (**A**) Diagram of the two-compartment recording chamber (*3*). (**B** to **D**) (Left) Timing of 5HT perfusion (gray bars) to somatic (B), synaptic (C), or both (D) compartments. Examples of recordings (middle) and summary graphs (mean ± SEM) (right). T1, T2, and LT tests are expressed as percent change from baseline. Asterisks, $P < 0.05$; paired *t* tests. In (B) $n = 8$ for T1 and T2 and $n = 6$ for LTF; in (C) $n = 6$ for T2 and LTF; in (D) $n = 10$ for T1 and T2 and $n = 6$ for LTF.

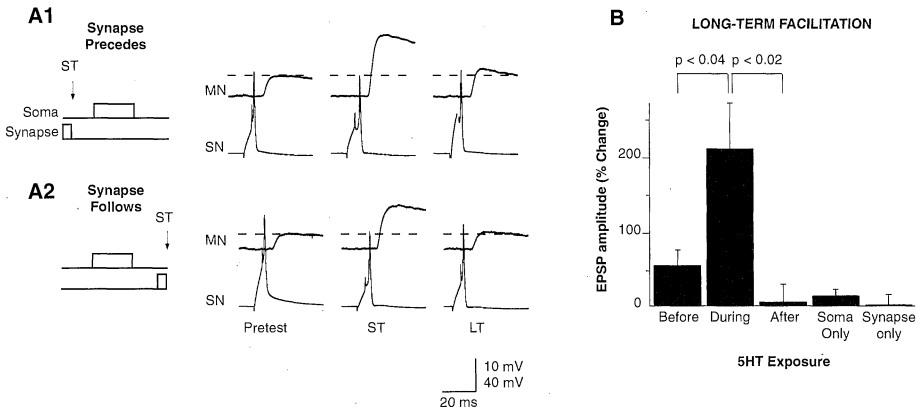

Fig. 2. Coincident induction of LTF has a narrow time window. The synaptic pulse of 5HT was applied either 20 min before (**A1**) or 15 min after (**A2**) somatic 5HT exposure. (Left) 5HT protocol. (Right) Examples of recordings: a pretest, the STF test (ST) after synaptic 5HT, and the LTF test (LT). (**B**) Comparison of EPSP amplitudes at the LT test points from preparations in Fig. 1 and in (A) ($n = 6$ for each group).

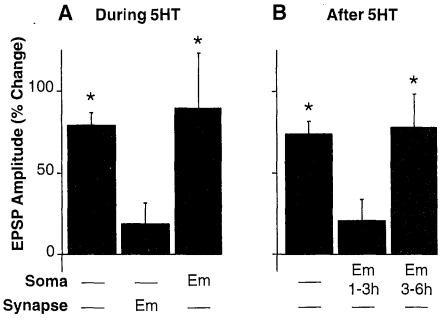

Fig. 3. Coincident induction of LTF requires two temporally distinct waves of protein synthesis. Summary for preparations treated with emetine during 5HT in the synaptic or the somatic compartment ($n = 5$ for each) (**A**) and after 5HT in the somatic compartment at the indicated times (**B**). No-emetine control, $n = 5$; emetine for 1 to 4 hours (Em1-4h), $n = 5$; and emetine for 3 to 6 hours (Em3-6h), $n = 4$. Each group was compared with its own no-emetine control. Asterisks, $P < 0.05$.

The temporal constraint shown in Fig. 2B could be achieved by activity of interneurons that have synaptic terminals in both ganglia (*9*). To examine this possibility, we blocked synaptic transmission with Ca^{2+}-free ASW containing 3× normal Mg^{2+} (165 mM $MgCl_2$) during 5HT application. In the absence of synaptic activity, significant LTF was nonetheless induced after coincident somatic and synaptic 5HT (+48.3 ± 19%; $P = 0.035$; $n = 8$) but not after somatic 5HT alone (+2.5 ± 8%; NS; $n = 8$). These results support the hypothesis that the coincident effect is restricted to the SN-MN synapse.

