Extracellular GABA waves regulate coincidence detection in excitatory circuits

Sergiy Sylantyev¹,², Leonid P. Savtchenko², Nathanael O’Neill³ and Dmitri A. Rusakov²

¹Rowett Institute, University of Aberdeen, Ashgrove Rd. West, Aberdeen, AB25 2ZD, UK
²UCL Queen Square Institute of Neurology, University College London, Queen Square, London, WC1N 3BG, UK
³Centre for Clinical Brain Sciences, University of Edinburgh, 49 Little France Crescent, Edinburgh, EH16 4SB, UK

Edited by: Ian Forsythe & Nathan Schoppa

Key points

- Rapid changes in neuronal network activity trigger widespread waves of extracellular GABA in hippocampal neuropil.
- Elevations of extracellular GABA narrow the coincidence detection window for excitatory inputs to CA1 pyramidal cells.
- GABA transporters control the effect of extracellular GABA on coincidence detection.
- Small changes in the kinetics of dendritic excitatory currents amplify when reaching the soma.

Abstract

Coincidence detection of excitatory inputs by principal neurons underpins the rules of signal integration and Hebbian plasticity in the brain. In the hippocampal circuitry, detection fidelity is thought to depend on the GABAergic synaptic input through a feedforward inhibitory circuit also involving the hyperpolarisation-activated $I_h$ current. However, afferent connections often bypass feedforward circuitry, suggesting that a different GABAergic mechanism might control coincidence detection in such cases. To test whether fluctuations in the extracellular GABA concentration [GABA] could play a regulatory role here, we use a GABA 'sniffer' patch in acute hippocampal slices of the rat and document strong dependence of [GABA] on network activity. We find that blocking GABAergic signalling strongly widens the coincidence detection window of direct excitatory inputs to pyramidal cells whereas increasing [GABA] through GABA uptake blockade shortens it. The underlying mechanism involves membrane-shunting tonic GABA$_A$ receptor current; it does not have to rely on $I_h$ but depends strongly on the neuronal GABA transporter GAT-1. We use dendrite-soma dual patch-clamp recordings to show that the strong effect of membrane shunting on coincidence detection relies on nonlinear amplification of changes in the decay of dendritic synaptic currents when they reach the soma. Our results suggest that, by dynamically regulating extracellular GABA, brain network activity can optimise signal integration rules in local excitatory circuits.

Sergiy Sylantyev is a Lecturer at Rowett Institute, University of Aberdeen.


© 2020 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society. DOI: 10.1113/JP279744

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
Introduction

High-precision input coincidence detection by principal neurons is essential for faithful information transfer by brain circuits (Konig et al. 1996). The timing and sequence of near-coincident pre- and postsynaptic spikes also control long-lasting changes of synaptic efficacy (Bi & Poo, 1998). Coincidence detection fidelity, at least in the well-explored hippocampal CA3–CA1 circuit, has been shown to depend on feedforward inhibition (Pouille & Scanziani, 2001), which is manifested as the biphasic EPSP–IPSPs recorded in the postsynaptic CA1 pyramidal cells (PCs) (Alger & Nicoll, 1982). In the EPSP–IPSP response, the later IPSP component curtails the decay of the early, excitatory component thus providing a sharper waveform for temporal signal integration. In addition, membrane shunting by the hyperpolarisation-activated current $I_h$ (Robinson & Siegelbaum, 2003) accelerates the IPSP component, thus further narrowing the input integration time window (Pavlov et al. 2011). The strong influence of shunting conductance on coincidence detection was also demonstrated using dynamic-clamp somatic current injections in cortical PCs (Grande et al. 2004), and in electrically compact neurons of the chicken nucleus laminaris (Tang et al. 2011).

Intriguingly, the critical role of feedforward inhibition in coincidence detection fidelity in the CA3–CA1 circuit has been discovered using extracellular stimulation of Schaffer collaterals (Pouille & Scanziani, 2001; Pavlov et al. 2011). In contrast, paired CA3–CA1 PC recordings in organotypic hippocampal slices (Debanne et al. 1996; Zhang et al. 2008), or selective optogenetic stimulation of CA3 PCs or Schaffer collateral axons in acute slices (Kohl et al. 2011; Jackman et al. 2014) produce robust monophasic EPSPs sufficient for PC spiking (Jackman et al. 2014), with no contribution from the intact inhibitory circuitry. Nor do CA1 PCs recorded in vivo appear to display biphasic EPSP–IPSP responses as a prevalent feature (Bahner et al. 2011; Kowalski et al. 2016). These observations indicate that the physiological activity of Schaffer collaterals does not necessarily engage feedforward inhibitory interneurons, instead activating CA1 PCs directly. The question therefore arises whether local network activity, other than feedforward inhibition, can control the coincidence detection of direct, monosynaptic excitatory inputs to principal neurons.

One powerful mechanism that generates sustained membrane-shunting conductance in principal neurons, in particular in hippocampal PCs, is tonic GABA$_A$ receptor current (Semyanov et al. 2003; Scimemi et al. 2005; Glykys & Mody, 2007). This tonic current arises from the incessant bombardment of GABA$_A$ receptors by GABA molecules that diffuse from remote synaptic sources, or is sometimes released stochastically from local synapses whose individual IPSCs are indistinguishable from noise. In this context, one important feature of GABAergic synapses is that GABA normally escapes the synaptic cleft activating target receptors within at least a several micron-wide volume of tissue (Olah et al. 2009; Rusakov et al. 2011). Tonic GABA current thus depends on the extracellular GABA concentration ([GABA]), which reflects the balance of network-driven GABA release and uptake (Glykys & Mody, 2007; Pavlov et al. 2014). However, it remains unclear to what degree the local network activity could dynamically control [GABA], given the sparsity of direct inhibitory inputs. A recent study employed a genetically encoded optical GABA sensor to detect a relatively brief (200–300 ms) rise in [GABA] in response to epileptiform discharges in the cortex (Marvin et al. 2019). Whether such short transients are indeed characteristic for extracellular GABA waves or whether their detection has been curtailed by the relatively low sensitivity of the sensor remains to be ascertained (Marvin et al. 2019).

