Regulation of Synaptic Depression Rates in the Cricket Cercal Sensory System

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Hill, Andrew A. V. and Ping Jin. Regulation of synaptic depression rates in the cricket cercal sensory system. J. Neurophysiol. 79: 1277–1285, 1998. To assess the roles of pre- and postsynaptic mechanisms in the regulation of depression, short-term synaptic depression was characterized at the synapses between sensory neurons and two interneurons in the cricket cercal sensory system. Changes in excitatory postsynaptic potential (EPSP) amplitude with repetitive stimulation at 5 and 20 Hz were quantified and fitted to the depletion model of transmitter release. The depression rates of different sensory neuron synapses on a single interneuron varied with the age of the sensory neurons such that old sensory neuron synapses depressed faster than young synapses. Although all synapses showed depression, short-term facilitation was selectively expressed only at sensory neuron synapses on one interneuron, the medial giant interneuron (MGI). These synapses showed concurrent facilitation and depression with high-frequency stimulation (100 Hz), whereas the synapses on another interneuron, 10-3, showed only depression at all stimulus frequencies. A previous study showed that the ability of a synapse to facilitate is correlated with the identity of the postsynaptic neuron. The present results indicate that depression and facilitation are regulated independently. Depression is regulated presynaptically in a manner related to sensory neuron age; whereas, facilitation is regulated by the postsynaptic target.

INTRODUCTION

The nervous system typically operates with bursts or trains of impulses rather than with single isolated impulses. During a train of impulses synaptic efficacy may vary because of short-term activity-dependent properties such as facilitation, depression, and posttetanetic potentiation (Magleby 1987; Sen et al. 1996; Zucker 1989). This variation of efficacy, on the basis of the immediate history of a synapse, forms a type of short-term “memory” that can confer rich computational properties upon a neural network (Antón et al. 1992; Buonomano and Merzenich 1995). For example, recent work has shown that short-term synaptic depression can provide a type of dynamic gain-control that allows rapidly and slowly firing afferents converging on a single neuron to produce equal postsynaptic responses (Abbott et al. 1997; Tsodyks and Markram 1997). Understanding how short-term synaptic properties are regulated is essential for understanding the development and fine tuning of neural circuits.

Studies of different systems have suggested various mechanisms for the regulation of synaptic dynamics from cell autonomous presynaptic regulation to extrinsic regulation by the target cell (Davis and Murphey 1994). Presynaptic regulation may be evident when the synapses of a single neuron have identical dynamic properties regardless of their postsynaptic targets or when a single postsynaptic cell receives synapses with different dynamic properties. For example, presynaptic regulation may occur in the locust where a single presynaptic motor neuron synapses with identical depression rates onto three different postsynaptic motor neurons (Parker 1995). Presynaptic regulation may also occur in the opener muscle of crayfish where a single muscle fiber receives synapses from a specific inhibitor axon that are poorly facilitating, while synapses from a common inhibitor axon show facilitation (Atwood and Bittner 1971). Examples of convergent synapses with distinct dynamic properties onto common postsynaptic target also exist in the rat spinal cord (Pinco and Lev-Tov 1994), the cerebral cortex (Bower and Haberly 1986) and the Drosophila neuromuscular junction (Kurdyak et al. 1994). Alternatively, postsynaptic regulation of synaptic function may occur in systems where synaptic dynamics are correlated with the identity of the postsynaptic cell. For example, at the lobster neuromuscular junction a single muscle fiber receives synapses with similar facilitation properties from a number of different motor neurons and a single motor neuron makes synapses that vary in their facilitation properties on different muscle fibers (Frank 1973). Postsynaptic regulation may also occur at the crayfish neuromuscular junction (Atwood and Bittner 1971), in the leech central nervous system (CNS) (Muller and Nicholls 1974), in the cat spinal cord (Koerber and Mendell 1991), in the Aplysia CNS (Gardner 1990), and in the cricket CNS (Davis and Murphey 1993).

The focus of the present study was to test the relative influence of pre- and postsynaptic regulatory mechanisms on the rates of synaptic depression at sensory neuron synapses in the cricket cercal sensory system. This system, consisting of an array of sensory neurons that make monosynaptic connections with primary interneurons, is well suited for the study of the regulation of dynamic properties of central synapses because both pre- and postsynaptic neurons are identified (Shepherd et al. 1988). Previous work showed that the ability of a synapse to show paired-pulse facilitation is correlated with the identity of the postsynaptic target neuron (Davis and Murphey 1993). In the present study, depression rates of identified sensory neuron synapse were found to vary with sensory neuron age. These data suggest that depression is regulated presynaptically in an age-dependent manner in contrast to facilitation that is regulated by the postsynaptic target.

