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## Corticothalamic network abnormalities underlying absence seizures

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► **To cite this version:**

Nathalie Leresche, Vincenzo Crunelli. Corticothalamic network abnormalities underlying absence seizures. *The Cerebral Cortex and Thalamus*, Oxford University Press, In press. hal-04229142

**HAL Id: hal-04229142**

**<https://hal.science/hal-04229142v1>**

Submitted on 5 Oct 2023

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1 **Corticothalamic network abnormalities**  
2 **underlying absence seizures**

3  
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17 Key words: Ca<sup>2+</sup> channels; channelopathy; genetic generalized epilepsy; HCN channels; Na<sup>+</sup>  
18 channels; neuronal synchronization; spike-wave discharges; somatosensory cortex; thalamic  
19 reticular nucleus; ventrobasal thalamic nucleus.

20  
21  
22 Word count: Abstract 202, Main Text: 4903. Number of references: 67  
23  
24

25 **Acknowledgments**

26 Work in our labs is supported by the CNRS, Sorbonne Université and Inserm (grants to NL)  
27 and the Ester Florida Neuroscience Research Foundation (grant 1502 to VC).  
28  
29

30 **Conflict of interest**

31 The authors declare no conflict of interest.  
32  
33

34 **Abstract**

35 Absence seizures (ASs) are genetic generalized seizures and one of the critical neurological  
36 phenotypes that originates from abnormalities in corticothalamic (CT) networks. Genetic  
37 analyses of cohorts with only ASs have identified 2p16.1 and 2q22.3 as significant loci and a  
38 few genes related to intrinsic and synaptic membrane channels. In normal animals, the genetic  
39 mutation of a single voltage- or ligand-gated channel in a single cortical or thalamic neuronal  
40 population can lead to spontaneous ASs. The electrographic activity of ASs invariably  
41 initiates from a localized cortical area but the full expression of these seizures' clinical  
42 symptoms requires interactions between cortical and thalamic networks. In contrast to focal  
43 and other genetic generalized seizures, the ictal activity of cortical and thalamic neurons  
44 during ASs is predominantly characterized by a decreased, but highly synchronized, firing  
45 with individual neurons often showing a different firing pattern from one seizure to the next..  
46 The high remittance rate of children with ASs indicates that CT networks, and/or their  
47 modulatory inputs from the basal ganglia and brain stem, have the inherent capacity to  
48 compensate for the developmental abnormalities that lead to ASs, but the mechanisms of  
49 remittance have not been investigated since all available models lack this feature of human  
50 ASs.

51

52

## 53 **1. Introduction**

54 As early as the first half of the 20th century, the German neurologist Hans Berger  
55 hypothesized that the 3Hz oscillations that he observed in the EEG of a patient during an  
56 absence seizure (AS) resulted from an abrupt withdrawal of tonic inhibitory influences  
57 exerted by the thalamus on the cortex (see Avoli, 2012). Thus, although at that time the  
58 mechanism of these electroencephalographic (EEG) oscillations (now known as spike-and-  
59 wave discharges, SWDs) was completely unknown, the cortex and the thalamus were already  
60 considered major players in the generation of this paroxysmal activity. Nowadays, there is a  
61 general consensus that ASs are a disease of corticothalamic (CT) networks with a critical  
62 modulation by the basal ganglia and brain stem (Crunelli et al., 2020).

63 Following a short summary of the clinical presentation, therapy and comorbidities of ASs, we  
64 first discuss their genetics and the mechanisms involved in their initiation and maintenance in  
65 humans and in models of ASs. The main body of this chapter is a focused review of the  
66 current state of knowledge of the molecular and cellular abnormalities in different neuronal  
67 populations of CT networks that can bring about ASs, using evidence both from  
68 investigations that have used selective genetic manipulations in normal non-epileptic animals  
69 and from studies in five genetic models with spontaneous ASs that have been validated for  
70 their strong face-, construct- and content-validity: the polygenic GAERS and WAG/Rij rats,  
71 and the monogenic stargazer (STG), tottering (TG) and lethargic (LH) mice (Pitkänen et al.,  
72 2017). Due to space limitations, studies using only pharmacological manipulations are not  
73 discussed.

74

## 75 **2. Clinical presentation of ASs**

76 An AS is a sudden and relatively brief lapse of consciousness associated with lack of  
77 voluntary movements and distinctive SWDs at 2.5-4Hz in the EEG (Crunelli et al., 2020).  
78 ASs are present, together with other seizure types, in many genetic generalised epilepsies  
79 (GGEs), here we focus on ASs observed in childhood absence epilepsy (CAE) since in this  
80 epilepsy type ASs are the only clinical symptom present and not compromised by other  
81 epileptic phenotypes. In CAE, ASs begin between 3 and 8 years of age and can occur up to  
82 ~200 per day. Approximately 70% of CAE patients go into spontaneous remission around  
83 adolescence (Crunelli and Leresche, 2002), though the mechanisms underlying remission  
84 have not been elucidated, since currently researched ASs models lack spontaneous remission.  
85 Pharmacological treatment of ASs relies primarily on ethosuximide (ETX), valproic acid,

86 lamotrigine or their combinations, but ~30% of children are pharmaco-resistant and ~60%  
87 show neuropsychiatric comorbidities (see Crunelli et al., 2020).

88

### 89 **3. Genetics of ASs**

90 Strong evidence exists for a genetic component in CAE, possibly of a polygenic nature  
91 (Perucca et al., 2020) and concordances of 70%–85% and 33% have been reported in  
92 monozygotic twins and first-degree relatives, respectively (Gruenbaum et al., 2021).  
93 However, most CAE patients do not have family history of epilepsy and siblings of affected  
94 individuals have an 8% risk of ASs, which is lower than the expected risk for a recessive  
95 (25%) or dominant (50%) inherited trait (Perucca et al., 2020).

96 Most AS genetic studies have used cohorts with a complex phenotype that included various  
97 epilepsies and other neurological deficits, rendering it difficult to demonstrate an association  
98 between gene abnormalities and ASs. Further, these studies focused on a few families and  
99 reported diverse mutations mainly in  $\gamma$ -aminobutyric acid receptor (GABA<sub>A</sub>R) subunits and  
100 voltage-gated Ca<sup>2+</sup> channels (reviewed in Crunelli and Leresche, 2002). More recently, in a  
101 large study of GGEs (that included CAE as well as juvenile absence epilepsy), no single gene  
102 reached exome-wide significance, though lead associations were found for *CACNA1G*,  
103 *EEF1A2* and *GABRG2*, and, notably, GABA<sub>A</sub>R genes, but not excitatory receptor genes, were  
104 enriched for missense variants (Feng et al., 2019).