Whether the [GABA]-dependent tonic membrane current influences the coincidence detection to a significant degree is not a trivial question. Blockade of GABA$_A$ receptors alters the membrane tonic conductance in CA1 PCs, which in voltage-clamp experiments ($V_m = -60$ mV) is reflected in a holding current change by 5–10 pA (Semyanov et al. 2003; Scimemi et al. 2005). The expected effect of this change on the time course of local dendritic synaptic currents is likely to be in the sub-millisecond or low millisecond range (Tran-Van-Minh et al. 2016). If dendritic signals were to undergo passive filtering while arriving at the soma, this small change would remain such, which would be unlikely to affect coincidence detection fidelity. However, blocking a similarly small membrane-shunting influence of $I_h$ changes the coincidence detection window by tens of milliseconds (Pouille & Scanziani, 2001; Pavlov et al. 2011), a phenomenon ascribed to active mechanisms of dendritic integration (Magee, 1999; Angelo et al. 2007). In this context, it would seem important to understand whether active dendritic filtering is a universal mechanism that amplifies changes in the local synaptic signal time course (such as changes triggered by [GABA] fluctuations), independently of their origin.
To address these issues, first, we implemented a highly sensitive outside-out GABA ‘sniffer’ patch (Isaacson et al. 1993; Wlodarczyk et al. 2013a) to evaluate the extent of activity-dependent extracellular GABA fluctuations in hippocampal tissue. Second, we established the relationship between tonic GABA conductance and the integration time window for direct excitatory inputs to CA1 PCs, and the contributing regulatory role of GABA transporters. Finally, we examined Schaffer collateral-elicited EPSCs in dual dendrite-soma patch recordings of CA1 PCs, to explore amplification of small kinetic changes in local synaptic currents in the course of dendritic integration.

**Methods**

**Ethical approval and animals**

The animal procedures were conducted in accordance with the United Kingdom Home Office (Scientific Procedures) Act (1986) Schedule 1, in full compliance with the relevant ethics policies UCL and the University of Edinburgh ethical committee regulations. 3–4-week-old male Sprague–Dawley or Wistar rats were bred on a Rat and Mouse Breeding Diet (Special Diet Services, Witham, UK) and water ad libitum, and maintained in a 12–12 h light–dark (L/D) cycle. Animals were killed in the first half of the light period of the L/D cycle with an overdose of isoflurane. After decapitation with guillotine, brains were rapidly removed and dissected, and hippocampi sliced. The experiments conform to the principles and regulations as described in the *Journal of Physiology* Editorial (Grundy, 2015).

**Electrophysiology**

Transverse 300 µm hippocampal slices were cut, incubated for 1 h in a solution containing (in mM): 124 NaCl, 3 KCl, 1 CaCl₂, 3 MgCl₂, 26 NaHCO₃, 1.25 NaH₂PO₄, 10 D-glucose, and bubbled with 95:5 O₂/CO₂, pH 7.4. Slices were next transferred to a recording chamber superfused with an external solution which was similar to the incubation solution except 2 mM CaCl₂ and 2 mM MgCl₂. Where specified, GABAₐ receptors were blocked with 50 µM picrotoxin (PTX), Iₚ with 10 µM ZD-7288, and AMPA receptor desensitisation with 10 µM cyclothiazide (CTZ); unless specified otherwise, 1 µM CGP52432 was added to rule out the influence of metabolotropic GABAₐ receptors.

The intracellular solution for voltage-clamp recordings contained (mM): 117.5 Cs-gluconate, 17.5 CsCl, 10 KOH-Hepes, 10 BAPTA, 8 NaCl, 5 QX-314 Cl⁻, 2 Mg-ATP, 0.3 GTP (pH 7.2, 295 mOsm); the intracellular solution for current-clamp recordings contained (mM): 126 K-gluconate, 4 NaCl, 5 KOH-Hepes, 10 glucose, 1 MgSO₄ × 7H₂O, 2 BAPTA, 2 Mg-ATP. Morphological tracer Alexa Fluor 594 was added in some experiments for cell visualisation. Patch-clamp recordings were performed using Multiclamp-700B amplifier; signals were digitised at 10 kHz. The pipette resistance was 3–6 MΩ for whole-cell recordings and 7–9 MΩ for outside-out patches.

Apical dendrites of CA1 PCs were patched whole-cell 50–150 µm from the soma. Two theta-glass pipette electrodes pulled to 2–4 µm filled with ACSF were used to stimulate Schaffer collaterals with 50–150 µs electrical stimuli; individual recording sweeps were collected at 15 s intervals. Simulation strength was adjusted so that: (a) each of the two afferent stimuli produced somatic EPSPs featuring approximately similar amplitudes; and (b) upon coincident stimulation of the two inputs the postsynaptic cell generated an action potential with the probability of >0.9 (which was tested by recording ~50 trials). In the coincidence-window experiments, 10 trials were routinely recorded for each time interval between the afferent input onsets. Data were represented as means ± SEM; Student’s unpaired or paired t test (or non-parametric Wilcoxon paired tests when distribution was non-Gaussian) was used for statistical hypothesis testing.