METHODS

Recording and stimulation

Adult female crickets (Acheta domestica) between 2 and 12 h after eclosion were anesthetized on ice for 1 h, dissected, and their
body cavities were filled with isotonic saline (Killian et al. 1993). Experiments were performed at 19–21°C. The sheath of the terminal abdominal ganglion was softened to ease electrode penetration by placing a piece of filter paper soaked in 3% (wt/vol) solution of protease (Sigma Type XIV) on the ganglion for 15–30 s. The interneurons were identified intracellularly by their characteristic background activity and response to sound (Bacon and Murphey 1984) and by dye injection (Hill et al. 1994). Electrodes (30–50 MΩ) were pulled from borosilicate capillary tubing (1.0 mm OD, 0.5 mm ID) with a Flaming/Brown micropipette puller (model P-97, Sutter instrument) and filled with 3 M potassium acetate. Identified sensory neurons were stimulated by placing a broken saline filled pipette over the cut end of their associated filiform hair. Action potentials were reliably evoked with 100–400 μs depolarizing current pulses and spontaneous activity was monitored and prevented with hyperpolarizing current. Recording and stimulation was done with Getting amplifiers (Getting Instruments) and data was collected with pCLAMP software (Axon Instruments).

To elicit synaptic depression sensory neurons were stimulated with trains of 60 pulses delivered at 5–100 Hz. High levels of background synaptic activity and variability in excitatory postsynaptic potential (EPSP) amplitude made it necessary to average data from at least 15 trials. A 60-s intertrial interval allowed for a complete recovery of the initial EPSP amplitude in each trial.

Data analysis

The depression of EPSP amplitude was quantified with the equations of the depletion model (Betz 1970; Hubbard et al. 1969; Kusano and Landau 1975; Liley and North 1953; Zucker and Bruner 1977). According to this model, depression occurs because the amount of transmitter available for release becomes depleted during repetitive stimulation. Repetitive stimulation results in an

![FIG. 1. A cutaway view of cricket abdomen reveals ventral nerve cord and an expanded view of terminal abdominal ganglion. The cricket cercal sensory system consists of a pair of abdominal sensory appendages called cerci that are covered with wind-sensitive filiform hairs. Associated with each hair is a sensory neuron (SN) that responds to air movements with bursts of action potentials and makes monosynaptic connections with interneurons (Landolfi and Miller 1995; Shepherd et al. 1988). A sensory neuron can be identified by the characteristic length and position of its associated hair. Sensory neurons were electrically stimulated by placing a broken saline filled electrode over cut ends of their associated hairs (see METHODS). Intracellular recordings were made from medial dendrite of MGI and soma of 10-3 (electrode symbols). These recording sites are electrotonically close to sites of synaptic contact; therefore, recorded excitatory postsynaptic potential (EPSPs) were large and fast rising.](http://jn.physiology.org/issue-files/1278/f1.large.jpg)

![FIG. 2. Synaptic depression and recovery of sensory neuron synapses. A: sensory neuron 3c was stimulated with 60 pulses at 20 Hz, while EPSPs were recorded in medial giant interneuron (MGI) (average of 25 trials; error bars indicate SE). EPSPs declined from and initial amplitude (V1) to a plateau amplitude (Vs). The solid line was based on an exponential curve fit, and Vs indicates predicted amplitude of the 2nd EPSP (see Eq. 1). Inset: averaged EPSP waveforms at different pulse numbers during a stimulus train (1, 3, 5, 10, 20, 40, 60; *, stimulus artifact). In this example, a synapse depressed with a time constant (τd) of 385 ms has a normalized plateau amplitude (V/NI) of 34.7% and has a fractional release F of 7.9% (F was calculated from V1 and V2; see Eq. 2). B: recovery from depression after a 20-Hz stimulus. Recovery was studied by applying single test pulses at various intervals after each conditioning train. This train and test pulse sequence was repeated many times to construct a recovery curve. Solid line fit of recovery phase was based on an exponential recovery (see Eq. 3). In this example, a synapse between sensory neuron 3c and MGI has a depression time constant (τd) of 348 ms, a recovery time constant (τr) was 22.8 s, and a mobilization time constant (τm) of 979 ms. Data points in recovery phase are averages of 6 trials; data points in conditioning train are averages of 42 trials; error bars indicate SE.](http://jn.physiology.org/issue-files/1278/f2.large.jpg)
exponential decline in EPSP amplitude ($V$) from an initial amplitude ($V_1$) to a plateau amplitude ($V_s$) expressed as