105 The first genome-wide association study of a large, pure CAE cohort (778 Caucasian, 15  
106 African) has identified two significant loci: 2p16.1 and 2q22.3 (International League Against  
107 Epilepsy Consortium on Complex Epilepsies, 2018). Though the precise genes in these loci  
108 that contribute to the CAE phenotype are still unknown, prioritized genes include *FANCL*,  
109 *BCL11A* and *ZEB2*, i.e., genes not linked to membrane channels or transmitter pathways that  
110 are generally considered key proteins for AS expression. Notwithstanding, mutations in  
111 *SCN1A*, *SCN8A*, *CACNA1H* and *CLCN2* have been identified in different Chinese CAE  
112 cohorts (Xie et al., 2019).

113 A large number of spontaneous single gene mutations bring about spontaneous ASs in mice  
114 (Frankel, 2009), some of which have been validated as ASs models, including *CACNG2* (in  
115 STG mice), *CACNA1A* (in TG mice) and *CACNB4*, (in LH mice). Whole-genome sequencing  
116 of the polygenic GAERS rats has identified *CACNA1H* (R1584P) as the only gene-variant  
117 that selectively co-segregate with high-seizuring F2 progenies (Casillas-Espinosa et al.,  
118 2017). Notably, a combined proteomic and metabolomic analysis of GAERS rats has found

119 an increase in pathways involved in synaptic transmission and metabolism of  
120 neurotransmitters and the down-regulation of the lysine degradation pathway in both cortex  
121 and thalamus (Harutyunyan et al., 2022). However, adult rats were used in this study, raising  
122 the issue of whether the observed changes in proteins and metabolites are the cause or a  
123 consequence of ASs.

124 In summary, single gene variants are causally linked to the expression of spontaneous ASs in  
125 mice models. However, the human homologs of these genes as well as the mutant genes  
126 found in the Chinese CAE cohorts are not located in the significant loci (2p16.1 and 2q22)  
127 identified in a large CAE cohort.

128

#### 129 **4. Cortical initiation networks of ASs**

130 Although ASs are classified as generalized seizures, many studies in humans report that  
131 SWDs originate from cortical regions before spreading to the entire cortical surface and other  
132 brain regions, though the cohorts of these studies had a mixed phenotype including different  
133 GGEs (reviewed in Crunelli et al., 2020). The first study on a pure CAE cohort reported  
134 cortical-selective increases in the amplitude of blood-oxygen-level-dependent (BOLD) signals  
135 occurring as early as 14s before the clinical and electrographic signatures of an AS could be  
136 observed (Bai et al., 2010). The cortical area(s) showing these pre-ictal increases in BOLD  
137 amplitude are mostly in frontal regions and can differ from child to child, but are generally  
138 consistent across seizures for a given child (Bai et al., 2010). Importantly, the same cortical  
139 areas show a post-ictal decrease in BOLD amplitude that can persist for up to 10s after  
140 seizure-offset (Bai et al., 2010).

141 Changes in BOLD signals also occur in the thalamus during ASs (particularly, in the anterior,  
142 centromedian, parafascicular and reticular nuclei), supporting its critical involvement in the  
143 expression of these seizures (Bai et al., 2010; Guo et al., 2016).

144 The lack of generalization at the onset of an AS, i.e., the existence of a cortical initiation  
145 network (CIN), had been originally reported in two rat models of ASs. It was found that the  
146 peri-oral region of the primary somatosensory cortex (S1) was the cortical initiation network  
147 in GAERS and WAG/Rij rats (Figure 1A) and that S1 Layer 5/6 excitatory pyramidal neurons  
148 were the first to fire at the start of SWDs (Figure 1B) (Meeren et al., 2002; Polack et al.,  
149 2007). Moreover, BOLD signals in awake GAERS rats recapitulate human BOLD results  
150 with an AS-linked decrease and increase in signal in S1 and ventrobasal (VB) thalamus,  
151 respectively (McCafferty et al., 2023).

152 All these pre-seizure changes observed with non-invasive imaging and EEG in humans and  
153 animal models may be the substrate for impaired consciousness, including loss of responses to  
154 external stimuli and a pause in ongoing interactive behaviours, which occur not only during,  
155 but even before the development of, SWDs (Guo et al., 2016). Notably, the magnitude of  
156 BOLD and EEG changes in the cortex and thalamus that precede an AS are positively linked  
157 to the severity of altered behavioural responses and consciousness during a seizure and may  
158 thus be pre-determined by the state of CT networks before seizure-onset (Bai et al., 2010;  
159 Guo et al., 2016). Notably, in GAERS rats, the expression of the AS-related behavioural  
160 phenotype requires the mutual interactions of cortical and thalamic networks, as shown by the  
161 lack of any overt behavioural sign when short (1-2sec) small amplitude SWDs are present in  
162 the cortex but not in the thalamus (Figure 1C) (Polack et al., 2007), indicating that the  
163 recruitment of the thalamus is a necessary step for the expression and maintenance of ASs  
164 (see Part 6 below for intralaminar thalamic nuclei).

165 In summary, it is now well established that 1) SWDs are not generalized from the start but  
166 originate from selective CINs, with S1 Layer 5/6 pyramidal neurons being the first to fire in  
167 animal models; 2) the cortex and thalamus are critical elements for the full expression of ASs;  
168 and 3) the severity of the clinical symptoms of ASs may be predicted by the degree of pre-  
169 seizure EEG and BOLD changes and predetermined by persistently abnormal CT networks.

170

## 171 **5. Mechanisms of altered excitability in deep layers of the CIN**

172 The presence of a CIN in animal models has allowed to study the mechanism(s) underlying  
173 the AS initiation. Strong evidence obtained *in vivo* and *in vitro* in four AS models (GAERS  
174 and WAG/Rij rats, STG and TG mice) has shown enhanced excitability of Layer 5/6  
175 pyramidal neurons (Kole et al., 2007; Polack et al., 2007) that is evident from the presence of  
176 spontaneous giant depolarizing potentials, an increased number of neurons with intrinsic  
177 strong bursting and N-methyl-D-aspartate (NMDA)-mediated EPSPs as well as an enhanced  
178 firing rate, response to weak stimuli and gain of input-output function of Layer 5/6 neurons  
179 (D'Antuono et al., 2005; Polack et al., 2007). Moreover, in WAG/Rij rats, it has elegantly  
180 been shown that a selective decrease in HCN1, but not HCN2 channels in the distal apical  
181 dendrites of Layer 5 pyramidal neurons leads to a decreased dendritic  $I_h$  current, larger and  
182 faster backpropagating action potentials and increased somato-dendritic coupling, so that the  
183 summation of synaptic potentials is enhanced (Figure 1D) (Kole et al., 2007). These intrinsic  
184 HCN channel-dependent changes in excitability are strengthened by a decreased peak

185 conductance and paired-pulse depression (PPD) of evoked GABA<sub>A</sub> inhibitory post-synaptic  
186 potentials (eIPSPs) in S1 Layer 5 (and Layer 2/3) pyramidal neurons and evoked excitatory  
187 post-synaptic potentials (eEPSPs) with a reduced PPD and sensitivity to baclofen, a GABA<sub>B</sub>R  
188 agonist. The net result of all these changes in synaptic activity in S1 Layer 5/6 pyramidal  
189 neurons of WAG/Rij rats is an increased EPSP/IPSP ratio since i) the PPD of both EPSPs and  
190 IPSP is decreased, ii) the number of NMDA EPSPs is increased, and iii) the peak conductance  
191 of IPSCs is decreased.

