

The mTOR pathway genes *mTOR*, *Rheb*, *Depdc5*, *Pten*, and *Tsc1* have convergent and divergent impacts on cortical neuron development and function

Reviewed Preprint

Published from the original preprint after peer review and assessment by eLife.

About eLife's process

Reviewed preprint posted

October 11, 2023 (this version)

Posted to bioRxiv

August 12, 2023

Sent for peer review

July 30, 2023

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Abstract

Brain somatic mutations in various components of the mTOR complex 1 (mTORC1) pathway have emerged as major causes of focal malformations of cortical development and intractable epilepsy. While these distinct gene mutations converge on excessive mTORC1 signaling and lead to common clinical manifestations, it remains unclear whether they cause similar cellular and synaptic disruptions underlying cortical network hyperexcitability. Here, we show that *in utero* activation of the mTORC1 activators, *Rheb* or *mTOR*, or biallelic inactivation of the mTORC1 repressors, *Depdc5*, *Tsc1*, or *Pten* in mouse medial prefrontal cortex leads to shared alterations in pyramidal neuron morphology, positioning, and membrane excitability but different changes in excitatory synaptic transmission. Our findings suggest that, despite converging on mTORC1 signaling, mutations in different mTORC1 pathway genes differentially impact cortical excitatory synaptic activity, which may confer gene-specific mechanisms of hyperexcitability and responses to therapeutic intervention.

eLife assessment

This manuscript examines shared and divergent mechanisms of disruptions of five different mTOR pathway genes on embryonic mouse brain neuronal development. The significance of the manuscript is **important**, because it bridges several different genetic causes of focal malformations of cortical development. The strength of evidence is **compelling**, relying on both gain and loss of function, demonstrating differential impact on excitatory synaptic activity, conferring gene-specific mechanisms of hyperexcitability. The results have both theoretical and practical implications for the field of developmental neurobiology and clinical epilepsy.

Focal malformations of cortical development (FMCDs), including focal cortical dysplasia type II (FCDII) and hemimegalencephaly (HME), are the most common causes of intractable epilepsy in children^{1,2}. These disorders are characterized by abnormal brain cytoarchitecture with cortical overgrowth, mislamination, and cellular anomalies, and are often associated with developmental delay and intellectual disability³. Early immunohistochemical studies identified hyperactivation of the mechanistic target of rapamycin complex 1 (mTORC1) signaling pathway in resected brain tissue from individuals with FCDII and HME, leading to the classification of these disorders as “mTORopathies”⁴. More recently, somatic mutations in numerous regulators of the mTORC1 pathway were identified as the genetic causes of FCDII and HME^{5–7}. Accumulating evidence shows that these mutations occur in a subset of dorsal telencephalic progenitor cells that give rise to excitatory neurons during fetal development, resulting in brain somatic mosaicism^{8,9}. These genetic findings provide opportunities for gene therapy approaches targeting the mTORC1 pathway for FCDII and HME.

mTORC1 is an evolutionarily conserved protein complex that promotes cell growth and differentiation through the regulation of protein synthesis, metabolism, and autophagy¹⁰. mTORC1 is composed of mTOR, a serine/threonine kinase that exerts the complex’s catalytic function, and several companion proteins. Activation of mTORC1 is controlled by a well-described upstream cascade involving multiple protein regulators¹¹. Stimulation by growth factors activates phosphoinositide 3-kinase (PI3K), which leads to the activation of phosphoinositide-dependent kinase 1 (PDK1) and subsequent phosphorylation and activation of AKT. Activated AKT phosphorylates and inactivates tuberous sclerosis complex 1/2 (TSC1/2 complex; consisting of TSC1 and TSC2 proteins), which releases the brake on Ras homolog enriched in brain (RHEB), a GTP-binding protein that directly activates mTORC1. This mTORC1-activating cascade is negatively controlled by the phosphatase and tensin homolog (PTEN) protein, which inhibits PI3K activation of PDK1. Additionally, mTORC1 signaling is regulated by a separate nutrient-sensing GAP Activity Towards Rags 1 (GATOR1) complex, which consists of DEP domain containing 5 (DEPDC5) and the nitrogen permease regulator 2-like (NPRL2) and 3-like (NPRL3) proteins¹². The GATOR1 complex serves as a negative regulator of mTORC1 that inhibits mTORC1 at low amino acid levels.