**Monitoring extracellular GABA with an outside-out ‘sniffer patch’**

Outside-out patches were pulled from dentate granule cells, lifted above the slice tissue and carefully lowered into the slice region of interest near the surface, as detailed previously (Sylantyev & Rusakov, 2013; Wlodarczyk et al. 2013a). These recordings were performed in voltage-clamp mode at Vₘ = -70 mV. Where specified, GABAₐR-mediated single-channel currents were recorded in the presence of 0.1 µM CGP-55845, 200 µM S-MCPG and 1 µM strychnine. Single-channel recordings were acquired at 10 kHz, noise >1 kHz was subsequently filtered out off-line. GABAₐ receptor specificity was routinely confirmed by adding 50 µM PTX at the end of recording. To assess changes in extracellular GABA, we used the open-time fraction of single-channel openings. This was calculated as tₒ/tᵣ ratio, where tₒ is the overall duration of all individual channel openings over recording time tᵣ. Some patches contained more than one GABAₐR channel and could therefore display simultaneous multiple channel openings: in such cases, all individual channel-opening durations were still added up, thus allowing the tₒ/tᵣ value to exceed 1. Single-channel openings were selected automatically by the threshold-detection algorithm of Clampfit software (Molecular Devices), with the minimum event duration of 0.2 ms, and the channel-opening current threshold set at 1.5 pA. In one set of experiments, as indicated, we used a ‘large’ sniffer patch to boost the number of GABAₐ receptors: this involved obtaining a
nucleated outside-out patch from dentate gyrus granule cell in the same slice, as described before (Sun et al. 2020). The burst protocol included eight trains of 10 pulses at 100 Hz, 1 s apart, delivered by a bipolar electrode placed in the stratum radiatum; this stimulation was below the threshold necessary for the induction of long-term synaptic potentiation. The average GABA<sub>A</sub> receptor-channel open-time fraction was calculated over a five-second interval after the eighth burst. To prompt spontaneous network discharges, we perfused slices with an Mg-free ACSF containing 5 mM KCl; single-channel openings were recorded before the development of any epileptiform activity in the slice. All recordings were made at 32–33°C. Field potential recordings from CA1 stratum pyramidale were performed with 1–2 MΩ glass electrodes filled with ACSF. ZD-7288, CTZ, SNAP-5114, SKF-89976A, NBQX, DNQX, CGP-55845, S-MCPG, strychnine and PTX were purchased from Tocris Bioscience. All other chemicals were purchased from Sigma-Aldrich.

**NEURON modelling: pyramidal cell**

Simulations were performed on a 3D-reconstructed pyramidal neuron from the hippocampal area CA1 (https://senselab.med.yale.edu/modeldb, NEURON accession number 7509) (Magee & Cook, 2000), with excitatory synapses distributed over the dendritic tree. The cell axial-specific resistance and capacitance were, respectively, \( R_a = 90 \) ohm cm, and \( C_m = 1 \mu F/cm^2 \). Excitatory synaptic conductance time course \( g_s(t) \) was modelled using the NEURON 7.0 function Exp2Syn (dual-exponential): \( g_s(t) = G_x(\exp(-t/\tau_1) - \exp(-t/\tau_2)) \) where \( \tau_1 \) and \( \tau_2 \) are the rise and decay time constants, respectively, and \( G_x \) is the synaptic combined conductance. The values of \( \tau_1 \) and \( \tau_2 \) were established empirically, by matching simulated somatic and dendritic EPSPs with experimental recordings (note that synaptic conductance does not necessarily follow AMPA receptor kinetics in response to sub-millisecond glutamate pulses in outside-out patches (Sylantyev et al. 2008, 2013). This procedure led to setting the values of \( \tau_1 \) and \( \tau_2 \) at 2.5 ms and 10 ms, respectively. The reverse potential of excitatory synapses was set at 0.

**Modelling tonic GABA<sub>A</sub> and \( I_h \) receptor currents**

Tonic GABA<sub>A</sub> receptor-mediated current (reversal potential \( E_{GABA} \) is between -75 and -55 mV) is an outwardly rectifying shunting current routinely detected in principal neurons (Semyanov et al. 2003; Sylantyev et al. 2008, 2013; Pavlov et al. 2009). Its conductance \( I_{GABA} = g_{GABA} \times O \times (V - E_{GABA}) \) was calculated using \( g_{GABA} = 3 \text{ mS cm}^{-2} \), where the state \( O \) is a proportion of channels in the open state, as estimated previously in CA1 PCs (Pavlov et al. 2009; Song et al. 2011). The transition from the open to the closed state was described by a straightforward kinetic scheme reported earlier (Pavlov et al. 2009).

The kinetic of \( I_h \) (the hyperpolarisation-activated cation current) was copied from the 3D-reconstructed NEURON cell model (accession number, 7509), which was optimised to fit experimental observations (Magee, 1999). The deactivation potential of \( I_h \) was -81 mV, unit conductance 0.1 mS cm<sup>-2</sup>, in line with previously published estimates (Magee, 1999; Pavlov et al. 2011).