$$V(t) = (V_1 - V_s) \exp(-t/\tau_d) + V_s \quad (1)$$

where $t$ is time and $\tau_d$ is the time constant of depression. Each action potential releases a constant fraction ($F$) of a store of readily releasable transmitter. Assuming that negligible replenishment of transmitter occurs between two stimuli the fractional release ($F$) can be found with the equation

$$F = 1 - V_s/V_1 \quad (2)$$

where $V_1$ is the initial EPSP amplitude and $V_s$ is the amplitude of the second EPSP. Recovery from depression can be fit with the equation

$$V(t) = (V_1 - V_s)[1 - \exp(-t/\tau_r)] + V_s \quad (3)$$

where $\tau_r$ is the time constant of recovery. Curve fits were performed with SigmaPlot graphing software to find the values of parameters that gave a best fit by a least-squares criterion (Jandel).

RESULTS

Characterization of synaptic depression at identified sensory neuron synapses

Identified sensory neurons were stimulated while recording from either the medial dendrite of medial giant interneuron (MGI) or the soma of 10-3 (Fig. 1). Low-frequency repetitive stimulation (5-20 Hz) lead to synaptic depression at all sensory neuron synapses. For example, when sensory neuron 3c was stimulated at 20 Hz the EPSPs recorded in MGI decreased from an initial amplitude ($V_1$) of 1.6 mV to a plateau amplitude ($V_s$) of 0.6 mV (Fig. 2A). Depression at identified synapses was quantified by determining three parameters: the normalized plateau amplitude ($V_s/V_1$), the time constant of depression ($\tau_d$), and the fractional release of transmitter ($F$) (Liley and North 1953; Zucker and Bruner 1977). To determine the time constant of depression ($\tau_d$) and the plateau amplitude ($V_s$) data were fit with an equation with a single exponential based on the depletion model of transmitter release (Eq. 1). The fractional release ($F$) from the store of readily releasable transmitter was calculated on the basis of the amplitudes of the first EPSP ($V_1$) and second EPSP ($V_2$) (Eq. 2). In practice, because of variability in the data caused by background synaptic noise and variation in transmitter release, the value of

FIG. 3. Synaptic depression varies with stimulus frequency, and facilitation occurs only at synapses on MGI. A: 2c to 10-3 synapse was stimulated at 5 and 20 Hz in a single animal resulting in depression time constants of 555 ms and 150 ms, respectively. ($V_1$ was 3.71 mV at 5 Hz and 3.74 mV at 20 Hz; small differences in amplitude were due to changes in recording quality over time.) Data points are means of 10-20 trials (error bars indicate SE; in some cases only every 5th error bar is shown). B: 4p to MGI synapse was stimulated at 5 and 20 Hz in a single animal resulting in depression time constants of 1,861 and 556 ms, respectively. ($V_1$ was 2.37 mV at 5 Hz and 2.17 mV at 20 Hz.) C: when stimulated at 100 Hz, a synapse on MGI concurrently facilitated and depressed. The solid line was based on a curve fit to an equation that includes facilitation and depression (Magleby 1987; Mallart and Martin 1967). Derived time constants of facilitation ($\tau_f$) and depression ($\tau_d$) were 28 and 86 ms, respectively ($V_1$ was 3.1 mV). The synapse on 10-3 depressed with a time constant of 60 ms ($V_1$ was 2.6 mV).
FIG. 4. Averaged depression parameters of identified synapses vary in an age-dependent manner. A: mean time constant of depression ($\tau_d$) for identified synapses on MGI and 10-3 (20-Hz stimulation). Bar graph is arranged in order of sensory neuron age; young sensory neurons are to left and old are to right (error bars indicate SE; n indicates number of synapses). Numeral in name of a sensory neuron indicates nympha1 instar in which sensory neuron was born. For example, sensory neuron 2c was born in 2nd of 10 instars that a cricket goes through to become an adult. –, synapses on MGI; □, synapses on 10-3. •, 5a/MGI synapse significantly different from 3c/MGI synapse ($P < 0.001$); +, 3c/10-3 synapse significantly different from 2c/10-3 synapse ($P < 0.001$) (all comparisons done with two-tailed t-test). B: mean normalized plateau amplitude ($V_s/V_1$) expressed as a percent (20-Hz stimulation). •, 5a/MGI synapse significantly different from 3c/MGI synapse ($P < 0.001$); +, 3c/10-3 synapse significantly different from 2c/10-3 synapse ($P < 0.001$); * 3c/10-3 synapse significantly different from 2c/MGI synapse ($P < 0.001$); * 3c/10-3 synapse significantly different from 2c/10-3 synapse ($P < 0.01$).