Local protein synthesis in hippocampal dendrites (*12*) and *Aplysia* neurites (*8*) has been implicated in the induction of long-term synaptic changes. To examine the role of protein synthesis, we blocked translation in the synaptic and somatic compartments independently. We perfused the translational blocker emetine (100 μM) into either compartment from 25 min before somatic 5HT treatment until 30 min after 5HT offset in both compartments (5HT applied as in Fig. 1D). Significant LTF was expressed in the control group (+74.2 ± 7.4%; $P < 0.001$) and in the somatic-emetine group (+78.2 ± 19.9%; $P = 0.017$); however, induction of LTF was blocked in the synaptic-emetine group (+21.0 ± 12.8%; NS) (Fig. 3A) (*13*). There was no significant difference between LTF in the control and somatic-emetine groups, and both were significantly elevated compared with the synaptic-emetine group ($P < 0.04$ in both cases) (*14*). Finally, emetine alone had no effect in either compartment (*15*).

These data show that coincident induction of LTF requires protein synthesis at the synapse, but not at the cell body, during 5HT exposure. The synaptic protein synthesis requirement is surprising because the synaptic compartment received only a single brief pulse of 5HT, which is normally capable of inducing only STF (which is protein synthesis–independent) but is incapable of inducing LTF (which is protein synthesis–dependent) (*6*). Although a dependence on synaptic protein synthesis for long-term synaptic enhancement was observed in previous studies (*7, 8, 12*), this requirement has been found at sites of induction of long-term plasticity but not at the sites that were marked by a brief tagging or capture signal that itself was subthreshold for long-term potentiation or LTF (*7, 8*). Our results indicate that (i) synaptic protein synthesis can be activated by a brief pulse of 5HT (which is subthreshold for LTF) and (ii) the newly synthesized proteins can contribute to induction of LTF (*16*).

Because 5HT-induced translation is known to occur in the SN cell bodies (*17*), we next tested whether somatic protein synthesis is required at a later time after 5HT exposure. Coincident LTF was blocked if emetine was applied to the soma compartment 1 to 3 hours after termination of 5HT exposure (+18.8 ± 13.0%; NS) but not 3 to 6 hours after 5HT [emetine, +89.5 ± 33.6%; no emetine control, +79.4 ± 7.3%; $P < 0.04$ for both (*18*)] (Fig. 3B). Thus, coincident LTF requires two temporally distinct waves of protein synthesis: an immediate wave at the synapse (*19*) and a delayed wave 1 to 3 hours later at the soma.

The surprisingly brief time window when the cooperative effect between soma and synapse must take place (Fig. 2B) suggests two possible mechanisms (Fig. 4). First, the window might be narrow because the processes set in motion by 5HT must coincide at the time of 5HT exposure (immediate coincidence, Fig. 4). This model excludes axonal transport of newly synthesized proteins from the remote synapses to the soma because retrograde transport in *Aplysia* is too slow to allow somatic interactions in a 15-min window (*20*). Instead, a more rapid form of interaction is necessary; for example, initiation of Ca^{2+} waves (*21*) or a chain of phosphorylation (*22*). Alternatively, the temporally constrained interaction need not occur at the time of 5HT exposure. It could be achieved with a coordinated delay line in which 5HT activates chains of events in each compartment that are initially independent but that come into register later (Fig. 4). This mechanism needs to be precisely tuned to keep the events initiated in the soma and synapse in temporal register (to maintain the 15-min window). In this model, retrograde axonal transport is a viable mechanism; it could contribute to a delay line by translocating newly synthesized synaptic proteins to the soma, where they could interact with translational events that occur at a later time (see Fig. 3B).

In conclusion, our results, taken with previous observations in hippocampus (*7*) and cultured SN-MN synapses in *Aplysia* (*8*), indicate that the molecular mechanisms involved in changes in synaptic strength at one synapse can interact with intracellular pathways activated in other regions of the cell. Here we show that subthreshold activation in two anatomically remote cellular regions (soma with proximal synapses and distal synapses) can have an interactive role in induction of long-term changes. These findings emphasize the fact that, even though the soma is often anatomically distant from the sites of long-term synaptic modification (*23*), in combination with local protein synthesis at the synapse it can play an active and temporally coordinated role in induction of long-lasting synaptic change.