192 Notably, a similar decrease in cortical inhibition is present in S1 of the TG mice, where a  
193 comprehensive study of EPSPs and IPSPs evoked either by thalamic stimulation or locally  
194 (either in Layer 4 or 5), has compellingly shown that the feed-forward inhibition from the  
195 thalamus to Layer 4 is markedly compromised and correlated to the developmental onset of  
196 ASs (Sasaki et al., 2006).

197 Notably, there is a lower expression of PV<sup>+</sup> interneurons in all S1 layers of WAG/Rij rats  
198 (Papp et al., 2018). Functionally, chemogenetic silencing of S1 PV<sup>+</sup> interneurons in normal  
199 mice is sufficient to generate ETX-sensitive ASs (Panthi and Leitch, 2019), whereas  
200 DREADD-mediated activation of S1 PV<sup>+</sup> interneurons, i.e., activation of local feed-forward  
201 inhibition, protects against pentylenetetrazol-induced SWDs (Panthi and Leitch, 2019) (see  
202 Part 7, below).

203 In summary, in WAG/Rij rats, we have a clear mechanistic explanation of the aberrant  
204 behaviour of S1 Layer 5/6 pyramidal neurons where SWDs originate: intrinsic HCN1 loss-of-  
205 function (leading to enhanced synaptic potential summation) combines with an increased  
206 EPSPs/IPSPs ratio to bring about the enhanced excitability observed in this neuronal  
207 population. A decreased cortical inhibition is also present in TG mice, but similar detailed  
208 mechanistic studies of S1 are not available for GAERS rats and STG and LH mice. PV<sup>+</sup>  
209 interneurons have an anti-absence role since their selective silencing in normal non-epileptic  
210 animals leads to AS expression.

211

## 212 **6. Cellular activity in the neocortex and thalamus during ASs**

213 Using electrophysiological and imaging approaches in non-anesthetized AS models, the ictal  
214 neuronal activities that occur in the cortex and thalamus have recently been studied with  
215 single-cell resolution. Using Ca<sup>2+</sup>-sensitive dyes in the primary visual cortex in STG mice,  
216 Meyer et al. (2018) reported that ~80% of neurons in all cortical layers reduce their activity  
217 before a SWD is detected in the EEG, while smaller neuronal pools show an increased, or no



218 change in, activity (Figure 2A). Interestingly, the ictal involvement of each neuron is not  
219 fixed but fluctuates from seizure to seizure. An overall decrease in neuronal activity during  
220 ASs has been confirmed in S1 cortical neurons of GAERS rats (McCafferty et al., 2023).  
221 However, on closer examination, four patterns of ictal activity could be identified. While 37%  
222 of neurons experienced a sustained ictal decrease in firing, 28% showed a transient firing  
223 peak at seizure-onset. Importantly, regardless of the type of firing, all cortical neurons show a  
224 marked increase in rhythmicity during SWDs compared to interictal periods and all changes  
225 precede seizure-onset by up to 80 seconds.

226 Simultaneous ensemble recordings in cortical neurons and VB thalamocortical (TC) and  
227 nucleus reticularis thalami (NRT) neurons during spontaneous ASs in GAERS rats and  $\gamma$ -  
228 hydroxybutyric acid (GHB)-induced ASs in Wistar rats under freely moving conditions show  
229 that cortical afferent activity drives thalamic firing and temporally frames thalamic output via  
230 feed-forward inhibition of TC neurons by NRT neurons (Figure 2D) (McCafferty et al.,  
231 2018). This results in a marked decrease in the overall firing of TC neurons (with only rare T-  
232 type  $\text{Ca}^{2+}$  channel-dependent burst firing being present ictally) (Figure 2B), which is causally  
233 linked to the constitutively enhanced tonic  $\text{GABA}_A$  current of TC neurons that is present in  
234 this AS model as well as in STG and LH mice (Cope et al., 2009). Nevertheless, the total  
235 firing of TC (and NRT) neurons is strictly in phase with each SWD cycle (Figure 2C),  
236 indicating that the synchrony and strength of the ictal output of TC neurons to the neocortex is  
237 not a feature of single, rhythmically bursting TC neurons, as previously suggested (Sorokin et  
238 al., 2017), but an emergent property of this neuronal population. Notably, an altered firing  
239 that precedes the start of an AS is also present in WAG/Rij rats and STG mice (Sorokin et al.,  
240 2017).

241 A clear limitation in our understanding of thalamic activity during ASs is that the vast  
242 majority of available data have been obtained in first-order somatosensory thalamic nuclei  
243 (see Part 7, below), whereas higher-order and intralaminar thalamic nuclei have been  
244 relatively neglected. Notwithstanding, the rodent thalamic posterior nucleus may be one of the  
245 key thalamic hubs in view of its critical involvement in pre- and post-ictal activity  
246 (Lüttjohann and Pape, 2019). Notably, TC neurons in intralaminar thalamic nuclei show a  
247 similar decrease in total firing as that of first-order thalamic nuclei during ASs but present  
248 two patterns of ictal burst firing: one with a transient increase in bursts at seizure-onset and  
249 one with a sustained increase in burst firing that lasts for the duration of the seizure (Atherton  
250 et al., 2023). Moreover, it is interesting to note that extracellular alkalosis elicits ASs by

251 activating intralaminar thalamic, but not cortical and first-order thalamic neurons of WAG/Rij  
252 rats (Salvati et al., 2022b), a finding of key clinical significance since hyperventilation is a  
253 trigger of ASs in many CAE patients.

254 Finally, although ASs are generated by CT network, both the direct and indirect basal ganglia  
255 pathways provide a fine control of the expression of these seizures (Deransart and Depaulis,  
256 2002). Ictal changes in MRI BOLD signals in the basal ganglia of CAE cohorts have been  
257 consistently reported (Bai et al., 2010). Moreover, genetic deletion of the Munc-18-1 protein  
258 in cortico-striatal Layer 5 neurons elicits ETX-sensitive ASs, and activation of DREADD-  
259 transfected striatal fast-spiking interneurons blocks the spontaneous ASs of mice with whole-  
260 brain KO of Munc-18-1 (Miyamoto et al., 2019).

261 In summary, most cortical neurons decrease their firing during ASs but there are significant  
262 neuronal pools that either increase or do not change their firing rate. In the thalamus, the total  
263 and burst firing rate of TC neurons are reduced but that of the GABAergic NRT neurons is  
264 increased. Each cortical and thalamic neuron may show different activity changes from one  
265 seizure to the next. Intrathalamic thalamic nuclei are critical for AS synchronization and  
266 maintenance.

