Synaptically Induced Long-Term Modulation of Electrical Coupling in the Inferior Olive

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SUMMARY
Electrical coupling mediated by gap junctions is widespread in the mammalian CNS, and the interplay between chemical and electrical synapses on the millisecond timescale is crucial for determining patterns of synchrony in many neural circuits. Here we show that activation of glutamatergic synapses drives long-term depression of electrical coupling between neurons of the inferior olive. We demonstrate that this plasticity is not triggered by postsynaptic spiking alone and that it requires calcium entry following synaptic NMDA receptor activation. These results reveal that glutamatergic synapses can instruct plasticity at electrical synapses, providing a means for excitatory inputs to homeostatically regulate the long-term dynamics of microzones in olivocerebellar circuits.

INTRODUCTION
Interest in electrical synapses between neurons in the mammalian brain has seen a dramatic resurgence in the past decade with the recognition that gap junction-mediated coupling is both widespread and cell type specific in adult mammalian neural circuits (Bennett and Zuki, 2004; Connors and Long, 2004; Hestrin and Galarrreta, 2005). The importance of electrical coupling in regulating synchronous activity in neuronal populations has been extensively explored using both experimental and modeling approaches (Manor et al., 1997; Deans et al., 2001; Bartos et al., 2002; Lezni and Llinás, 2005; Blenkinsop and Lang, 2006; De Grujil et al., 2012). Given that electrically connected neurons also receive chemical synaptic input, a growing body of work has demonstrated that the interplay between electrical and chemical synapses is crucial for determining patterns of synchrony on the millisecond timescale not only in the inferior olive (Lang et al., 1996; Marshall and Lang, 2009; Wise et al., 2010) but also in neocortical (Gibson et al., 1999; Beierlein et al., 2000) and cerebellar (Vervaeke et al., 2010) interneuron networks. Moreover, there is good evidence that chemical neurotransmitters can modulate the strength of electrical synapses. The potential importance of such a transsynaptic interaction between chemical and electrical synapses is underlined by the close anatomical proximity between the two synapse types observed in the “mixed” electrical and chemical synapses found in many parts of the nervous system (Sloper and Powell, 1978; Rash et al., 1996). Thus, most attention has been focused on short-term interactions between electrical and chemical synapses on the millisecond timescale, but it has long been speculated that chemical synapses may also drive long-term regulation of mammalian electrical synapses (Connors and Long, 2004). Electrical synapses can undergo long-term modification by spiking activity (Haas et al., 2011), metabotropic neurotransmitters (Landsman and Connors, 2005; Mills and Massey, 1995), and dopaminergic activation (Kothmann et al., 2009). While experiments in goldfish Mauthner cells have shown that activation of fast glutamatergic synapses can produce long-term potentiation of neighboring electrical synapses (Yang et al., 1990; Pereda and Faber, 1996; Smith and Pereda, 2003), whether chemical synaptic input can also regulate the strength of mammalian electrical synapses in the long term remains unclear.

The electrically coupled neurons of the inferior olive represent a particularly attractive system for attacking this question. Electrical coupling is mediated by Connexin 36 gap junctions formed between dendritic spines of neighboring olivary cells (Long et al., 2002). Importantly, the gap junctions are located in close proximity to glutamatergic and GABAergic synapses housed within a glomerular structure (Llinás et al., 1974; Sotelo et al., 1974; de Zeeuw et al., 1989, 1990a, 1990b): an anatomical arrangement that provides an excellent substrate for intersynaptic interaction. While fast, short-term modulation of olivary electrical coupling by both GABAergic and glutamatergic synaptic inputs has long been suggested (Llinás, 1974; De Zeeuw et al., 1998; Lang, 2002; Jacobson et al., 2008; Hoge et al., 2011; Bazzigaluppi et al., 2012), no direct evidence exists to support long-term modulation of electrical synapses in the mammalian inferior olive. Here we have addressed this question by performing simultaneous patch-clamp recordings between coupled neighboring olivary neurons. We demonstrate robust, long-term depression of electrical coupling triggered by physiological patterns of glutamatergic synaptic input.