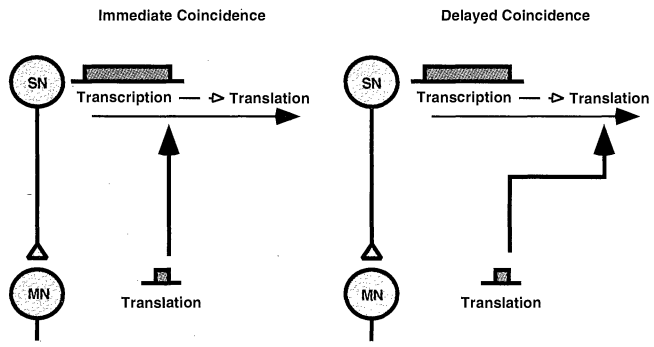

Fig. 4. Two potential mechanisms that could account for the narrow time window for coincident induction of LTF. (**A**) Immediate coincidence: a 5-min 5HT pulse at the synapse induces local protein synthesis, generating a signal that interacts immediately (during 5HT) with processes triggered by somatic 5HT. (**B**) Delayed coincidence: although the synaptic 5HT pulse occurs during somatic 5HT treatment, the processes activated in these two regions are initially independent but are precisely timed so that they intersect later to induce LTF.

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9. Although we refer to the two compartments as somatic (pleural ganglion) and synaptic (pedal ganglion) because they include the SN somata and their remote synapses, respectively, both compartments also contain interneurons (INTs) that make synapses with the SNs or MNs, and the SNs make synapses onto proximal INTs in the pleural ganglion [Y. Xu, J. P. Pieroni, L. J. Cleary, J. H. Byrne, *J. Neurophysiol.* **73**, 1313 (1995); L. J. Cleary and J. H. Byrne, *ibid.* **70**, 1767 (1993)].
10. We made recordings from monosynaptically connected SN-MN pairs. To prevent firing, we hyperpolarized the MN membrane potential to −70 mV. There was no spontaneous activity in SNs in either artificial seawater or 5HT. We used only synapses that (i) did not decrement (<20% decrease in amplitude) during the three pretests (which were averaged for a baseline) and (ii) showed ST responses during 5HT exposure (>75% of preparations). ST responses included STF, increased SN spike width, and decreased SN spike threshold [D. A. Baxter and J. H. Byrne, *J. Neurophysiol.* **64**, 978 (1990); E. T. Walters, J. H. Byrne, T. J. Carew, E. R. Kandel, *ibid.* **50**, 1543 (1983)]. For procedural details, see (*3*).
11. First, we performed factorial analyses of variance (ANOVAs), followed by paired t tests (two-tailed). In Figs. 1 and 2, there was a significant overall differ-

ence between different 5HT treatments with the LTF test ($F_{4,25} = 7.86$; $P < 0.001$). There were no differences with the T1 ($F_{3,29} = 0.93$; $P = 0.44$) and STF ($F_{3,27} = 0.72$; $P = 0.55$) tests.
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13. A factorial ANOVA indicated an overall difference in LTF among groups ($F_{2,12} = 4.99$; $P = 0.027$). Significant STF was expressed in all groups: controls, +154.8 ± 15.5%; synaptic-emetine, +92.9 ± 29.5%; somatic-emetine, +109.7 ± 33.6%; $P < 0.02$ in all cases.
14. The magnitude of coincident LTF in the controls as well as in the somatic-emetine (Fig. 3A) and somatic-emetine (4 to 6 hours) (Fig. 3B) groups is quite comparable [see also (*3*)]. However, the absolute magnitude of LTF in these groups is less than that observed in our initial experiments (Fig. 1). We do not know the source of this variability, but it underscores the importance of having each experimental group compared with its own set of controls (run simultaneously), which was the case in all our experiments.
15. STF: −16.0 ± 2.8%, NS (somatic-emetine); −15.5 ± 2.4%, NS (synaptic-emetine). LTF: −15.8 ± 10.4%, NS (somatic-emetine); −4.0 ± 12.2%, NS (synaptic emetine), paired *t* tests.
16. It is possible that our results reflect a capture-like mechanism [see (*8*)]. For example, if the 25-min 5HT pulse to the somatic compartment induced LTF at SN-INT synapses in the pleural ganglion, the synaptic pulse in the pedal ganglion could be viewed as inducing capture at the remote synapse. If true, this would extend the notion of capture in two ways: (i) in this case, protein synthesis is required immediately at the site of capture, and (ii) there is a tight temporal constraint (15 min) imposed on the induction-capture process occurring at two anatomically remote sites.
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18. A factorial ANOVA showed a significant overall difference among groups ($F_{2,11} = 4.24$; $P = 0.043$).
19. The synaptic compartment (pedal ganglion) contains both the presynaptic SN terminals and postsynaptic MN neurites and somata. Thus the translation-dependent synaptic signal required for LTF induction (Fig. 3A) could be presynaptic, postsynaptic, or both. Distinguishing between pre- and postsynaptic contributions is experimentally feasible in this system [L.-E. Trudeau and V. F. Castellucci, *J. Neurosci.* **5**, 1275 (1995); D. L. Glanzman, *J. Neurobiol.* **25**, 666 (1994)]. Thus we are currently examining the effects of blocking translation in individual SNs and MNs.
20. The length of the connective is 2 to 3 mm, and the estimated rate of fast transport in *Aplysia* neurons is about 1.5 mm/hour [J. D. Gunstream, G. A. Castro, E. T. Walters, *J. Neurosci.* **15**, 439 (1995); R. T. Ambron, R. Schmied, C. C. Huang, M. Smedman, *ibid.* **12**, 2813 (1992)]. Thus communication between synapse and soma requires 40 min to >1 hour by this mechanism.
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23. In CA1 cells of the hippocampus, the soma is not essential for induction of long-term synaptic plasticity (*12*) [U. Frey, M. Krug, R. Brodemann, K. Reymann, H. Matthies, *Neurosci. Lett.* **97**, 135 (1989)]; however, this does not indicate that the soma is unable to participate in the induction process, especially under conditions of subthreshold activation at remote synaptic sites.
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Shape Representations and Visual Guidance of Saccadic Eye Movements