267

## 268 **7. Induced genetic alterations in CT networks that lead to ASs**

269 To understand how alterations in different neuronal populations of CT networks lead to the  
270 expression of ASs, i.e., to an abnormal function of these networks, many studies have used  
271 genetic tools to manipulate voltage- and ligand-gated membrane channels in normal animals.  
272 In the following, we provide a detailed summary of all the studies that genetically  
273 manipulated voltage- and ligand-gated membrane channels in normal non-epileptic animals  
274 and compare these findings with studies that have investigated abnormalities in voltage- and  
275 ligand-gated membrane channels of five well-validated AS models: GAERS and WAG/Rij  
276 rats, and STG, TG and LH mice. Due to space limitations, we report changes in the  
277 expression levels of intrinsic and synaptic membrane channels only if their functional  
278 consequences have been investigated. Moreover, the abnormalities are described in  
279 comparison with the respective non-epileptic control animals of each model.

### 280 *7.1 Ligand-gated channels*

281 GABA<sub>A</sub>R  $\alpha$ 3 subunit knock-out (KO) mice do not express spontaneous ASs but show a  
282 decrease in GHB-induced SWDs (Winsky-Sommerer et al., 2008), whereas GABA<sub>A</sub>R  $\beta$ 3  
283 subunit KO mice show a complex epileptic phenotype that only at times includes ASs

284 (DeLorey et al., 1998). Spontaneous ASs are observed in mice knock-in (KI) for the human  
285  $\gamma 2$  subunit R43Q mutation (Tan et al., 2007) (which had been identified in probands with  
286 febrile seizures and ASs (see Crunelli and Leresche, 2002), whereas whole-brain KO of  
287 GABA<sub>B</sub>R1 or GABA<sub>B</sub>R2 lead only to rare or no spontaneous SWDs, respectively (Gassmann  
288 et al., 2004; Schuler et al., 2001).

289 Paradoxically, whole brain ablation of one of the subunits of the  $\alpha$ -amino-3-hydroxy-5-  
290 methyl-4-isoxazolepropionic acid (AMPA) receptors (*GRIA4* KO mice) results in  
291 spontaneous ASs with decreased EPSCs in NRT but not TC neurons (Paz et al., 2011).  
292 Notably, decreased eEPSCs are present in TC neurons of TG mice and reduced NMDA and  
293 non-NMDA eEPSCs in LH mice (Caddick et al., 1999).

294 A common finding in GAERS rats and STG and LH mice is the constitutively enhanced tonic  
295 GABA<sub>A</sub> current of TC neurons that results from a non-genetic loss-of-function of GAT1 (one  
296 of the GABA transporters) that is necessary and sufficient for AS expression (Cope et al.,  
297 2009). In TC neurons of LH mice, GABA<sub>B</sub> eIPSCs are decreased but there is no change in  
298 GABA<sub>A</sub> eIPSCs and baclofen-evoked currents (Caddick et al., 1999). The lack of changes in  
299 GABA<sub>A</sub> IPSCs is shared by other models since no difference was found in GABA<sub>A</sub> miniature  
300 IPSCs (mIPSCs) and eIPSCs in TC neurons of GAERS rats (Bessaïh et al., 2006; Cope et al.,  
301 2009) and TG mice (Caddick et al., 1999), respectively. An increased amplitude, and  
302 decreased frequency and duration of mIPSCs but no change in PPD was reported in GAERS  
303 NRT neurons (Bessaïh et al., 2006).

304 As far as excitatory transmitter function is concerned, a detailed analysis of synaptic  
305 potentials in NRT neurons has only been carried out in STG mice. Using a combination of  
306 electrical stimulation and photolysis of caged-glutamate, it was elegantly shown that a  
307 trafficking defect of AMPA receptors (i.e., decreased synaptic and increased perisynaptic  
308 receptors) leads to a reduction of AMPA EPSCs and a compensatory increase of NMDA  
309 EPSCs efficacy, leading to an increased NMDA/AMPA charge of EPSCs of both thalamic  
310 and cortical origin (Lacey et al., 2012).

### 311 *7.2 Voltage-gated Ca<sup>+2</sup> channels*

312 Selective knock-down (KD) of Cav2.1 channels in Layer 6 pyramidal neurons of normal mice  
313 leads to spontaneous ETX-sensitive ASs accompanied by increased T-type Ca<sup>2+</sup> currents in  
314 the TC and NRT neurons and increased burst firing in the latter but not the former thalamic  
315 neural population (Bomben et al., 2016) (Figure 3). Since no changes in cortical Cav2.1

316 channels expression were observed with light microscopy, T-type  $\text{Ca}^{2+}$  currents and  
317 associated burst firing was not investigated in cortical excitatory and inhibitory neurons in  
318 these Layer 6 pyramidal neuron-selective KD mice, making it difficult to accept the authors'  
319 conclusion that changes in thalamic neuron excitability were the only ones causally linked to  
320 AS expression. Indeed, ablation of  $\text{Cav}2.1$  channels in adult mice brings about ASs that are  
321 not associated with changes in T-type  $\text{Ca}^{2+}$  currents or burst firing in TC neurons (Miao et al.,  
322 2019). Similarly, selective KO of  $\text{Cav}2.1$  channels in PV+ and somatostatin-positive (SST+)  
323 cortical interneurons leads to ASs with no change in T-type  $\text{Ca}^{2+}$  currents or burst firing of TC  
324 neurons (Figure 3) (Rossignol et al., 2013), demonstrating that a constitutive or induced  
325 increase in these TC neuron parameters, as observed in TG mice and mice with selective  
326 Layer 6 pyramidal neurons KD of  $\text{Cav}2.1$  channels, is not necessary for the expression of  
327 ASs.

328  $\text{Cav}2.3$  channels are expressed in cortical and NRT, but not TC neurons, and their whole-  
329 brain KO leads to a decrease in GHB-induced ASs (Zaman et al., 2011). However, whether  
330 this pathological phenotype is due to NRT or cortical  $\text{Cav}2.3$  channels remains to be  
331 investigated.

332 Whole-brain overexpression of  $\text{Cav}3.1$  channels lead to spontaneous ETX-sensitive ASs  
333 (Ernst et al., 2009), whereas mice with KO of these channels show a decrease in baclofen and  
334 GHB-induced SWDs (Kim et al., 2001). Notably, the spontaneous ASs observed in  $\text{Cav}2.1$   
335 KO mice (Bomben et al., 2016; Miao et al., 2019; Song et al., 2004) are abolished by the  
336 simultaneous KO of  $\text{Cav}3.1$  channels. However, despite the substantial expression of  $\text{Cav}3.1$   
337 channels in cortical territories (Talley et al., 1999), the analysis of the cellular/network  
338 abnormalities in these single and double KO mice was only carried out in the thalamus. So,  
339 though these studies strongly point to a key role of  $\text{Cav}3.1$  channels in the genesis of ASs,  
340 they do not clarify the brain area(s) and neuronal population(s) where these channels are  
341 critical for AS expression (see below).