Pathogenic mutations in numerous regulators that activate mTORC1 signaling, including *PIK3CA*, *PTEN*, *AKT3*, *TSC1*, *TSC2*, *MTOR*, *RHEB*, *DEPDC5*, *NPRL2*, and *NPRL3*, have been identified in HME and FCDII⁹. Genetic targeting of these genes in mouse models consistently recapitulates the epilepsy phenotype, supporting an important role for these genes in seizure generation^{13,14}. However, while all these genes impinge on the mTORC1 pathway, many of them also participate in mTORC1-independent functions through parallel signaling pathways^{13,15–19}, and it is unclear whether mutations affecting different mTORC1 pathway genes lead to cortical hyperexcitability through common neural mechanisms. In this study, we examined how disruption of five distinct mTORC1 pathway genes, *Rheb*, *mTOR*, *Depdc5*, *Pten*, and *Tsc1*, individually impact pyramidal neuron development and electrophysiological function in the mouse medial prefrontal cortex (mPFC). Collectively, we found that activation of the mTORC1 activators, *Rheb* and *mTOR*, or inactivation of the mTORC1 repressors, *Depdc5*, *Tsc1*, and *Pten*, largely leads to similar alterations in neuron morphology and membrane excitability but differentially impacts excitatory synaptic activity. The latter has implications for cortical network function and seizure vulnerability and may affect how individuals with different genotypes respond to targeted therapeutics.

Expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} leads to varying magnitudes of neuronal enlargement and mispositioning in the cortex

To model somatic gain-of-function mutations in the mTORC1 activators, we individually expressed plasmids encoding *Rheb*^{Y35L} or *mTOR*^{S2215Y}, respectively, in select mouse neural progenitor cells during late corticogenesis via *in utero* electroporation (IUE) (Fig. 1a, b). These pathogenic variants were previously detected in brain tissue from children with FCDII and HME associated with intractable seizures^{20–25}. We specifically targeted a subset of late-born progenitor cells that generate excitatory pyramidal neurons destined to layer 2/3 in the medial prefrontal cortex (mPFC) to mimic frontal lobe somatic mutations and the genetic mosaicism characteristic of these lesions. To model the somatic loss-of-function mutations in mTORC1 repressors, we expressed plasmids encoding previously validated CRISPR/Cas9 guide RNAs against *Dedpdc5*²⁶, *Tsc1*²⁷, or *Pten*²⁸ to individually knockout (KO) the respective genes using the same IUE approach (Fig. 1a, b). As a control for the activating mutations, we expressed plasmids encoding fluorescent proteins under the same CAG promoter. As a control for the CRISPR/Cas9-mediated knockouts, we used an empty CRISPR/Cas9 vector containing no guide RNA sequences. To verify that the expression of these plasmids leads to mTORC1 hyperactivation, we assessed the phosphorylated levels of S6 (i.e., p-S6), a downstream substrate of mTORC1, using immunostaining in brain sections from postnatal day (P) 28–43 mice. As expected, we found that expression of the *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} plasmids all led to significantly increased p-S6 staining intensity, supporting that the expression of each of these plasmids leads to increased mTORC1 signaling (Fig. 1c, d, Table 1, Fig. S1a).