Tirin Moore

One hallmark of primate vision is that the direction of gaze is constantly shifting to position objects of interest appropriately on the fovea, where visual acuity is greatest. This process must involve the close cooperation of oculomotor and visual recognition mechanisms because visual details must be translated into specific motor commands. This paper describes the correspondence between the presaccadic activity of V4 neurons and the degree of visual guidance of saccadic eye movements to objects of different form. The results suggest that neurons that participate in coding visual stimuli are also involved in guiding the eyes to prominent features of objects.

Because only a small fraction of the primate retina has heightened acuity, the point of fixation must constantly be moved about to allow detailed visual processing of objects of interest within the visual scene. Moreover, this must be done so that each change in gaze places the eye at convenient locations on the target stimulus once the movement is completed. For example, when scanning this text, the reader's eyes must accurately jump from word to word so that when each item is fixated it can be processed rapidly and the next eye movement can be planned. Studies of eye movements during reading have shown that the speed at which subjects scan text is determined partly by where each eye movement places the fovea within words and that for each word there appears to be an optimal landing position for the eye (*1*). To accomplish this requires that each individual eye movement be guided by detailed visual information obtained from locations peripheral to the current point of fixation. During all types of visual scanning, saccadic eye movements of both humans and monkeys follow the detail of visual images to a striking degree (*2*). This fact suggests that visual cortical mechanisms responsible for coding stimulus form are also actively involved in guiding eye movements to salient features of objects.

Most studies of oculomotor mechanisms have ignored the possible role of visually selective neurons in programming eye movement commands. Among the two apparent processing streams within the primate visual cortex (*3*), only the dorsal projecting visual areas, areas in the posterior parietal cortex, have been implicated in oculomotor control. In contrast, ventral visual cortical areas that contain neurons selective for stimulus features, such as color and orientation, have been primarily regarded as passive perceptual mechanisms (*4*). The major reason for this view is that dorsal stream visual areas contain neurons that respond in conjunction with saccadic eye movements and that electrical stimulation of some dorsal areas can evoke eye movements (*5*). There is, however, little evidence of the involvement of ventral stream visual areas in the programming of eye movements.

Extrastriate area V4 is the major source of visual input to the inferior temporal cortex (*6*), the terminus of the ventral stream; thus, neurons within V4 are very sensitive to stimulus form and color (*7*). Neurons within this area are modulated by focal attention in the absence of eye movements (*8*). However, they are also activated in advance of visually guided saccadic eye movements (*9*). The saccade-related activation within this area may merely reflect the fact that shifts in attention typically precede shifts in gaze, but it also may reflect a mechanism by which detailed visual information useful in guiding the eyes to salient features of objects is synchronized with the saccade command. We examined this possibility by studying the correspondence between neural activation preceding eye movements to targets of different form and the metrics of saccadic eye movements.

We recorded the activity of 91 single neurons in extrastriate area V4 of two monkeys (*Macaca mulatta*) performing a visually guided delayed saccade task. In this task, the monkeys were trained to make saccadic eye movements to stable visual stimuli presented within the visual receptive field (RF) of a V4 neuron (*10*). The response of a V4 neuron during the saccade task is shown in Fig. 1A. The responses of the neuron during the first half of each trial are aligned to the onset of

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