342 Notably, elevated T-type  $\text{Ca}^{2+}$  currents (mainly due to  $\text{Cav}3.1$  channels) are present in TC  
343 neurons of different thalamic nuclei of four AS models (WAG/Rij rat, and STG, TG and LG  
344 mice) (Broicher et al., 2008; Zhang et al., 2002). The block of ASs by whole-brain genetic  
345 ablation of  $\text{Cav}3.1$  channels in STG, TG and LH mice has been causally linked to the loss of  
346 function of these channels in TC neurons (Song et al., 2004). However, such conclusion is  
347 flawed since the block of ASs in these mice could also be due to the simultaneous ablation of  
348  $\text{Cav}3.1$  channels in the cortex where they are highly expressed (Talley et al., 1999). Indeed,

349 ASs in GAERS rats are not affected by selectively blocking Cav3.1 channels and related burst  
350 firing of TC neurons with a potent T-type Ca<sup>2+</sup> channels antagonist (McCafferty et al., 2018).  
351 Notwithstanding, TC neuron firing is necessary for AS expression since brief optogenetic  
352 manipulation of TC neurons abort ASs in WAG/Rij rats and STG mice (Sorokin et al., 2017).  
353 Mice with whole-brain KO or selective KD of Cav3.3 channels in the NRT do not show  
354 spontaneous ASs, but an unexpected increase in GHB-induced ASs (Lee et al., 2014) (Figure  
355 3). The same phenotype is observed in double KO mice of Cav3.3 and Cav3.2 channels (Lee  
356 et al., 2014) where the T-type Ca<sup>2+</sup> current of NRT neurons is completely abolished. Thus,  
357 notwithstanding the key role of the NRT neurons T-type Ca<sup>2+</sup> current (and the burst firing that  
358 it generates) in physiological activities expressed by CT networks (Crunelli et al., 2018), full  
359 ablation of these NRT channels leads to potentiation of pharmacologically induced ASs.  
360 Whether this is due to the increased tonic firing of NRT neurons that is present in these single  
361 and double KO mice (Lee et al., 2014) or results from alterations in the activity of cortical  
362 neuronal populations remains to be elucidated since the analysis of the cellular and network  
363 abnormalities of these mice was only carried out in the thalamus.

364 Elevated T-type Ca<sup>2+</sup> currents are also present in the NRT neurons of GAERS and WAG rats  
365 (Broicher et al., 2008; Cain et al., 2018) but have not been studied in the NRT of STG, TG  
366 and LH mice. In GAERS rats, this increased current is due to the R158P missense variant of  
367 *CACNA1H* (the Cav3.2 channel gene) and selective KD of these channels in NRT neurons  
368 markedly reduces ASs and normalizes their elevated burst firing (Cain et al., 2018).  
369 Moreover, KI of the human *CACNA1H* variant C456S in S1 of normal non-epileptic rats  
370 elicits spontaneous ASs in >60% of the injected animals (Wang et al., 2015).

### 371 *7.3 Voltage-gated Na<sup>+</sup> and Na<sup>+</sup>/K<sup>+</sup> channels*

372 Ablation of Nav1.2 channels in the whole-brain or selectively in telencephalic and  
373 diencephalic neurons leads to spontaneous ETX-sensitive ASs with smaller SWDs being  
374 present in the thalamus compared to those in S1, medial prefrontal cortex, and hippocampus  
375 (Ogiwara et al., 2018). Ablation of Nav1.6 channels either in the whole-brain, only in  
376 inhibitory neurons or in the NRT (Figure 3) brings about ETX-sensitive ASs, whereas no  
377 seizures are observed when these channels are ablated in either all cortical neurons, in  
378 glutamatergic excitatory neurons, or only in inhibitory neurons of the cortex, hippocampus,  
379 and striatum (Makinson et al., 2017).

380 Mice with whole-brain KO of hyperpolarization-activated, cyclic nucleotide-gated Na<sup>+</sup>/K<sup>+</sup>  
381 channels subtype 2 (HCN2) show spontaneous ASs (Ludwig et al., 2003) but HCN4 channel

382 KO mice do not (Zobeiri et al., 2019). However, extensive analysis of thalamic neuron  
383 abnormalities but no data on cortical neurons were provided in these two studies, leaving a  
384 knowledge gap on the relative contribution of HCN2 and HCN4 channels in the cortical and  
385 thalamic sectors of the CT network. In TC neurons of different first-order thalamic nuclei of  
386 both GAERS and WAG/Rij rats, there is an increased  $I_h$  (Budde et al., 2005; Cain et al., 2015;  
387 Kanyshkova et al., 2012), that most likely results from an increased HCN1 channel density  
388 with no change in HCN2 and HCN4 expression (Cain et al., 2015). Notably, the increased  
389 density of HCN1 channels in thalamic nuclei of WAG/Rij rats (Kuisle et al., 2006) is in  
390 contrast to their decreased expression in S1 (Kole et al., 2007) (see Part 5, above), indicating  
391 that in a given AS model, and potentially in humans with ASs, the same channels can be  
392 differentially expressed in diverse sectors of the CT network. Notably, pharmacological block  
393 of all HCN subtypes systemically, or locally in S1 or VB, blocks ASs (Iacone et al., 2021).

394 In summary, the following significant conclusions arise from these studies:

- 395 1. genetic ablations of diverse single channel abnormalities in single neuronal populations of  
396 the CT network lead to spontaneous ETX-sensitive ASs (Figure 3); Cav2.1 channels in  
397 cortical layer 6 neurons (Bomben et al., 2016), Cav2.1 channels in cortical PV+ and SST+  
398 interneurons (Rossignol et al., 2013), Nav1.6 channels in NRT neurons (Makinson et al.,  
399 2017), phospholipase C  $\beta$ 1 subunit in NRT neurons (Chang et al., 2022) and phospholipase  
400 C  $\beta$ 4 subunit in TC neurons (Cheong et al., 2009), whereas selective KD of Cav3.3  
401 channels in NRT neurons does not lead to spontaneous ASs but increases GHB-induced  
402 SWDs (Lee et al., 2014);
- 403 2. secondary (compensatory) changes in a CT sector other than the one where the primary  
404 genetic manipulation had been made may be the critical element for ASs expression  
405 indicated by the increased T-type  $Ca^{2+}$  currents in TC neurons of mice with selective KD  
406 of Cav2.1 channels in cortical Layer 6 neurons (Bomben et al., 2016);
- 407 3. different changes of membrane proteins expression may occur in diverse areas of CT  
408 network, as indicated by the decreased and increased expression of HCN1 channels in the  
409 cortex and thalamus, respectively, of WAG/Rij rats (Cain et al., 2015; Kole et al., 2007);
- 410 4. in view of the cortical location of SWDs initiation in humans and animal models (see Parts  
411 4 and 5, above), it is unfortunate that almost all investigations that used whole-brain  
412 genetic manipulations have studied abnormalities only in thalamic but not cortical neurons,  
413 even when the manipulated channels are (highly) expressed in both the cortical and  
414 thalamic sectors of CT networks.