Considering the cytoarchitectural abnormalities associated with mTORC1 hyperactivation, we compared neuron soma size and positioning in the cortex following *in utero* activation of *Rheb* and *mTOR* and inactivation of *Dedpdc5*, *Pten*, and *Tsc1* in P28–43 mice. While all experimental conditions led to increased neuron soma size, the magnitude of the enlargement was dependent on the specific gene that was targeted (Fig. 1c, e, Table 1, Fig. S1b). In particular, expression of *Rheb*^{Y35L} and *mTOR*^{S2215Y} led to the largest soma size changes, with a >3-fold increase from control. Expression of *Pten*^{KO} led to a similarly large increase of 2.7-fold, while expression of *Dedpdc5*^{KO} and *Tsc1*^{KO} led to a 1.7 and 2.1-fold increase, respectively. The increase in the *Pten*^{KO} condition was significantly higher than both the *Dedpdc5*^{KO} and *Tsc1*^{KO} conditions, and the increase in the *Tsc1*^{KO} condition was significantly higher than the *Dedpdc5*^{KO} condition. Although the above analysis was performed at P28–43, the enlargement of neuron soma sizes was already detected by P7–9 (Fig. S2a–c, Table S1). In terms of neuronal positioning, all experimental conditions, except for *Pten*^{KO}, resulted in neuron misplacement (Fig. 1f–h, Table 1). The *Rheb*^{Y35L} and *mTOR*^{S2215Y} conditions led to the most severe phenotype: ~70–80% of the neurons were misplaced outside of layer 2/3 (Fig. 1g), with the mispositioned neurons evenly scattered across the deeper layers (Fig. 1h). For the *Dedpdc5*^{KO} and *Tsc1*^{KO} conditions, ~45–60% of the neurons were misplaced outside of layer 2/3 (Fig. 1g), with the mispositioned neurons found closer to layer 2/3 (Fig. 1h). Taken together, these studies show that the expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} leads to varying magnitudes of neuronal enlargement and mispositioning in the cortex. Of note, *Pten*^{KO} neurons, despite exhibiting a 2.7-fold increase in neuron soma size, were mostly correctly positioned in layer 2/3. These findings suggest that while all experimental conditions lead to increased soma size, not all lead to neuron mispositioning, suggesting defective migration and the subsequent impact on neuron positioning occur independently of cell size.

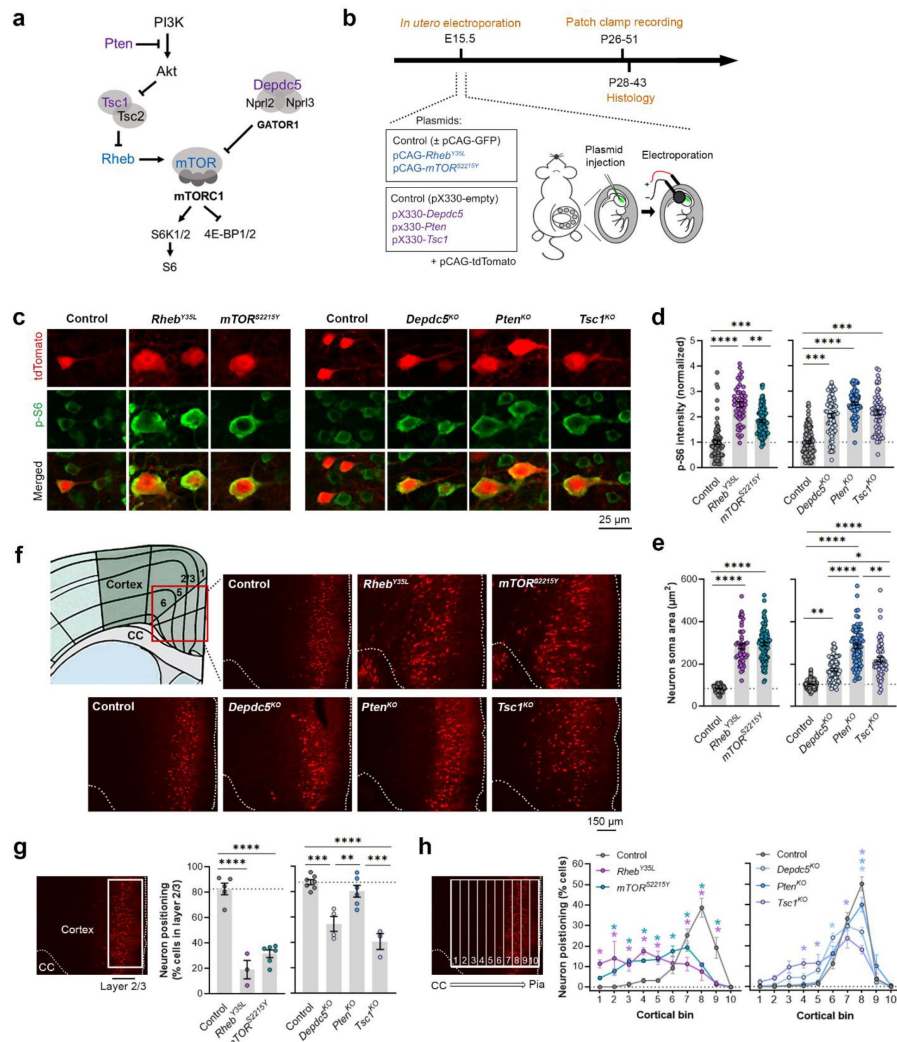


Figure 1

Expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} leads to varying magnitudes of neuronal enlargement and mispositioning in the cortex.