FIG. 5. Two sensory neurons make synapses with different depression rates on a single interneuron, whereas a single sensory neuron makes synapses with identical depression rates on 2 interneurons. A: synapses made by sensory neurons 5a and 3c on a common interneuron (MGI) in a single animal depress with different time constants of 979 and 534 ms, respectively. EPSPs have been normalized to $V_1$ ($V_1$ was 2.40 mV for 5a/MGI synapse and 2.23 mV for 3c/MGI synapse). Data points are means of 10–20 trials (error bars indicate SE). B: synapses between 3c and 10-3 and 3c and MGI, were recorded consecutively in a single animal. Time constants of 3c/10-3 synapse and 3c/MGI synapse were nearly identical with values of 371 and 386 ms, respectively. ($V_i$ was 1.64 mV for 3c/MGI synapse and 2.45 mV for 3c/10-3 synapse.)

$V_2$ predicted from the curve fit curve was used rather than the actual value.

Synaptic depression at the sensory neuron synapses appears to be due to a decrease in transmitter release rather than changes in postsynaptic membrane properties. In principle, an increase in postsynaptic conductance during a stimulus train could cause a decrease in EPSP amplitude. A change in conductance, however, would be accompanied by a proportional decrease in the membrane time constant resulting in a shortening of the time course of the passive decay of
Recovery from depression after a stimulus train

After a train of stimulation EPSPs recovered in amplitude exponentially with a recovery time constant ($\tau_r$) (Eq. 3). For example, one synapse between sensory neuron 3c and MGI tested had a recovery time constant of 22.8 s (Fig. 2B). According to the depletion model, the rate of transmitter mobilization to the releasable pool is directly proportional to the level of transmitter depletion; therefore, the time constant of transmitter mobilization ($\tau_m$) during a stimulus train should equal the time constant of recovery of EPSP amplitude after a train ($\tau_r$) (Liley and North 1953). The $\tau_m$ was calculated from $F$ and $\tau_d$ (Zucker and Bruner 1977). In contrast to the prediction of the depletion model, the $\tau_m$ was an average of eightfold faster than the $\tau_r$. The $\tau_r$ was 10.2 $\pm$ 7.2 s and the $\tau_m$ was 1.28 $\pm$ 0.61 s for the same synapses (mean $\pm$ SD, $n = 5$; the $\tau_r$ was found at only 5 synapses because of the long periods of time with stable intracellular recordings required). These data show that the rate of transmitter mobilization is faster during stimulation than after tetanic stimulation. Thus transmitter mobilization is not simply a function of the level of transmitter depletion as predicted by the depletion model.

Depression rate is frequency dependent and facilitation occurs at synapses on MGI

The time constant of depression ($\tau_d$) and the normalized plateau amplitude ($V/V_i$) varied with the stimulus frequency in a manner consistent with the depletion model. Synapses on 10-3 stimulated at 20 Hz depressed with shorter time constants ($\tau_d$) and lower normalized plateau amplitudes ($V/V_i$) in comparison with 5-Hz stimulation (Fig. 3A). Likewise, synapses on MGI show a similar frequency dependence when stimulated at 5 and 20 Hz (Fig 3B). However, at high-stimulation frequencies such as 100 Hz the synapses on MGI showed concurrent short-term facilitation and depression, whereas the synapses on 10-3 show only depression (Fig. 3C). The presence of facilitation at synapses on MGI at high frequencies is in accord with previous work that showed paired-pulse facilitation at these synapses (Davis and Murphey 1993).