RESULTS
Synaptic Stimulation of Olivary Neurons Depresses Electrical Coupling
We obtained simultaneous recordings from electrically coupled pairs of olivary neurons in the principal olive and medial
accessory olives in rat brainstem slices. Electrical coupling was measured by injecting negative current pulses into either cell (Devor and Yarom, 2002; Landisman and Connors, 2005) and assessing the resulting voltage change in the noninjected cell. Coupling was detected between almost all neighboring neurons (with a coupling probability higher than 80%). The mean coupling coefficient was 0.014 ± 0.001 (measured at a resting potential of −54.2 ± 0.4 mV; input resistance 32.7 ± 0.6 MΩ, n = 111 pairs). We then activated excitatory synaptic input to the neurons and increased stimulus strength until the evoked excitatory postsynaptic potentials (EPSPs) reliably induced spiking (spiking probability averaged over both cells ≥0.5). For each pair, we recorded the electrical coupling by alternating delivery of negative current pulses to each cell for a baseline period. This was followed by an induction protocol consisting of 50 synaptic stimuli at 1 Hz, with steady-state depolarizing current such that the neurons fired the characteristic burst of spikes observed in olivary neurons in response to sensory stimulation in vivo (Chorev et al., 2007; Khosrovani et al., 2007).

Following the induction protocol, the average coupling coefficient was significantly lower in nine out of ten pairs of connected cells (Figure 1; average reduction of 47% ± 9.9% from an initial coupling coefficient of 0.012 ± 0.003; p < 1 × 10⁻³, n = 10 pairs). This depression of coupling was sustained for more than 15 min, with the longest recordings showing plasticity 25 min after induction. Changes in coupling can result from either changes in input resistance or junctional conductance, and this conductance can be estimated indirectly by combining transfer resistances and input resistance. Using this estimate of gap junctional conductance confirms that coupling remains significantly reduced after induction (48% ± 12% reduction; p < 1 × 10⁻⁴; Figure S1B available online). Experiments were also performed in voltage clamp to provide a more direct readout of coupling (Figures S1B–S1D). Cells were held at −55 mV during the baseline and postinduction period. For plasticity induction, synaptic stimuli were paired with short (10 ms), 10 mV depolarizations to allow the cells to fire bursts of unclamped spikes. After induction, coupling was significantly reduced (by 15% ± 1% of control; p < 0.01, n = 7 cells), consistent with our current-clamp experiments.

Finally, we tested the effect on coupling coefficient of high-frequency olivary spiking in the presence of more intense synaptic input. Spikes at 4 Hz, evoked by depolarizing current pulses, were paired with 25 Hz bursts of synaptic input timed to provide synaptic glutamate release throughout the postsynaptic spike (Figure S2A). This “theta”-like activity was designed to mimic pairing protocols that are typically used to induce synaptic plasticity in other brain areas. We used 100 pairings, yielding a comparable number of spikes to the maximum number used for the 1 Hz pairing protocol. Although a small increase in coupling coefficient was seen in two out of five pairs, on average there was...
Mechanism of Electrical Coupling Plasticity

We next investigated the conditions required for the induction of the depression of coupling. To test whether olivary bursting on its own could change the coupling, we used an induction protocol that consisted of steady-state depolarization and 50 brief current pulses (30 ms, 800 pA) at 1 Hz, which reliably triggered the olivary burst in all of the cells (Figure 2). In contrast to synaptic stimulation, this protocol produced a small but statistically insignificant increase in coupling (by 7% ± 13%; p = 0.42; n = 7 pairs). We also performed experiments where plasticity induction was carried out in the absence of spiking (Figure S3). In this case, induction consisted of 50 synaptic stimuli at 1 Hz with no accompanying depolarizing current pulses, which resulted in depression of coupling (32% ± 13% depression after baseline, n = 7 pairs, p < 0.05). Therefore, action potential bursts alone are insufficient to produce changes in coupling strength, and action potentials are not required for triggering plasticity with synaptic stimulation.

To rule out the contribution of GABAergic synaptic mechanisms to the plasticity, we repeated the induction protocol in the absence of spiking (Figure S3). In this case, induction consisted of 50 synaptic stimuli at 1 Hz with no accompanying depolarizing current pulses, which resulted in depression of coupling (32% ± 13% depression after baseline, n = 7 pairs, p < 0.05). Therefore, action potential bursts alone are insufficient to produce changes in coupling strength, and action potentials are not required for triggering plasticity with synaptic stimulation.