(a) Diagram of the PI3K-mTORC1 pathway. Activation of mTORC1 signaling is controlled by positive (blue) and negative (purple) regulators within the pathway. **(b)** Diagram of overall experimental timeline and approach. IUE was performed at E15.5. A cohort of animals was used for patch clamp recording at P26-51 and another cohort was used for histology at P28-43. **(c)** Representative images of tdTomato+ cells (red) and p-S6 staining (green) in mouse mPFC at P28-43. **(d)** Quantification of p-S6 staining intensity (normalized to the mean control) in tdTomato+ neurons. **(e)** Quantification of tdTomato+ neuron soma size. **(f)** Representative images of tdTomato+ neuron (red) placement and distribution in coronal mPFC sections. Red square on the diagram denotes the imaged area for all groups. CC, corpus callosum. **(g)** Quantification of tdTomato+ neuron placement in layer 2/3. Left diagram depicts the approach for analysis: the total number of tdTomato+ neurons within layer 2/3 (white square) was counted and expressed as a % of total neurons in the imaged area. Right bar graphs show the quantification. **(h)** Quantification of tdTomato+ neuron distribution across cortical layers. Left diagram depicts the approach for analysis: the imaged area was divided into 10 equal-sized bins across the cortex, spanning the corpus callosum to the pial surface (white grids); the total number of tdTomato+ neurons within each bin was counted and expressed as a % of total neurons in the imaged area. Right bar graphs show the quantification. For graphs **d**, **e**: n = 4-8 mice per group, with 6-15 cells analyzed per animal. For graphs **g**, **h**: n = 3-7 mice per group, with 1 brain section analyzed per animal. Statistical comparisons were performed using **(d, e)** nested one-way ANOVA (fitted to a mixed-effects model) to account for correlated data within individual animals, **(g)** one-way ANOVA, or **(h)** two-way repeated measures ANOVA. Post-hoc analyses were performed using Holm-Šidák multiple comparison test. *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001. All data are reported as the mean of all neurons or brain sections in each group ± SEM.

Fig. 1d: p-S6 INTENSITY

	Control	<i>Rheb</i> ^{Y35L}	<i>mTOR</i> ^{S2215Y}	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5</i> ^{KO}	<i>Pten</i> ^{KO}	<i>Tsc1</i> ^{KO}	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	1.00	2.50	1.84	36.46, 2, 12 <0.0001	1.00	2.04	2.52	2.17	25.31, 3, 19 <0.0001
± SD	± 0.7	± 0.7	± 0.6		± 0.5	± 0.8	± 0.5	± 0.8	
No. of animals	5	4	6		8	5	6	4	
No. cells/ animal	15	15 (6 for one mouse)	15		15	15	15 (8, 11 for two mice)	15	
Total cells	75	51	90		120	75	79	60	

Fig. 1e: NEURON SOMA SIZE

	Control	<i>Rheb</i> ^{Y35L}	<i>mTOR</i> ^{S2215Y}	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5</i> ^{KO}	<i>Pten</i> ^{KO}	<i>Tsc1</i> ^{KO}	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	84.3	283.2	294.8	57.17, 2, 12 <0.0001	105.0	174.7	285.2	222.6	49.30, 3, 19 <0.0001
± SD	± 15.9	± 86.4	± 80.0		± 21.0	± 55.8	± 90.8	± 87.3	
No. of animals	5	4	6		8	5	6	4	
No. cells/ animal	15	15 (6 for one mouse)	15		15	15	15 (8, 11 for two mice)	15	
Total cells	75	51	90		120	75	79	60	

Fig. 1f: NEURON POSITIONING (% cells in layer 2/3)