**Simulating coincidence detection**

The simulated PC was equipped with 40 excitatory synapses scattered along apical dendrites and divided into two separate equal groups, 20 synapses each, to mimic two independent afferent inputs. A random number generator was used to activate synaptic inputs with the average probability \( P_i = 0.35 \). The synaptic conductance of individual synapses was adjusted to induce a postsynaptic spike with >0.9 probability upon the coincident activation of the two synaptic groups. In practice, we tested this using around ~100 trials, achieving a spike success rate of between 95 and 99. Routinely, one synaptic group was activated at 50 ms after the ‘sweep’ onset, with the other group activated at different time points, between 30 ms before and 30 ms after the first group onset. To estimate the coincidence detection window, the spike probability was calculated, throughout varied time intervals, 10 times (which thus produced 10 different sets of stochastically activated synapses; on average \( 0.35 \times 20 = 7 \text{ synapses per trial} \), which was similar to the experimental design used.

**Statistical summary and software accessibility**

Experiments involved straightforward statistical (paired-sample) designs, with the statistical units represented by individual cells (one cell per acute slice), which contribute the main source of variance with respect to the variable of interest. Sampling was quasi-random, in line with the established criteria for patch-clamp experiments. Leaky cells (holding current \( >20–30 \text{ pA at } V_h = -65 \text{ mV} \) were discarded. The data were routinely presented as a scatter of measurements from individual cells or patches, and additionally described as means ± 95CI where indicated. The width of coincidence windows was represented by the 2σ value of best-fit Gaussian (where σ is standard deviation) for the average window profile (displayed as mean ± SEM, n = number of cells) at each time point, whereas the average σ estimate was shown as mean ± SD. To statistically compare the coincidence windows between experimental...
epochs, we calculated the $\sigma$ value in each individual cell (as the underlying window-shape model), which thus represented a statistical unit. Statistical hypotheses pertinent to the mean difference involved a paired-sample $t$ test or one-way ANOVA, as indicated (OriginPro, OriginLab RRID: SCR_01 4212). All software codes are available on request and will be deposited for free access upon publication.

Results

Neuronal activity can elevate extracellular GABA level several-fold

To understand the magnitude of activity-dependent fluctuations in [GABA], we used a highly sensitive GABA ‘sniffer’, an outside-out cell membrane patch held by the recording micro-pipette in the extracellular medium (Isaacson et al. 1993; Wlodarczyk et al. 2013a) (Fig. 1A). The sniffer patch reports the opening of individual GABA$_{\Lambda}$ receptor channels, with the event frequency varying with [GABA]. With a consistent procedure of pipette preparation and patch pulling (Sylantyev & Rusakov, 2013), its [GABA] sensitivity can be calibrated (Fig. 1B). The sniffer-patch method thus reports the dynamics of volume-average [GABA] in the extracellular space adjacent to the patch.

In the first sniffer-patch experiment, we applied a short series of high frequency stimuli to Schaffer collaterals (eight trains of 10 pulses at 100 Hz, 1 s apart). This increased the GABA receptor open-time fraction in the patch threefold (mean $\pm$ 95CI: from 0.12 $\pm$ 0.02 to 0.39 $\pm$ 0.05), which corresponds to the [GABA] increase from $\sim$300 nM to $\sim$900 nM (Fig. 1C–D), for at least 5 s post-burst. A qualitatively similar increase could be routinely observed after a single spontaneous network discharge when we perfused the slice with the Mg-free ACSF to boost its excitability (Fig. 1E–F). These experiments detected [GABA] transients that were an order of magnitude longer than those revealed with the optical GABA sensor in similar conditions (Marvin et al. 2019), arguing for the high sensitivity of the present method. In another experiment, we used a much larger sniffer patch (nucleated patch from granule cells; see Methods), to boost the baseline GABA$_{\Lambda}$ receptor channel-opening rate, and found that the blockade of AMPA receptors with NBQX reduced this rate by half (Fig. 1G–H).

Our results thus argue that boosting neuronal activity can generate 2–3-fold transient changes in tissue-average [GABA], lasting for seconds after the activity boost ends. While demonstrating activity-associated increases in [GABA], these experimental protocols generate variable effects on the scale of seconds, which is not suitable for the millisecond-range monitoring of coincidence detection (Pouille & Scanziani, 2001; Pavlov et al. 2011). However, the observed range of [GABA] change (Fig. 1) appears compatible with the effect of blocking GABA transport, which roughly doubles tonic GABA$_{\Lambda}$ receptor-mediated current in CA1 PCs, and with the effect of blocking GABA$_{\Lambda}$ receptors which removes the current (Semyanov et al. 2003; Scimemi et al. 2005). Thus, to achieve comparable with our observations (Fig. 1) yet stable changes in [GABA] in both directions, our tests of coincidence detection employed the blockade of either GABA$_{\Lambda}$ receptors or GABA transporters, as outlined below.

Tonic GABA current affects coincidence detection beyond the effect of $I_h$

It has previously been shown that $I_h$ plays a major role in narrowing the coincidence detection window in the CA3–CA1 feedforward inhibition circuit (Pavlov et al. 2011). We asked whether tonic GABA conductance has a similar effect, and if so whether the effects of $I_h$ and GABA occlude. First, to rule out the di-synaptic feedforward inhibition circuit, we used theta-glass bipolar stimulating electrodes (see Methods) that provide a highly localised engagement of afferent fibres in the stratum radiatum, adjusting their positions so that no IPSP component could be detected throughout (Fig. 2B, diagram and traces). This was in striking contrast with the biphasic EPSP–IPSP responses characteristic for experiments that involve feedforward inhibition (Pouille & Scanziani, 2001; Pavlov et al. 2011) (see next section for further control of monosynaptic transmission). Next, we confirmed that the decay of monosynaptic EPSPs in CA1 PCs decelerated under $I_h$ blockade by ZD7288 (ZD) (Magee, 1999), but also found that the GABA$_{\Lambda}$ receptor blocker PTX prompted further EPSP deceleration (Fig. 2A). Both effects could be readily replicated in a 3D-reconstructed, realistic NEURON model of a CA1 PC (Magee & Cook, 2000) (https://senselab.med.yale.edu/modeldb, NEURON accession number 7509) (Fig. 2A). These observations suggested that the effect of $I_h$ blockade on the EPSP kinetics does not occlude the effect of tonic GABA$_{\Lambda}$ current.