To investigate whether NMDA receptors modify gap junctional coupling, we assessed the influence of NMDA receptors on the depression of coupling. We hypothesized that calcium entry, through NMDA receptors and other sources, was responsible for the depression of coupling, and therefore repeated the experiment in the absence of D-AP5 but with 10 mM BAPTA (Figures 3C and 3D), a high-affinity calcium chelator, in the internal solution. This prevented any change in coupling by the induction protocol (coupling after induction 95% ± 10% of baseline, p = 0.49; n = 4 pairs).

What are the downstream effectors of NMDA-receptor-mediated calcium entry? One possible candidate is CaMKII, which is known to be activated by NMDA-receptor-driven calcium entry (Lisman et al., 1990; Pereda and Faber, 1996; Pereda et al., 1998; Smith and Pereda, 2003), and which is present close to olivary Connexin 36 plaques in the inferior olive (Alev et al., 2008). We therefore repeated the plasticity experiments with KN62, a selective CaMKII inhibitor (Tokumitsu et al., 1990), in the pipette solution (10 μM). No significant plasticity was observed under these conditions (coupling after induction 89% ± 29% of baseline, p = 0.70; Figures S4C and S4D).

Plasticity Induction Is Specific to Electrical Coupling without Affecting Chemical Synapses

Since complex spike synchrony depends on both synaptic input and electrotonic coupling between olivary neurons (Marshall et al., 2007; Wise et al., 2010), it is important to know how the strength of chemical synapses is affected by protocols that modify gap junctional coupling. To test this, we assessed the chemical synaptic response (i.e., the evoked EPSP) along with electrical coupling strength. During the baseline and monitoring periods, we used a stimulus strength that would allow direct monitoring of the EPSP (without occlusion of the EPSP by olivary bursts). The induction protocol consisted of a steady-state depolarization (0–500 pA), with 100 synaptic stimuli at 1 Hz. The following induction (coupling after induction 120% ± 18% of baseline, p = 0.093; n = 7 pairs).

We hypothesized that calcium entry, through NMDA receptors and other sources, was responsible for the depression of coupling, and therefore repeated the experiment in the absence of D-AP5 but with 10 mM BAPTA (Figures 3C and 3D), a high-affinity calcium chelator, in the internal solution. This prevented any change in coupling by the induction protocol (coupling after induction 95% ± 10% of baseline, p = 0.49; n = 4 pairs).

NMDA and connexin molecules have been seen in other systems (Yang et al., 1990; Pereda and Faber, 1996; Pereda et al., 1998; Smith and Pereda, 2003), so we investigated whether NMDA receptor activation is necessary for the plasticity of electrical coupling. Using the same induction protocol as for Figure 1 in the presence of D-AP5 (50 μM), a potent NMDA receptor antagonist (Figures 3A and 3B), no significant depression of electrical coupling was observed.
Neuron Synapses Downregulate Electrical Coupling

Chemical Synapses Downregulate Electrical Coupling

Figure 3. Plasticity of Coupling Depends on NMDA Receptor Activation and Calcium Entry

(A and B) Plasticity induction (protocol as in Figure 1) in the presence of D-AP5 (50 μM) prevents changes in the coupling coefficient (A). The population data are shown in (B) (n = 7 pairs; p = 0.093). (C and D) Plasticity induction (protocol as in Figure 1) with 10 mM BAPTA in the internal solution prevents changes in the coupling coefficient (C). The population data are shown in (D) (n = 4 pairs; p = 0.49).

SYNAPTIC PLASTICITY MECHANISMS AT OLIVARY ELECTRICAL SYNAPSES

We show that depression of electrical coupling can be triggered by physiological patterns of synaptic input to olivary neurons involving low-frequency (1 Hz) stimulation of excitatory inputs, similar to the physiological frequency of firing of olivary neurons in awake animals (Armstrong and Rawson, 1979; Lang et al., 1999), but in contrast with plasticity of electrical coupling in the thalamus, which requires tetanic synaptic stimulation (Landisman and Connors, 2005). Higher-frequency stimulation (25 Hz) paired with 4 Hz olivary spikes did not induce changes in electrical coupling, although we cannot not rule out that other stimulation patterns may also trigger plasticity.