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## 8. Conclusions

Abnormal genes found either in small Chinese CAE cohorts or in mice AS models are not located in the significant loci (2p16.1 and 2q22) identified in the only large genome-wide CAE study, though *CACNA1H* variants are present in Chinese probands and the GAERS rat model of ASs. Selective ablation of Cav2.1, Cav3.3, and Nav1.6 channels as well as phospholipase C  $\beta$ 1 and  $\beta$ 4 subunits in either Layer 6 pyramidal neurons, cortical PV+ and SST+ interneurons, TC or NRT neurons of normal non-epileptic animals leads to ASs. In contrast to focal seizures and other GGEs, the ictal activity of cortical and thalamic neurons is predominantly characterized by a decreased, but highly synchronized, firing with all component members of a neuronal population often changing firing pattern from one seizure to the next. Selective chemogenetic and optogenetic manipulation of S1 PV+ interneurons and TC neurons, respectively, conclusively demonstrates that these neuronal populations are necessary for AS expression. The evidence in normal non-epileptic animals that a single manipulation of different voltage- and ligand-gated membrane channels does lead to ASs indicates the liability of CT networks towards the generation of these seizures. On the other hand, the high remittance rate of children with CAE indicates that CT networks, and/or their modulatory inputs from the basal ganglia and brain stem, have the inherent capacity to compensate for the developmental abnormalities that lead to ASs. However, the mechanism of remittance has not been investigated since all available AS models lack this feature of the human disease.