Depression rates vary with sensory neuron age

To study the regulation of depression identified sensory neuron synapses of different ages were stimulated at 20 Hz and an average depression time constant for each identified synapse was calculated (Fig. 4A). Old sensory neurons consistently depressed faster than the young sensory neurons (Fig. 4A). For example, sensory neuron 2c to 10-3 synapse depresses significantly faster than the sensory neuron 3c to 10-3 synapse. Similarly, the synapse between sensory neuron 3c and MGI depressed significantly faster than the synapse between 5a and MGI. This result was also found when two sensory neurons were tested consecutively while recording from a single interneuron ($n = 3$). For example, sensory neuron 3c depresses with a faster time constant than sensory neuron 5a (Fig. 5A). The normalized plateau amplitude ($V/V_i$) also varied with the age of the sensory neurons such that old sensory neurons depressed to a significantly lower plateau (Fig. 4B and 5A). There was no correlation between the initial EPSP amplitude and depression rate (Table 1).

The correlation between sensory neuron age and depression rate suggests that there is a presynaptic component to the regulation of depression, but conceivably the postsynaptic neuron could also contribute to the regulation of depression rate. In general, because of a continual process of synaptic rearrangement, old sensory neurons synapse with 10-3, whereas young sensory neurons synapse with MGI (Chiba et al. 1988). Thus the population of synapses on 10-3 depress faster than the population of synapses on MGI. To test whether or not postsynaptic neurons contribute to the regulation of depression rate, a single sensory neuron, 3c, that contacts both MGI and 10-3 was stimulated and the depression rates of its synapses were compared. Consecutive intracellular recordings within a single animal showed that the depression rate of its synapses were compared. Consecutive intracellular recordings within a single animal showed that the time constants of depression were indistinguishable at the synapses on these two interneurons (Fig. 5B; $n = 2$ animals). Consistent with this finding, the mean depression time constants of the synapses of 3c on the two interneurons were not significantly different (Fig. 4A; $t$-test, $P = 0.531$). The lack of correlation between depression rates and the identity of the postsynaptic neuron may indicate that the postsynaptic neuron does not contribute to the regulation of depression rate. However, testing additional sensory neurons that simultaneously contact both interneurons would provide and more definitive proof of this hypothesis.

The differences in depression rates of the identified synapses could theoretically be due to differences in the fraction ($F$) of the releasable pool of transmitter released with each impulse, or to differences in the time constant of mobilization ($\tau_m$) (Zucker and Bruner 1977). At sensory neuron synapses in the cricket $F$ was found to vary between 2 and 14% depending on the identity of the sensory neuron (Fig. 4C). The depletion hypothesis predicts that synapses with a high $F$ depress faster than synapses with a low $F$. In agreement with this prediction, $F$ is high for synapses that depress quickly such as the 2c to 10-3 synapse and low for synapses that depress slowly such as the 4p to MGI synapse (Fig. 4C). There were no consistent trends in the values of the time constant of mobilization ($\tau_m$) for different identified synapses

<table>
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<th>TABLE 1. Filiform hair length and synaptic connectivity of sensory neurons</th>
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<td><strong>Sensory Neuron</strong></td>
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<td>5a</td>
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Values are means $\pm$ SD; values in parentheses indicate number of synapses tested. MGI, medial giant interneuron. EPSP, excitatory postsynaptic potential. NC, no connection. * From Chiba et al. 1988.
Synaptic depression may be due to the depletion of transmitter

The kinetics of synaptic depression at cricket sensory neuron synapses are compatible with many of the predictions of the depletion model of transmitter release. The decrease in EPSP amplitude during a train of stimuli can be fit with an equation with a single exponential that decays to a plateau. In addition, synapses depressed faster and reached a lower plateau with high-frequency stimulation than with low-frequency stimulation. Also, in agreement with the depletion hypothesis synapses with a high fractional release \( F \) depress more rapidly than synapses with a low \( F \) (Hubbard et al. 1969; Kusano and Landau 1975). In contrast, there was no apparent trend between depression rate and the other parameter that affects the kinetics of depression, the time constant of transmitter mobilization \( \tau_m \). Although depression in the cricket is compatible with the depletion hypothesis, other mechanisms of depression such as presynaptic autoinhibition and the inactivation of presynaptic \( Ca^{2+} \) current could have similar kinetics; and can not be discounted (Klein et al. 1980; Redman and Silinsky 1994).