We demonstrate that induction of this form of long-term depression crucially depends on synaptic NMDA receptor activation and postsynaptic calcium elevations. Interestingly, these induction requirements are similar to those observed for long-term plasticity at chemical excitatory synapses throughout the brain (Bliss and Collingridge, 1993; Malenka and Bear, 2004). It is therefore surprising that the stimulated excitatory synapses that drove the electrical plasticity appeared to be resistant to change following the induction protocol. This indicates specificity of plasticity for the electrical synapses, in contrast to experiments in goldfish neurons (Yang et al., 1990; Charchol et al., 2007), and suggests that the olivary chemical synapses require different patterns of activity to induce plasticity.

We found that postsynaptic action potential bursts caused by intracellular current injections alone were not sufficient to cause plasticity, in contrast to a recent study in the thalamus (Haas et al., 2011). This suggests that calcium entry through voltage-gated calcium channels is insufficient to trigger the plasticity and that calcium entry through chemical synapses in proximity to the gap junctions could be playing an important role. Anatomical work has demonstrated that NMDA receptors are located within several microns of gap junctions at the olivary synapse (Hoge et al., 2011). Indeed, Hoge et al. (2011) already speculated that NMDA-receptor-mediated modulation of coupling could underlie the heterogeneous coupling coefficients found in the olive. Furthermore, it is known that CaMKII, which is activated by
NMDA-receptor-mediated calcium entry (Lisman et al., 2002), is present close to Connexin 36 plaques in the inferior olive and that CaMKII and connexins can interact (Alev et al., 2008). Our experiments demonstrating that a CaMKII blocker prevents plasticity suggest that this is a candidate molecular effector, as recently demonstrated for NMDA-receptor-mediated activity-dependent plasticity of gap junctional coupling in the retina (Kothmann et al., 2012).

**Functional Implications**

There is a growing awareness that plasticity in cerebellar circuits related to motor learning can take place at many sites, involving changes in both synaptic strength and/or intrinsic membrane currents (Hansel et al., 2001; Boyd et al., 2004). Our study provides an additional site for long-term changes in cerebellar circuits that involves changes in electrical coupling between a defined cell type.

How might this plasticity be functionally useful? Synchronous activity among groups of neighboring olivary neurons defines functional microzones that via climbing fiber input in turn drive synchronous activity of Purkinje cells. This microzonal organization is thought to act as a population code that represents distinct forms of sensory information. Synchrony in the olivocerebellar system is driven both by shared synchronous excitatory input to olivary neurons and electrical coupling. Our demonstration of plasticity of this coupling could provide the olivocerebellar system with a flexible way to remodel its microzonal architecture (Apps and Garwicz, 2005; Wise et al., 2010). While there is evidence that short-term modulation of oligocoupling can be driven by both glutamatergic and GABAergic inputs (Llinás, 1974; Lang, 2002; Jacobson et al., 2008; Hoge et al., 2011; Bazzigaluppi et al., 2012), which could provide dynamic regulation of microzone structure on the millisecond-to-second timescale, a long-term mechanism such as that shown here is required to sustain changes involved in cerebellar motor learning. In support of this model, there is evidence that long-term alterations in electrical coupling in the olive can impair cerebellar motor learning (Van Der Giessen et al., 2008). Since chemical synapses were not altered by our induction paradigm, glutamatergic synapses in the inferior olive may represent independent loci for shaping the patterns of synchrony underlying motor coordination. The long-term downregulation of electrical coupling by excitatory input may also represent a homeostatic mechanism for balancing activity during periods of synaptically driven synchrony.

**EXPERIMENTAL PROCEDURES**

**Slice Preparation**

Transverse brain slices of the inferior olive (250 μm) were prepared from Sprague-Dawley rats (postnatal days 18–21) in accordance with national and institutional guidelines. Rats were anesthetized with isoflurane and subsequently decapitated. The brain was removed and submerged in ice-cold artificial cerebrospinal fluid (ACSF) bubbled with carbogen (95% O2, 5% CO2). The slicing ACSF contained 227 mM sucrose, 25 mM NaHCO3, 10 mM glucose, 5 mM KCl, 1.25 mM NaH2PO4, 0.5 mM CaCl2, and 3.5 mM MgCl2. The brain was cut parallel to the plane of slicing, and cyanoacrylate adhesive was used to fix the brain to the platform of a Leica VT-1200 S vibratome. Slices were transferred to a holding chamber and incubated for 30 min at 34°C in standard ACSF containing 125 mM NaCl, 25 mM NaHCO3, 25 mM glucose, 2.5 mM KCl, 1.25 mM NaH2PO4, 2 mM CaCl2, and 1 mM MgCl2 (pH 7.4). Slices were then kept at room temperature until they were transferred to a recording chamber and continuously superfused with oxygenated standard ACSF. All recordings were made at 33°C ± 1°C from slices that had been maintained at this temperature for at least 20 min (in light of the fact that gap junctional coupling in the inferior olive is temperature sensitive [Payton et al., 1969]).