	Control	<i>Rheb</i> ^{Y35L}	<i>mTOR</i> ^{S2215Y}	One-way ANOVA F (DFn, DFd) p-value	Control	<i>Depdc5</i> ^{KO}	<i>Pten</i> ^{KO}	<i>Tsc1</i> ^{KO}	One-way ANOVA F (DFn, DFd) p-value
Mean ± SD	82.7 ± 10.2	19.2 ± 12.6	31.6 ± 7.4	F (2, 11) = 55.09 <0.0001	87.6 ± 5.3	54.8 ± 11.7	80.6 ± 11.3	40.9 ± 10.8	F (3, 16) = 22.81 <0.0001
No. of animals	5	3	6		7	4	6	3	

Fig. 1h: NEURON POSITIONING (% cells in bins)

	No. of animals	Two-way repeated measures ANOVA				No. of animals	Two-way repeated measures ANOVA		
		F (DFn, DFd)	p value				F (DFn, DFd)	p value	
Control	5	Bin x Group	F (18, 99) = 12.58	<0.0001	Control	7	Bin x Group	F (27, 144) = 5.802	<0.0001
<i>Rheb</i> ^{Y35L}	3	Bin	F (9, 99) = 16.14	<0.0001	<i>Depdc5</i> ^{KO}	4	Bin	F (9, 144) = 95.04	<0.0001
<i>mTOR</i> ^{S2215Y}	6	Group	F (2, 11) = 0.3745	0.6961	<i>Pten</i> ^{KO}	6	Group	F (3, 16) = 1.021	0.4095
					<i>Tsc1</i> ^{KO}	3			

Fig. 2b: MEMBRANE CAPACITANCE (pF)

	Control	<i>Rheb</i> ^{Y35L}	<i>mTOR</i> ^{S2215Y}	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5</i> ^{KO}	<i>Pten</i> ^{KO}	<i>Tsc1</i> ^{KO}	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	121.6	402.3	462.4	109.6, 2, 20 <0.0001	130.8 ±	205.0 ±	340.0 ±	295.9 ±	37.77, 3, <0.0001
± SD	± 36.6	± 105.4	± 147.0		38.1	69.4	142.5	109.2	127
No. of animals	10	5	8		10	5	6	8	
No. cells/ animal	1-7	4-8	1-7		3-8	4-8	1-8	1-5	
Total cells	43	25	35		48	28	28	27	

Fig. 2c: MEMBRANE CONDUCTANCE (nS)

	Nested one-way ANOVA ^a		Nested one-way ANOVA ^a
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Table 1

Statistical results (for main figures)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	F, DFn, DFd p-value
Mean	10.6	20.1	23.7	33.58, 2, 18 <0.0001	8.0	13.1	18.6	13.8	17.83, 3, 25 <0.0001
± SD	± 3.8	± 5.3	± 7.4		± 2.4	± 4.5	± 9.2	± 4.1	
No. of animals	8	5	8		10	5	6	8	
No. cells/ animal	3-6	4-8	1-6		3-8	4-8	1-8	1-5	
Total cells	34	24	30		47	27	27	28	

Fig. 2d: RMP (mV)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	-74.5	-69.0	-64.9	24.20, 2, 20 <0.0001	-69.7	-70.0	-67.6	-64.7	4.292, 3, 25 0.0142
± SD	± 3.8	± 5.1	± 5.3		± 5.0	± 5.3	± 5.3	± 7.3	
No. of animals	10	5	8		10	5	6	8	
No. cells/ animal	1-7	4-8	1-7		3-8	4-8	1-8	1-5	
Total cells	42	25	36		52	28	28	31	

Fig. 2f: AP INPUT-OUTPUT CURVE

	No. of neurons	Mixed-effects ANOVA Fixed effects (type III)	F (DFn, DFd)	p-value		No. of neurons	Mixed-effects ANOVA Fixed effects (type III)	F (DFn, DFd)	p-value
Control	36	Current step	F (20, 1657) = 263.4	<0.0001	Control	50	Current step	F (20, 2579) = 600.7	<0.0001
<i>Rheb^{Y35L}</i>	22	Group	F (2, 83) = 39.60	<0.0001	<i>Depdc5^{KO}</i>	27	Group	F (3, 129) = 22.84	<0.0001
<i>mTOR^{S2215Y}</i>	28	Current step x group	F (40, 1657) = 22.84	<0.0001	<i>Pten^{KO}</i>	28	Current step x group	F (60, 2579) = 14.66	<0.0001
					<i>Tsc1^{KO}</i>	28			