In the classical depletion model the rate transmitter mobilization to the releasable pool is directly proportional to the level of depletion; therefore, the time constant of transmitter mobilization \( \tau_m \) during a train equals the time constant of EPSP amplitude recovery \( \tau_r \) after a tetanic train (Liley and North 1953). At the sensory neuron synapses of the cricket \( \tau_r \) was \( \sim 10 \) s, which is consistent with the range \( 4 - 20 \) s) found at other synapses (Betz 1970; Gersdorff and Matthews 1997; Katz et al. 1993; Kusano and Landau 1975; Swandulla et al. 1991; but see Zucker and Brunner 1977). In contrast, the calculated \( \tau_m \) was \( \sim 1.3 \) s. Thus transmitter mobilization was faster during a train than afterwards by about eightfold. Evidence from other systems also suggests that transmitter mobilization increases during a stimulus train. At the squid giant synapse the time constant of mobilization during a tetanic train is 10-fold faster than the time constant of recovery afterwards (Kusano and Landau 1975).

Our data show that in the cricket, as in these systems, although depression may occur through the depletion of transmitter, other factors besides the depletion of transmitter may affect transmitter mobilization. Numerous studies have shown that the movement of synaptic vesicles to the readily releasable pool is \( Ca^{2+} \) dependent (Greenberg et al. 1993; Neher and Zucker 1993; Pieribone et al. 1995). Perhaps, there is an increased influx of \( Ca^{2+} \) during tetanic stimulation that leads to a transient increase in the rate of transmitter mobilization. Alternatively, the rate of transmitter mobilization may become slower after a stimulus train. For example, at the frog neuromuscular junction vesicle endocytosis becomes slower after prolonged tetanic stimulation leading to slower refilling of the depleted reserve transmitter pool (Wu and Betz 1998).

Depression rate is regulated by sensory neuron age

Depression rates of identified sensory neurons varied with the age of the sensory neurons such that old sensory neurons depressed faster than young sensory neurons (Fig. 6). This observation could be seen in the average depression rates of different sensory neurons recorded in a number of animals,
as well as in instances in which two sensory neurons of different ages were consecutively stimulated while recording from a single interneuron. This result suggests that there is a presynaptic component to the regulation of synaptic depression rate at the sensory neuron synapses. Interestingly, a single sensory neuron that simultaneously synapses with both MGI and 10-3 shows identical depression rates on both interneurons. One interpretation of this result is that depression rate is not influenced by the identity of the postsynaptic neuron. However, in the absence of additional data from other sensory neurons that contact both interneurons, it is not possible to discount the idea that the postsynaptic neurons may also influence depression.

The mechanism that specifies depression rate in the cricket is not a function of the age of the synaptic terminals, but rather the age of the sensory neuron soma. During postembryonic development the sensory neurons undergo a continual process of synaptic rearrangement in which they shift their target neurons (Chiba et al. 1988). For example, from the eighth instar to the adult (10th instar) the 2c-to-MGI synapse decreases in amplitude while the 2c to 10-3 synapse increases. Thus assuming that an increase in synaptic strength reflects the growth of synaptic terminals, although the soma of sensory neuron 2c is relatively old (born in the 2nd instar) its synaptic terminals on 10-3 are only a few instars old. Therefore depression rate is correlated with the age of the sensory neuron soma rather than with the age of the synaptic terminals impinging on a postsynaptic neuron.

Depression and facilitation are regulated independently

In contrast with the presynaptic regulation of synaptic depression, facilitation is regulated postsynaptically. Sensory neuron synapses on MGI facilitate, whereas those on 10-3 do not facilitate. Additionally, a single sensory neuron that contacts both MGI and 10-3 makes synapses that facilitate on MGI, but not on 10-3 (Davis and Murphey 1993). Thus depression is regulated through an influence of the postsynaptic neuron, perhaps through a retrograde signal that acts locally at the synaptic terminals impinging upon the neuron. Although this phenomenon is suggestive of retrograde signaling, as in many systems, the identity of the signal is unknown (Davis and Murphey 1994).