To see how these mechanisms influence coincidence detection of monosynaptic inputs, we sought to stimulate two sets of direct Schaffer collateral connections to CA1 PCs in the stratum radiatum using a similar arrangement for two stimulating theta-glass bipolar electrodes. The stimulus strength was further adjusted to induce a postsynaptic spike with >0.9 probability upon the exact temporal coincidence of the two inputs. As expected, increasing the time interval between the two inputs produced postsynaptic spikes with the progressively decreasing probability. Fitting the spiking probability...
Figure 1. GABA sniffer detects several-fold fluctuations in the extracellular GABA level induced by neural activity changes

A, experiment diagram illustrating recordings in an acute hippocampal slice, with the ‘sniffer patch’ (see Methods) held in the extracellular space. B, calibration of the GABA ‘sniffer’ patch: average values of the open-time fraction (grey circles, mean; smaller hollow circles, individual data; n = 10 cells), expressed in millisecond per second; red line, best-fit Hill approximation; small variability points to a highly reproducible sniffer-patch protocol. C, typical single-channel activity (1 s interval shown) recorded in experiments as in A, in baseline conditions (Control) and within 5 s of electrical stimulation of Schaffer collaterals (post-burst; eight series of 10 pulses at 100 Hz, 1 s apart). Dotted lines, GABA_A,R channel closed and open current levels. D, summary of experiments shown
Together with the absence of the IPSC component, Individual synaptic inputs produced EPSPs stochastically, with a release probability of \( P_i = 0.35 \) (see Methods) as estimated earlier (Rusakov & Fine, 2003). These simulations and their outcome faithfully replicated our experiments (Fig. 2C), confirming the biophysical underpinning of our interpretation.

**Tonic GABA current regulates coincidence detection without engaging \( I_h \)**

In the next experiment, we sought to determine whether the tonic GABA current could significantly affect the coincidence detection window when \( I_h \) remains intact. Therefore, we added PTX following a recording session in baseline conditions. In such tests, PTX application increased the EPSP amplitude by only \( \sim 5\% \) (Fig. 3A) while hyperpolarising the cell membrane by \( 3.52 \pm 2.41 \) mV (mean \( \pm 95\% \) CI, \( p = 0.0285; \) Fig. 3B), consistent with previous observations (Semyanov et al. 2003; Scimemi et al. 2005; Pavlov et al. 2009). This was in striking contrast to the properties of the biphasic EPSP–IPSP responses generated by the CA3–CA1 excitation and feedforward inhibition circuit, in which PTX application increases the EPSP amplitude at least twofold, with a prominent prolongation of the rise time (Pouille & Scanziani, 2001; Pavlov et al. 2011). Together with the absence of the IPSC component (Fig. 2A), these data effectively rule out the di-synaptic feedforward inhibition circuitry from our tests. In addition, blocking AMPA and NMDA receptors in our experiments left no evoked signal in CA1 PCs (Fig. 3C), confirming no direct stimulation of local interneurons.

Thus, we found that application of PTX dramatically widened the coincidence window, \( \langle 2\sigma = 22.9 \pm 3.35 \text{ ms} \rangle \) compared with \( 9.68 \pm 1.82 \text{ ms} \) in control; mean \( \pm SD; \) \( p < 0.001; \) \( n = 6 \) cells; Fig. 3D). Because the effect was compatible with that under both \( I_h \) and GABA receptor blockade (Fig. 2B), these observations argue that the influence of tonic GABA current on coincidence detection does not necessarily require \( I_h \). The effects of PTX in baseline conditions and under \( I_h \) blockade were comparable, arguing for the independent, additive nature of the two mechanisms. Again, simulating these experiments with a realistic CA1 PC model confirmed biophysical underpinning of the observed phenomena (Fig. 3E).

**Coincidence detection is controlled mainly by neuronal GABA transporters**

Tonic GABA current depends on \([GABA]\) which is in turn controlled by several types of GABA transporter expressed by nerve and glial cells (Scimemi, 2014) as blocking GABA transport roughly doubles this current in CA1 PCs (Semyanov et al. 2003; Scimemi et al. 2005). This effect is comparable to the 2–3-fold increase in \([GABA]\) after a burst of network activity (Fig. 1D). Here, we therefore asked whether elevating extracellular GABA by inhibiting GABA transporters would alter the coincidence detection window in our experiments.