Fig. 2g: RHEBOBASE (pA)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	544.4	1356.0	1422.0	26.74, 2, 77 <0.0001	484.4	737.3	1071.0	935.7	16.84, 3, 25 <0.0001
± SD	± 225.3	± 634.6	± 624.2		± 180.1	± 315.2	± 503.5	± 444.4	
No. of animals	7	5	6		10	5	6	8	
No. cells/ animal	4-6	4-7	1-7		3-7	4-7	1-8	1-5	
Total cells	32	24	24		50	27	28	28	

Fig. 2h: AP THRESHOLD (mV)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	-39.2	-44.0	-41.0	1.937, 2, 78 0.1511	-35.8	-39.0	-40.0	-37.9	0.6587, 3, 25 0.5852
± SD	± 6.3	± 12.3	± 8.4		± 9.4	± 7.9	± 14.4	± 11.1	
No. of animals	7	5	6		10	5	6	8	
No. cells/ animal	4-6	3-7	1-6		2-6	3-7	1-7	1-5	
Total cells	33	23	25		42	25	26	25	

Fig. 2i: AP PEAK AMPLITUDE (mV)

	Nested one-way ANOVA ^a		Nested one-way ANOVA ^a
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Table 1 (continued)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	F, DFn, DFd p-value
Mean	138.1 ±	139.0 ±	120.3	20.51, 2, 15 <0.0001	135.0	136.1	138.3	126.1	4.239, 3, 116 0.0070
± SD	10.1	11.6	± 8.9		± 9.1	± 12.9	± 21.1	± 7.8	
No. of animals	7	5	6		10	5	6	8	
No. cells/ animal	4-6	3-7	1-6		2-6	3-7	1-7	1-5	
Total cells	33	23	25		43	25	27	25	

Fig. 2j: AP half-width (ms)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	1.79	1.50	1.44	18.45, 2, 15 <0.0001	1.76	1.65	1.44	1.52	3.679, 3, 25 0.0254
± SD	± 0.30	± 0.18	± 0.14		± 0.43	± 0.23	± 0.24	± 0.23	
No. of animals	7	5	6		10	5	6	8	
No. cells/ animal	4-6	3-7	1-6		2-6	3-7	1-7	1-5	
Total cells	33	23	25		43	25	27	25	

Fig. 3b: HCN4 INTENSITY

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean	1.00	1.30	1.36	7.499, 2, 12 0.0077	1.00	1.26	1.24	1.22	6.579, 3, 18 0.0034
± SD	± 0.16	± 0.25	± 0.31		± 0.16	± 0.36	± 0.18	± 0.20	
No. of animals	5	4	6		8	5	5	4	
No. cells/ animal	15 (10 for one mouse)	15 (4 for one mouse, 11 for one mouse)	15 (14 for one mouse)		15 (13 for one mouse)	15 (12 for two mice, 14 for one mouse)	15 (7 for one mouse)	15 (8 for one mouse)	
Total cells	70	45	89		118	68	67	53	

Fig. 3d: IV CURVE

	No. of neurons	Mixed-effects ANOVA Fixed effects (type III)	F (DFn, DFd)	p-value		No. of neurons	Mixed-effects ANOVA Fixed effects (type III)	F (DFn, DFd)	p-value
Control	42	Voltage step	F (6, 537) = 821.1	<0.0001	Control	47	Voltage step	F (6, 714) = 569.5	<0.0001
<i>Rheb^{Y35L}</i>	24	Group	F (2, 95) = 144.5	<0.0001	<i>Depdc5^{KO}</i>	28	Group	F (3, 126) = 20.08	<0.0001
<i>mTOR^{S2215Y}</i>	32	Voltage step x group	F (12, 537) = 92.68	<0.0001	<i>Pten^{KO}</i>	27	Voltage step x group	F (18, 714) = 22.98	<0.0001
					<i>Tsc1^{KO}</i>	28			