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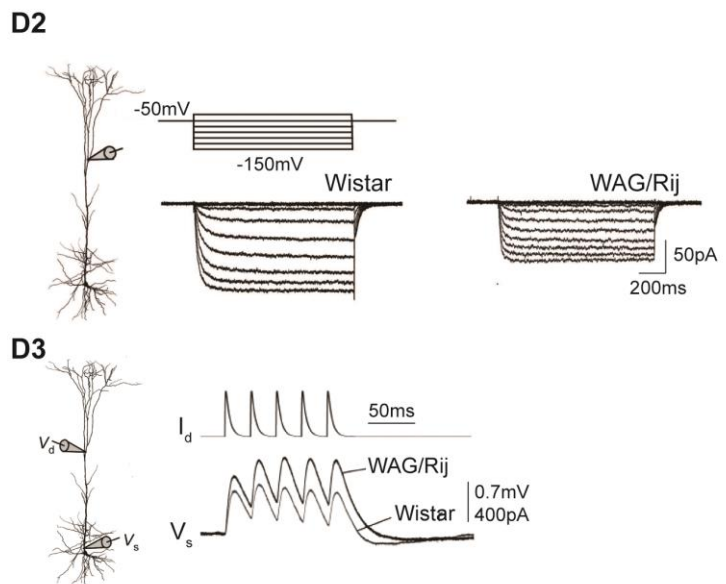
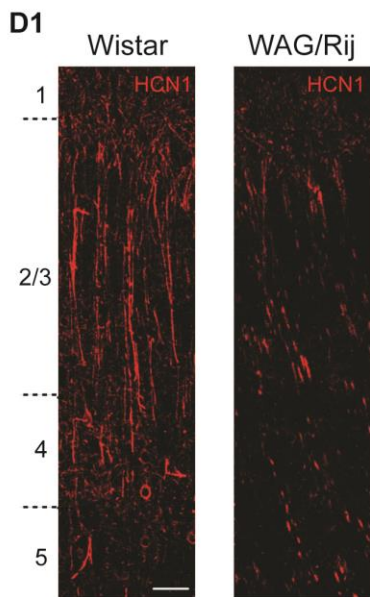
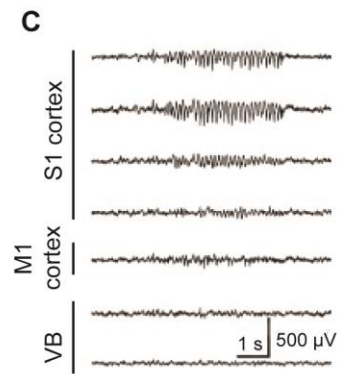
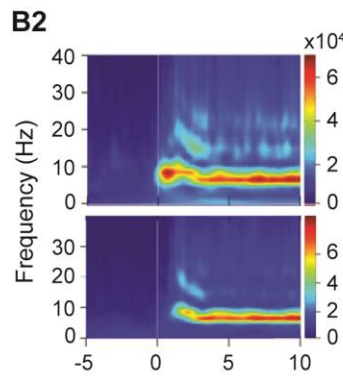
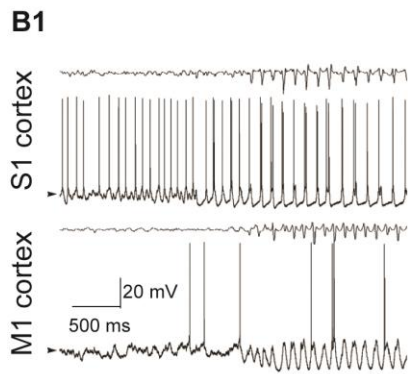
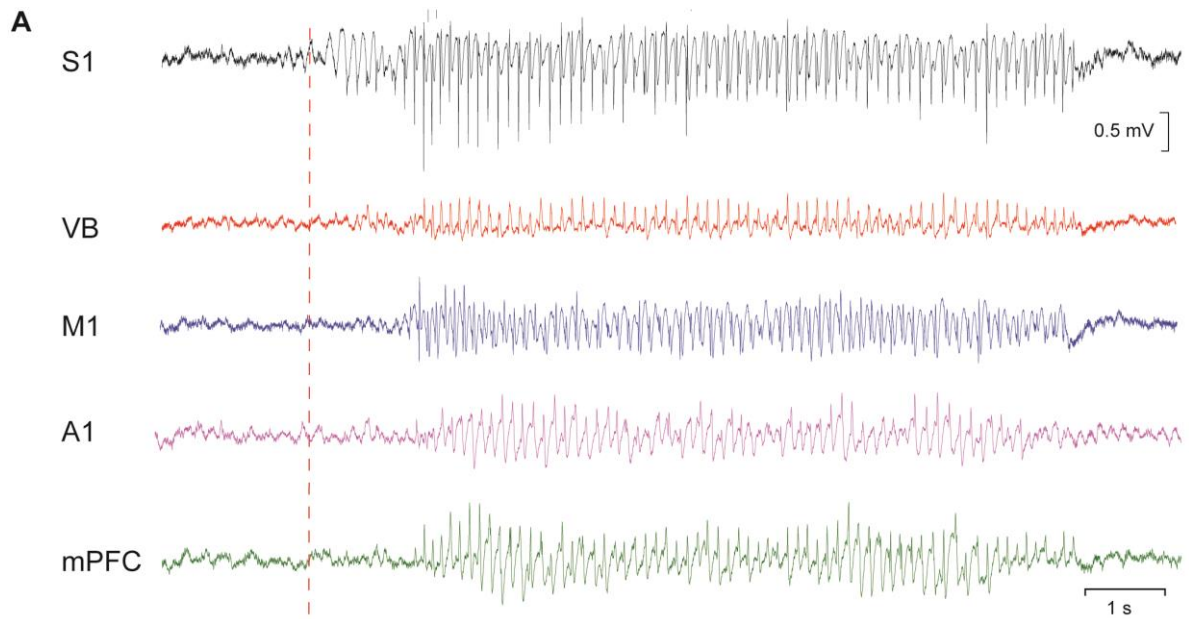
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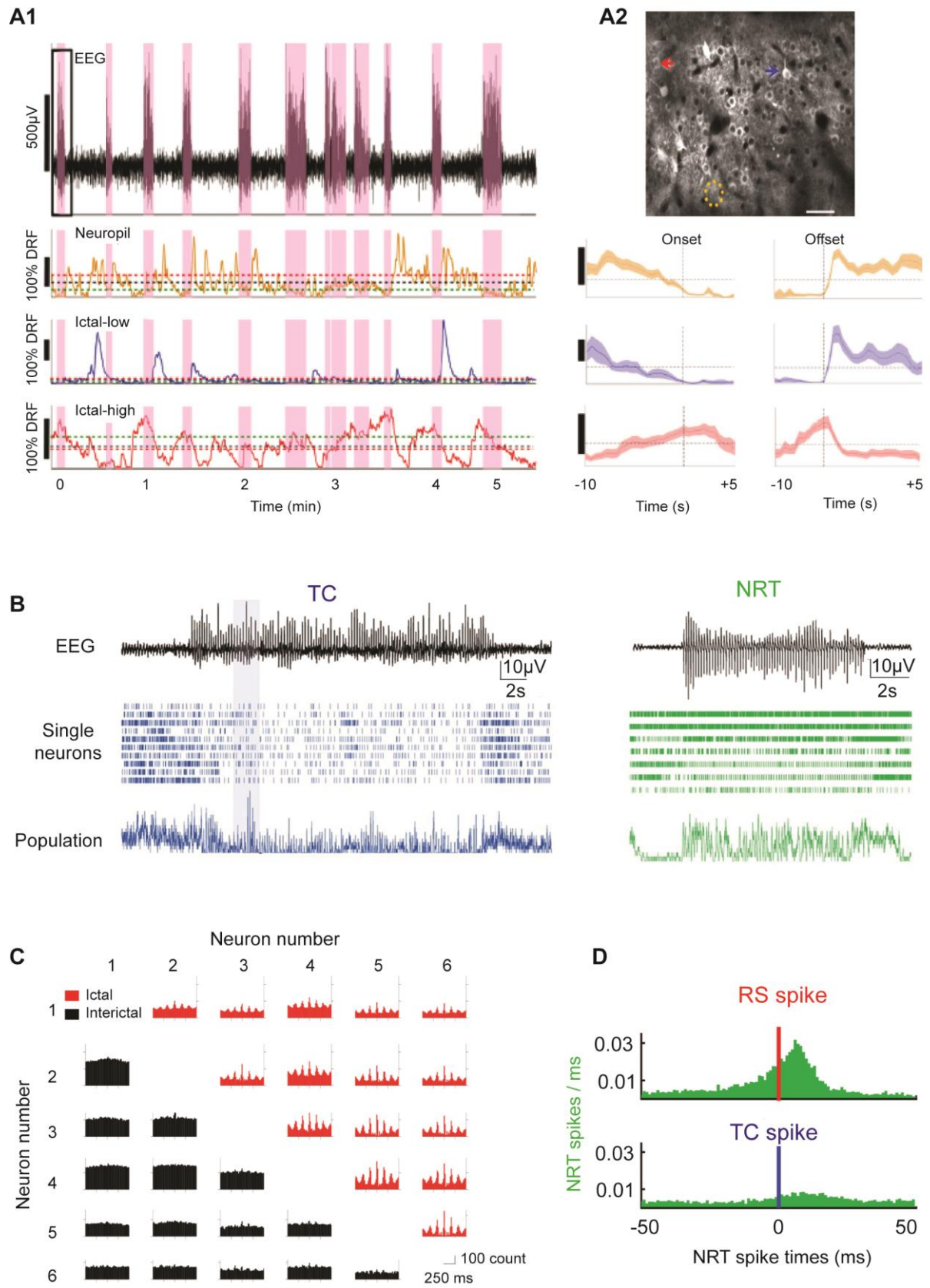
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694 **Figure 1. Cortical initiation of absence seizures (ASs) and cellular abnormalities in**  
695 **Layer 5 neurons of AS models.**

696 **(A)** Electroencephalographic (EEG) traces from the indicated cortical and thalamic areas in a  
697 freely moving GAERS rat show the initiation of SWDs in the primary somatosensory cortex  
698 (S1); VB: ventrobasal thalamic nucleus, M1: primary motor cortex, A1: primary auditory  
699 cortex, mPFC: medial prefrontal cortex. **(B1)** Interictal and ictal intracellular activity (bottom  
700 trace in each pair) of Layer 5 neurons, recorded in the same GAERS rat simultaneously with  
701 the corresponding EEG (top trace in each pair). Note the hyperactivity of the neuron located  
702 in the primary somatosensory cortex (S1 cortex), the cortical initiation network in this animal  
703 model, compared to the neuron in the primary motor cortex (M1 cortex). **(B2)** Averaged time-  
704 frequency maps showing the occurrence of 6-8Hz SWDs in S1 before M1. **(C)** EEG traces  
705 from different sites in the CT network of a GAERS rat show large amplitude SWDs in S1  
706 (and very small SWDs in M1) but not in the VB, the somatotopic thalamic nucleus of S1,  
707 which were not accompanied by any behavioural sign. **(D1)** HCN1 immunofluorescence in S1  
708 shows weaker labeling in a WAG/Rij rat compared to a control Wistar rat (scale bar, 100 $\mu$ m).  
709 **(D2)** Dendritic cell-attached patch-clamp recordings in the apical dendrites of an S1 Layer 5  
710 pyramidal neuron show significantly lower amplitude of  $I_h$  in a WAG/Rij rat compared to a  
711 control Wistar rat. **(D3)** Simultaneous dendritic and somatic whole-cell recordings in an S1  
712 Layer 5 pyramidal neuron. EPSPs were simulated by current injection in the dendrite ( $I_d$ , top  
713 trace) and their summation at the soma ( $V_s$ , bottom traces) was increased in a WAG/Rij rat  
714 neuron compared to a control Wistar rat neuron. Adapted from McCafferty et al. (2018) (A),  
715 Polack et al. (2007) (B, C) and Kole et al. (2007) (D1-D3).