Our pilot simulations with the model circuit (as in Figs 2C and 3E) predicted that increasing membrane shunt from the baseline level could sharply narrow the input coincidence window over which postsynaptic spikes are generated. Ultimately, shortcutting membrane conductance could prevent the postsynaptic cell from firing. Therefore, to avoid a collapse (null-width) of the coincidence window upon the increased shunt, in these experiments we adjusted stimulus strength to start with a relatively wide coincidence interval in baseline conditions. In the first test, we used nipecotic acid (NipA), a GABA transporter blocker, which can also activate GABA\(_A\) receptors as a false neurotransmitter (Roepstorff
Figure 2. Precision of coincidence detection for distinct excitatory inputs to CA1 pyramidal cells depends on GABAA current

A, upper traces: characteristic EPSPs recorded in the CA1 pyramidal cell soma (10 trial average) in control conditions, after adding 10 μM ZD7288 (+ZD) and subsequently 50 μM PTX (+ZD+PTX), as indicated, normalised to baseline response (scale bar). Graph: summary of these experiments (mean and individual data points, n = 6 cells; difference at p < 0.001, one-way three-level ANOVA). Lower traces: similar tests replicated in silico with a NEURON CA1 pyramidal cell model (ModelDB https://senselab.med.yale.edu, accession numbers 2796 and 7509), with 40 synapses scattered along apical dendrites; baseline Ih unit conductance and unit tonic GABA_A current are, respectively, 0.1 mS cm^{-2} and ~3 mS cm^{-2}, as estimated earlier (Magee, 1999; Song et al. 2011; Wlodarczyk et al.
Dendritic processing amplifies small changes in the EPSC decay

Our data indicate that blocking tonic GABA current leads only to a 3–4 mV change in membrane potential (Fig. 3B), consistent with earlier data ascribing 5–10 pA to whole-cell tonic GABA current at $V_h = -60$ mV (Semyanov et al. 2003; Scimemi et al. 2005). Such a small change is highly unlikely to alter the decay of fast dendritic EPSPs at individual synapses by more than a millisecond (Tran-Van-Minh et al. 2016; Jayant et al. 2017) yet it prolongs the decay of somatic EPSPs by 5–10 ms (Fig. 2A), which is paralleled by a 10–20 ms change in the coincidence detection window (Figs 2B and 3D). Whether such a small change at dendritic synapses is indeed amplified when reaching the soma has been a subject of debate: passive (linear) filtering does not amplify signal fluctuations. Therefore, to understand whether active filtering is an inherent feature of dendritic integration that can boost small changes in the kinetics of local synaptic currents, regardless of $I_h$ or GABA influence, we carried out dual dendrite-soma whole-cell recordings in CA1 PCs. In these tests, $I_h$ was inhibited by holding cells in voltage-clamp with QX-314 inside (Perkins & Wong, 1995), and GABA$_A$ receptors were blocked with 50 μM PTX. Again, we stimulated a single axo-dendritic Schaffer collateral synapse using an extracellular bipolar theta-glass pipette electrode placed within a few microns of the patched and visualised dendrite (Fig. 5A, image). The single-synapse origin of recorded unitary dendritic EPSCs (uEPSCs, voltage-clamp mode) was confirmed by documenting their near-perfectly uniform shape over multiple trials, with a release failure rate of ~60–70% characteristic for this circuitry (Rusakov & Fine, 2003) (Fig. 5A, traces).

To understand how a change in the uEPSC waveform transfers from a dendritic synapse to the soma, we employed two complementary experimental designs. First, we reversed the holding voltage, in soma and dendrites, from -70 mV to +40 mV (NMDA receptors were blocked by 50 μM APV). Outside-out patch experiments with sub-millisecond glutamate application have previously shown that activation of AMPA receptors in these is strictly voltage-independent (Sylantyev et al. 2008). However, with the synaptic cleft intact, postsynaptic current reversal retards escape of negatively charged glutamate from the synaptic cleft, thus slowing down the AMPA receptor-mediated EPSC decay (Sylantyev et al. 2008, 2013). Indeed, in the present experiments voltage reversal decelerated the decay of dendritic uEPSCs by 0.66 ± 0.09 ms (mean ± 95% CI here and thereafter; $n = 5$; Fig. 5B–C). This deceleration was fully consistent with the effect of glutamate electrodiffusion measured earlier in electrically compact cerebellar granule cells (Sylantyev et al. 2013). At the same time, voltage reversal prolonged...
Figure 3. Precision coincidence detection of excitatory inputs by CA1 pyramidal cells depends on tonic GABAA current

A, EPSP amplitude in control conditions and after application of 50 µM PTX (mean ± 95CI): 15.0 ± 1.02 mV and 15.8 ± 0.76 mV, respectively (n = 7 cells); dots, individual cell data; bars, mean value. B, change in the CA1 pyramidal cell membrane potential $V_m$ upon application of 50 µM PTX (mean ± 95CI): 3.52 ± 2.45 mV (n = 7, p = 0.0285). C, a test to rule out direct electrical stimulation of interneurons (GABA receptors intact, voltage-clamp mode); traces, characteristic EPSCs in control conditions, after application of the AMPA receptor blocker NBQX (20 µM) and subsequent addition of the NMDA receptor blocker APV (50 µM), as indicated. D, traces, one-cell example of somatic EPSPs (10 consecutive traces), with or without generated action potentials, at different time intervals between two presynaptic inputs, as indicated (ms), in control conditions (top) and after adding 50 µM PTX (PTX, green), as indicated. Bar graphs, summary of the average spiking probability over the inter-pulse intervals (mean ± SEM; n = 6 cells; colour coding as indicated; error bar position shows fixed time points); Gaussian-model paired-sample t test shows difference in mean 2σ values (coincidence window width) at $p < 0.001$ for control vs. PTX. E, traces, simulated EPSPs replicating experiments in D, with stochastic synaptic release (10 traces shown for each condition; notations as in D). Histograms, the outcome of simulation experiments; coincidence windows for control and +PTX cases were, respectively: 12.5 ± 0.72 and 24.2 ± 1.2 ms (Gaussian-fit 2σ ± SD); other notations as in D.