In other systems the expression of facilitation and depression have been shown to result from the regulation of a single parameter, the basal level of transmitter release. For example, crustacean neuromuscular junction synapses with high basal transmitter release levels depress, whereas synapses with low levels facilitate (Bittner 1968; Katz et al. 1993). At many synapses, lowering transmitter release by reducing the extracellular Ca$^{2+}$ concentration can relieve depression and promote the expression of facilitation (Katz et al. 1993; Mennerick and Zorumski 1995; Thies 1965; Zucker 1989). In contrast, facilitation and depression in the cricket are not likely to result from the regulation of a single process. First, lowering the extracellular Ca$^{2+}$ concentration did not reveal facilitation at synapses on 10-3 (Davis 1994). Second, there is no correlation between the initial EPSP amplitude and depression rate or the ability of a synapse to show facilitation (Table 1, Davis and Murphey 1993). Finally, a single sensory neuron makes synapses on MGI and 10-3 with the same depression rate and fractional release, yet shows facilitation only on MGI. This evidence supports the idea that facilitation and depression in the cricket are regulated independently of basal transmitter release. The independent regulation of basal transmitter release and short-term plasticity has been demonstrated at the Ia-afferent to motor neuron synapse in the cat. Although in general facilitation occurred at synapses with small EPSPs, in a given motor neuron there was no relationship between the initial EPSP amplitude and the short-term plasticity exhibited (Koerber and Mendell 1991).

The independent regulation of short-term synaptic properties also occurs developmentally in a number of systems where specific synaptic properties emerge sequentially at significant time intervals after the establishment of a functional synapse. In the mollusc, Achatina fulica, synapses show synaptic depression and short-term facilitation early in postembryonic development and later show a PTP-like synaptic plasticity (Pawson and Chase 1988). Similarly, in Aplysia depression and presynaptic inhibition are present in the juvenile stage, whereas posttetanic potentiation and heterosynaptic facilitation appear later at discrete developmental stages (Carew 1989; Ohmori 1982; Rayport and Kandel 1986).

Does presynaptic activity influence depression rate?

The observed age dependence of depression rates in the sensory neurons in the cricket could be caused by various developmental changes. One possibility is that the electrical activity levels of sensory neurons determine the depression rate. Old sensory neurons have high activity levels because their spontaneous spiking rates are high (50–125 Hz; Landolfa and Miller 1995) and because their associated filiform hairs have low mechanical thresholds for deflection (Shimozawa and Kanou 1984). Young sensory neurons, in contrast, do not fire spontaneously when their associated hairs are undeflected and have high mechanical thresholds for activation. Presynaptic activity levels have been shown to affect depression rate at the crayfish neuromuscular junction (Lennicka and Atwood 1989; Pahapill et al. 1985).

Functional significance of short-term synaptic properties

Short-term plasticity of the synapses between sensory neurons and interneurons in the cricket may be regulated to preserve the response properties of the interneurons throughout postembryonic development. Previous studies have shown that synaptic strength is regulated to maintain the characteristic frequency response properties of the interneurons to sound. As a sensory neuron ages its optimal frequency becomes lower because its associated filiform hair grows in length (Osborne 1996; Shimozawa and Kanou 1984). The cercal sensory system compensates for this change through a continual process of synaptic rearrangement that keeps the quality of sensory input to the interneurons constant (Chiba et al. 1992). Perhaps in addition, it is necessary that short-term synaptic plasticity be modified as a sensory neuron ages. Throughout postembryonic develop-
ment MGI responds phasically to a constant tone stimulus, whereas 10-3 responds tonically (Chiba et al. 1992; Kanou and Shimozawa 1984). Computer simulations have shown that the depression rates of the sensory neuron synapses have a large influence on the temporal response properties of the interneurons (Hill 1996). For example, in a model with synapses that show depression, the compound EPSP resulting from a constant stimulus peaks and then declines to a plateau. If an interneuron has a relatively high spike threshold such as MGIs then its response to a constant stimulus will be phasic with spike output only at the onset of the stimulus. Thus perhaps the depression rates of the synapses of young sensory neurons on MGI are matched to the temporal response of MGI. The tonic response of 10-3 to tones is more difficult to explain given that its sensory neuron synapses show rapid depression. However, in the experiments presented here the spontaneous firing rates of sensory neurons were reduced to zero with injected current. However, under more natural conditions the old sensory neurons that synapse with 10-3 have high resting firing rates of 50–125 Hz (Landolfa and Miller 1995). Thus the synapses on 10-3 may be constantly depressed and therefore the tonic temporal response of 10-3 may be the result of a reduction in the dynamic range of its afferent synapses. It would be interesting to determine the natural activity states of these synapses to determine how short-term synaptic properties affect the temporal response properties of the interneurons.

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