**Slice Electrophysiology**

Patch pipettes were pulled from borosilicate glass on a PC-10 puller (Narishige) to a resistance of 5 MΩ for somatic recordings. The internal solution contained 130 mM KMeSO4, 7 mM KCl, 0.1 mM EGTA, 2 mM Na2ATP, 2 mM MgATP, and 0.3 mM Na2GTP (pH 7.2) (0.5% biocytin was included in some recordings). For voltage-clamp experiments, we used the same internal, except that KMeSO4 was replaced with 130 mM CaMeSO4. Olivary neurons in the principal and medial accessory olives were identified using infrared-DIC optics.
and somatic patch-clamp recordings were made under direct visual control (Stuart et al., 1993; Matky et al., 2009), with most recordings being made from the principal olive. We selected somata within 50 µm of each other to maximize the probability of obtaining coupled cells (Devor and Yarom, 2002). Cells were rejected if their resting potential was depolarized to −40 mV. Coupling was assessed in current-clamp mode by injecting negative current pulses alternately (from −400 to −800 pA, every 4 to 6 s) in both cells. Bridge balance was monitored and corrected online and offline. For stimulation of synaptic inputs, a bipolar tungsten electrode (stimulus duration 50–100 µs) was placed in the white matter at the border of the olivary subnucleus from which the recording was obtained. During induction in current clamp, continuous depolarizing current was used to maintain a baseline membrane potential of 44 ± 1 mV, ensuring that cells fired with the physiological burst pattern seen in vivo and enhancing relief of magnesium block of NMDA receptors in experiments where spiking was not triggered by depolarizing current steps. Each slice was only used for one paired recording. To assess the strength of chemical synapses, we injected a 300 ms hyperpolarizing pulse (1 nA) in both cells and triggered an EPSP when the voltage had reached the steady state. Biocytin processing was performed using standard techniques (Horikawa and Armstrong, 1988), with overnight paraformaldehyde (0.5%) fixation followed by conjugation with streptavidin-Alexa Fluor 488 (Invitrogen). Filled neurons were imaged using a 40x oil-immersion objective (NA 1.3) on a spinning-disc confocal microscope (Perkin-Elmer).

**Data Acquisition and Analysis**

Data were low-pass filtered at 3–10 kHz and acquired at 20–100 kHz using an ITC-18 board (Instrutech) in conjunction with AxoGraph (AxoGraph Scientific) software. Analysis was carried out using custom-written software for MATLAB (MathWorks) and Igor Pro (WaveMetrics). The coupling coefficient was calculated as the ratio of the steady-state postjunctional and presynaptic voltage deflection caused by a prejunctional negative current injection (see Figure 1C). We report the coupling coefficient averaged between the two directions. Coupling conductance was estimated using the following formula (Hoge et al., 2011): 

\[ g_c = (R_c)^{-1} = \left( \frac{R_{11} \times R_{22} - TR^2}{TR} \right)^{-1} \]

where \( TR \) is the transfer resistance between the two cells averaged over both directions, and \( R_{11} \) and \( R_{22} \) are the input resistances of cell 1 and 2, respectively. About 30% of the recorded cells exhibited subthreshold oscillations, and in a minority of cells (<10%) the oscillations were sufficiently large that they precluded accurate measurement of coupling coefficients. For the chemical synapse, we used the peak of the EPSP to assess synaptic strength. All data are reported as mean ± SEM unless otherwise indicated. Differences between groups were tested for statistical significance using Student’s two-tailed t test.

**SUPPLEMENTAL INFORMATION**

Supplemental Information includes four figures and can be found with this article online at http://dx.doi.org/10.1016/j.neuron.2014.01.005.

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**REFERENCES**