© 2020 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society.
the pairwise-recorded somatic EPSCs by $1.38 \pm 0.31$ ms (Fig. 5C; difference in the uEPSC decay between $+40$ and $-70$ mV at $p = 0.0021$, paired $t$ test), which is a twofold amplification of the change seen in dendrites.

To extend this test to multi-synaptic activation, we increased the afferent stimulus strength while placing the stimulating pipette further away from the dendritic patch electrode (Fig. 5D). Here, the voltage asymmetry of the

---

Figure 4. Coincidence detection of excitatory inputs is controlled by GABA transporters

A, traces, characteristic EPSPs (10 consecutive traces), with or without generated spikes, at different time intervals between two stimuli, as indicated (ms), in control conditions. Bar graphs, summary of the average spiking probability over the inter-pulse interval (mean ± SEM) in control conditions ($n = 12$ cells), with $600 \mu M$ nipecotic acid ($+\text{NipA}; n = 8$), and subsequently $50 \mu M$ PTX ($+\text{NipA}+\text{PTX}; n = 7$); colour coding as indicated; error bar position shows fixed time points. Gaussian-model paired-sample $t$ tests indicate difference between mean 2σ values (coincidence window width) at $p = 0.0026$ for control vs. NipA, $p = 0.0438$ for NipA+PTX vs. NipA, and $p < 0.001$ for one-way ANOVA with the three-level factor of drug application. B, experiment as in A, but with $100 \mu M$ SKF-89976A ($+\text{SKF}; n = 9$ cells) added. Other notations as in A; Gaussian-model paired-sample $t$ test shows difference between mean 2σ values at $p = 0.00185$ for control vs. SKF samples. C, experiment as in A, but with $100 \mu M$ SNAP-5114 ($+\text{SNAP}; n = 21$ cells) added. Other notations as in A–B; Gaussian-model paired-sample $t$ test indicates difference between mean 2σ values at $p < 0.001$ for control vs. SNAP samples.

Figure 5. Changes in the dendritic EPSC kinetics are amplified at the soma

A, dendritic patch recordings of single-synapse, unitary EPSCs (uEPSCs) in a CA1 pyramidal cell (DIC and Alexa Fluor 594 channel); patch and stimulating pipettes shown. Traces, two uEPSC examples (minimal stimulation) showing failures and one-quantum responses. 

B, reversing $V_h$ from -70 mV to +40 decelerates uEPSC decay; one-synapse example including a failure (5-trial average; light grey line, trace at -70 mV normalised to that at +40 mV).

C, summary, decay times of uEPSCs recorded at -70 mV and +40 mV, in dendrites (mean ± 95CI: 1.9 ± 0.49 and 2.56 ± 0.44 ms, respectively; $p = 0.00206$, paired t test) and the soma (mean ± 95CI: 3.2 ± 0.98 and 4.58 ± 1.06 ms, respectively; $p = 0.00105$, paired t test), as indicated ($n = 5$ cells); same colour depicts recordings from the same cell.

D, dual-patch soma-dendrite experiment (DIC and Alexa Fluor); no detectable reverse dialysis into the dendritic pipette (dend); local sub-dendritic stimulation electrode (stim) shown.

E, traces, one-cell example of dendritic (top) and somatic (bottom) multi-synaptic EPSCs at -70 and +40 mV, as indicated.
EPSC decay increased to 2.68 ± 0.47 ms in dendrites, and to 16.4 ± 3.5 ms in the soma (mean ± 95CI; \( n = 6, p < 0.001; \) Fig. 5E). Thus, without involving \( I_h \) or tonic GABA current, non-linear dendritic summation can amplify small changes in the dendritic EPSC decay several-fold.

In the second experiment, we used similar settings but retarded the dendritic EPSC kinetics using cyclothiazide (CTZ), an AMPA receptor desensitisation blocker applied in sub-saturation concentrations (10 \( \mu \text{M} \)) to avoid any significant increases in release probability by CTZ. Again, while CTZ decelerated the decay of dendritic EPSCs by only 3.13 ± 0.76 ms, the slowdown at the soma was 14.0 ± 4.5 ms (mean ± 95CI; \( n = 6, p = 0.00638; \) Fig. 5F), which is more than a fourfold increase. Finally, we repeated the electrodiffusion experiment (Fig. 5A–E) in the presence of CTZ, to see if voltage asymmetry and its somatic amplification remain significant for slower synaptic currents. As in the tests above, the depolarisation-dependent deceleration of local dendritic EPSCs (at \( V_m = +40 \text{ mV} \)) increased more than twofold when reaching the soma (mean ± CI95: from 6.82 ± 1.06 to 14.03 ± 4.49 ms, \( n = 6, p = 0.0255; \) Fig. 5G–H).