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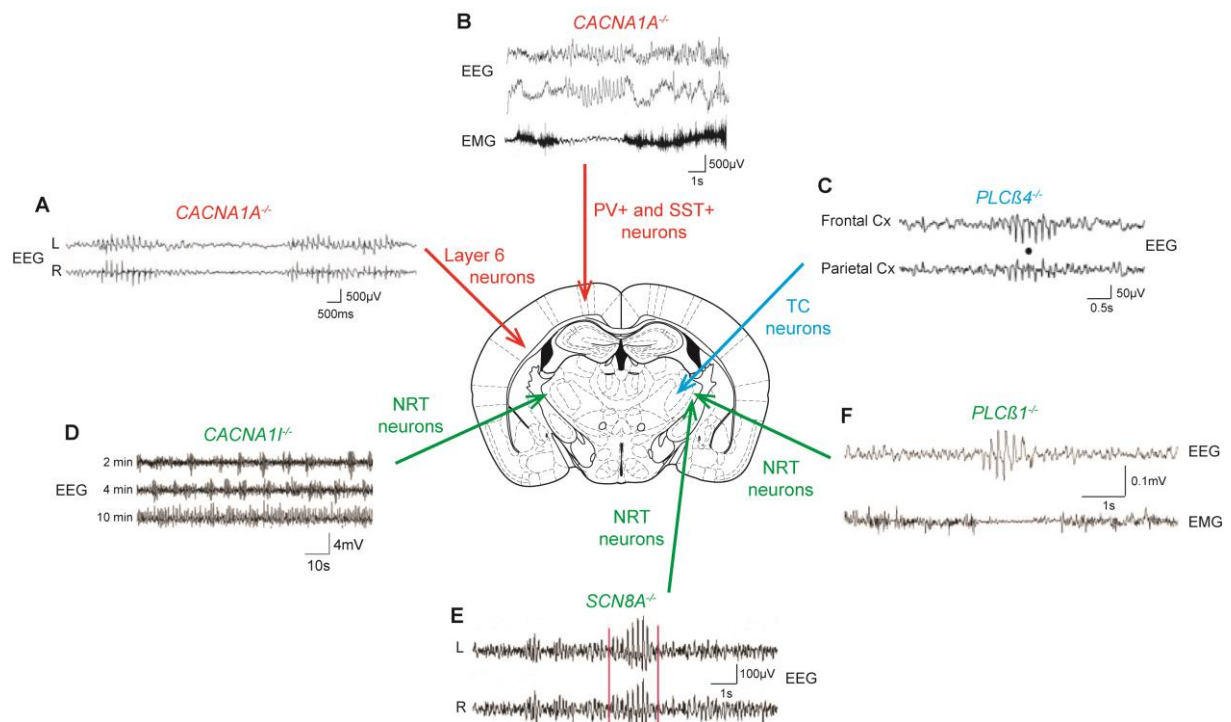
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**Figure 2. Activity of cortical and thalamic neurons during absence seizures (ASs).**



721 **(A1)** Concomitant electroencephalographic (EEG) (top trace) and intracellular  $\text{Ca}^{2+}$  changes  
722 from Layer 2/3 GCaMP6-filled neurons in the visual cortex of a head-restrained STG mouse.  
723 The  $\text{Ca}^{2+}$  changes of each neuron/neuropil patch over time are shown with the seizure epochs  
724 highlighted in pink. Mean ictal activity (green dashed line), mean interictal activity (red  
725 dashed line), and overall mean activity (black dashed line). **(A2)** The average activity (vertical  
726 bar = 20%  $\Delta\text{F}/\text{F}$ ) time-locked to the seizure onset and offset is shown for exemplary neuropil  
727 (top), a neuron with low activity during ASs (ictal-low, middle) and a neuron with high  
728 activity during ASs (ictal-high, bottom). The ictal-low and ictal-high neuron are marked by a  
729 blue and red arrow, respectively in the 2-photon microscopy image shown at the top, with the  
730 neuropil area highlighted by a yellow dotted circle. Scale bar = 50 $\mu\text{m}$ . **(B)** EEG (top trace)  
731 and spike-time raster plots from 10 thalamocortical (TC) neurons in the ventrobasal thalamic  
732 nucleus and 7 nucleus reticularis thalami (NRT) neurons simultaneously recorded with a  
733 silicon probe in a freely moving GAERS rats. Most TC neurons show a decrease in firing rate  
734 during the ASs, which is also evident from the population activity (bottom trace). NRT  
735 neurons show two different types of ictal firing: one group increases their firing ictally (top  
736 three cells in raster-plot) and another group shows a decreased activity (bottom four cells).  
737 **(C)** Cross-correlograms of the total firing of 6 simultaneously recorded GAERS TC neurons  
738 during interictal periods (black plots) and ASs (red plots). Despite the overall decrease in  
739 firing during ASs (red plots), there is a marked increase in neuronal synchrony. **(D)**  
740 Histograms of the firing of an NRT neuron recorded simultaneously with a cortical regular  
741 spiking (RS) neuron (top) or a TC neuron (bottom) in a freely moving GAERS rat. Note that  
742 the ictal NRT neuron firing (green bars) is mainly driven by the cortical RS neuron spikes  
743 rather than the TC neuron spikes. Time zero marks the firing of the RS and TC neurons (red  
744 and blue lines, respectively). Adapted from Meyer et al. (2018) (A) and McCafferty et al.  
745 (2018) (B-D).  
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749 **Figure 3. Single genetic ablations that lead to absence seizures (ASs).**

750 Schematic brain drawing (center panel) showing the location of the different single mutations  
 751 induced in either Layer 6 neurons, cortical parvalbumin- and somatostatin-positive (PV+ and  
 752 SST+, respectively) interneurons, thalamocortical (TC) and nucleus reticularis thalami (NRT)  
 753 neurons that have been shown to elicit spontaneous ASs (A, B, C, E, and F) or increase  $\gamma$ -  
 754 hydroxybutyric acid-induced ASs (D). Panels show electroencephalographic (EEG) and  
 755 electromyographic (EMG) activity in mice with the illustrated genetic ablation. Minutes on  
 756 the left-hand side of the traces in D indicate the time from the  $\gamma$ -hydroxybutyric acid injection  
 757 (Cx: cortex; L: left; R: right). Adapted from Bomben et al. (2016) (A), Rossignol et al. (2013)  
 758 (B), Cheong et al. (2009) (C), Lee et al. (2014) (D), Makinson et al. (2017) (E), and Chang et  
 759 al. (2022) (F).

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