Discussion

It has long been suggested that feedforward inhibition is a key feature enabling precise coincidence detection, and thus accurate information transfer, in central neural circuits (Pouille & Scanziani, 2001; Perez-Orive et al. 2002; Calixto et al. 2008; Pavlov et al. 2011). Some of these studies employed a classical experimental design in acute brain slices, in which afferent fibres are stimulated using an extracellular electrode. However, studies in the hippocampal CA3–CA1 circuit that employed either pre–post-synaptic cell pair recordings or selective optogenetic stimulation of Schaffer collaterals, documented spike-generating monophasic EPSPs in CA1 PCs, with no detectable GABAergic component (Debanne et al. 1996; Zhang et al. 2008; Kohl et al. 2011; Jackman et al. 2014). Similarly, in vivo recordings in hippocampal CA1 PCs appear to routinely show monophasic subthreshold EPSPs (Bahner et al. 2011; Kowalski et al. 2016). As these observations highlighted the functional significance of direct excitatory inputs to CA1 PCs, it was important to understand what mechanisms can adaptively control the coincidence detection of such inputs.

The combined excitatory and feedforward inhibitory transmission in the CA3–CA1 circuit manifests itself as a prominent biphasic EPSP–IPSP response in CA1 PCs (Pouille & Scanziani, 2001; Pavlov et al. 2011). This response is sensitive to \( I_h \), which thus has a profound influence on coincidence detection in the postsynaptic PC (Pavlov et al. 2011). To enable stimulation of direct excitatory inputs to CA1 PCs, here we used theta-glass bipolar electrodes that provide highly localised excitation of Schaffer collaterals. The EPSPs recorded under this protocol had no IPSP component, and upon the blockade of GABA\(_A\) receptors or \( I_h \) showed negligible changes compared with the prominent, twofold increases in the amplitude and rise time, which has been characteristic for the case of feedforward inhibition (Pouille & Scanziani, 2001; Pavlov et al. 2011). These observations confirmed that our protocols enabled us to explore the integration of monosynaptic inputs to CA1 PCs.

It has long been acknowledged that in CA1 PCs (and probably other principal neurons), membrane-shunting conductance carried by \( I_h \) plays a key role in shaping somatic response in the course of dendritic integration (Magee, 1999; Angelo et al. 2007; George et al. 2009). \( I_h \) has also been responsible for significant control over the coincidence detection of CA3–CA1 signals in the presence of feedforward inhibition (Pavlov et al. 2011). Another, well-acknowledged and no less prominent, source of membrane shunting has been tonic GABAergic inhibition which depends on local [GABA] and exerts strong control over the cell spiking response (e.g. Hausser & Clark, 1997; Semyanov et al. 2003; Prescott et al. 2006; Pavlov et al. 2014). We therefore asked whether, in the absence of direct inhibitory inputs, \( I_h \) and tonic GABA current could regulate the temporal coincidence of excitatory inputs to PCs.

© 2020 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society.
Unlike the expression of $I_h$, which must be a ‘stationary’ feature of individual cells, tonic GABA current depends on the dynamic equilibrium of GABA release and uptake (Glykys & Mody, 2007; Pavlov et al., 2014), which may vary from region to region (Lee & Maguire, 2014), reflecting the local activity of neuronal networks and astroglia (Semyanov et al., 2004; Glykys & Mody, 2007; Woo et al., 2018). Indeed, we used a highly sensitive GABA sniffer-patch method to demonstrate that changes in neural network activity in the slice could alter [GABA] 2–3-fold. It has previously been shown that blocking GABA transport, or indeed blocking GABA$_{	ext{A}}$ receptors, generates a comparable (opposite-sign) change of the tonic GABA current in CA1 PCs (Semyanov et al., 2003; Scimemi et al., 2005; Pavlov et al., 2014). We could thus employ the blockade of GABA$_{	ext{A}}$ receptors and of GABA uptake as a way to replicate activity-dependent changes in [GABA], but with the advantage of having a steady-state condition enabling coincidence detection measurements.

We found that, indeed, GABA$_{	ext{A}}$ receptor blockade and the suppression of GABA uptake result, respectively, in the widening and the narrowing of the coincidence detection window, and that the presence of $I_h$ did not seem to influence the effect of [GABA]. Among the GABA transporters, the neuronal GAT-1 type turned out to have the key contributing role. Intriguingly, expression of GABA transporters can be functionally regulated by tyrosine phosphorylation (Law et al., 2000), which could, in theory, provide an adaptive mechanism to regulate [GABA] and therefore coincidence detection.

Finally, we noticed that manipulations with [GABA] in our experiments could produce only a tiny (sub-millisecond or millisecond range) change in the kinetics of dendritic EPSPs. At the same time, changes in the coincidence detection window were in the range of 10–20 ms. Because passive dendritic filtering cannot explain such amplification, we employed dual soma-dendrite recordings to see whether a small change in the kinetics of local dendritic EPSPs. At the same time, changes (sub-millisecond or millisecond range) change in the coincidence detection window were in the range of 10–20 ms. Because passive dendritic filtering cannot explain such amplification, we employed dual soma-dendrite recordings to see whether a small change in the kinetics of local dendritic EPSPs.


Additional information

Data availability statement
The raw data are available on request and will be deposited for download.

Competing interests
The authors declare no known conflicts of interest.

Author contributions
SS designed and carried out the electrophysiological experiments and analyses; LPS designed and carried out computer simulations; NN carried out selected physiological experiments; DAR narrated the study, designed selected experiments and simulations, carried out selected analyses, and wrote the manuscript, to which all the authors contributed.

Funding
This study was supported by the Wellcome Trust Principal Fellowship (212251_Z_18_2), ERC Advanced Grant (323113), and European Commission NEUROTWIN grant (857562) to DAR; University of Edinburgh Chancellor’s Fellowship to SS.

Keywords
extracellular GABA, input coincidence detection, Hebbian learning

Supporting information
Additional supporting information may be found online in the Supporting Information section at the end of the article.

Statistical Summary Document