Fig. 3e: ΔIV CURVE

	No. of neurons	Mixed-effects ANOVA Fixed effects (type III)	F (DFn, DFd)	p-value		No. of neurons	Mixed-effects ANOVA Fixed effects (type III)	F (DFn, DFd)	p-value
Control	42	Voltage step	F (6, 537) = 83.01	<0.0001	Control	47	Voltage step	F (6, 720) = 78.95	<0.0001
<i>Rheb^{Y35L}</i>	24	Group	F (2, 95) = 61.77	<0.0001	<i>Depdc5^{KO}</i>	28	Group	F (3, 126) = 16.35	<0.0001
<i>mTOR^{S2215Y}</i>	32	Voltage step x group	F (12, 537) = 33.33	<0.0001	<i>Pten^{KO}</i>	27	Voltage step x group	F (18, 720) = 5.506	<0.0001
					<i>Tsc1^{KO}</i>	28			

Fig. 3f: I_h AMPLITUDE at -90 mV (pA)

Table 1 (continued)

				Nested one-way ANOVA ^a						Nested one-way ANOVA ^a
	Control	<i>Rheb</i> ^{T35L}	<i>mTOR</i> ^{S2215Y}	F, DFn, DFd p-value		Control	<i>Depdc5</i> ^{KO}	<i>Pten</i> ^{KO}	<i>Tsc1</i> ^{KO}	F, DFn, DFd p-value
Mean	-4.4	-53.1	-212.9	29.22, 2, 20 <0.0001		-8.7	-18.6	-28.0	-51.2	10.34, 3, 25 <0.0001
± SD	± 7.2	± 56.7	± 151.4			± 12.1	± 23.7	± 41.1	± 31.2	
No. of animals	10	5	8			10	5	6	8	
No. cells/ animal	1-7	4-8	1-7			3-8	4-8	1-8	1-5	
Total cells	42	24	36			47	28	27	29	

Fig. 3h: IV CURVE (ZATERBADINE, *mTOR*^{S221})

	No. of neurons	Two-way repeated measures ANOVA		
		F (DFn, DFd)	p value	
Pre-zatebradine	4	Voltage step F (6, 18) = 19.45	<0.0001	
Post-zatebradine	4	Group F (1, 3) = 58.36	0.0047	
		Voltage step x group F (6, 18) = 27.54	<0.0001	

Fig. 3i: ΔIV CURVE (ZATEBRADINE, *mTOR*^{S22515Y})

	No. of neurons	Two-way repeated measures ANOVA		
		F (DFn, DFd)	p value	
Pre-zatebradine	4	Voltage step F (6, 18) = 17.70	<0.0001	
Post-zatebradine	4	Group F (1, 3) = 49.57	=0.0059	
		Voltage step x group F (6, 18) = 13.65	<0.0001	

Fig. 3l: RMP (mV; ZATERBADINE, control, *mTOR*^{S22515Y})

	No. of neurons	Two-way repeated measures ANOVA		
		F (DFn, DFd)	p value	
Pre-zatebradine (control)	6	Treatment F (1, 9) = 37.42	0.0002	
Post-zatebradine (control)	6	Group F (1, 9) = 2.747	0.1318	
Pre-zatebradine (<i>mTOR</i> ^{S22515Y})	4	Treatment x group F (1, 9) = 33.83	0.0003	
Post-zatebradine (<i>mTOR</i> ^{S22515Y})	4			

Fig. 4b: sEPSC FREQUENCY (Hz)

				Nested one-way ANOVA ^a						Nested one-way ANOVA ^a
	Control	<i>Rheb</i> ^{T35L}	<i>mTOR</i> ^{S2215Y}	F, DFn, DFd p-value		Control	<i>Depdc5</i> ^{KO}	<i>Pten</i> ^{KO}	<i>Tsc1</i> ^{KO}	F, DFn, DFd p-value
Mean ± SD	4.4 ± 1.7	3.3 ± 0.8	4.7 ± 2.1	2.550, 2, 15 0.1114		3.9 ± 1.4	5.1 ± 1.7	4.8 ± 1.5	5.3 ± 1.9	4.054, 3, 89 0.0095
No. of animals	7	5	6			9	5	5	8	
No. cells/ animal	3-6	4-5	2-7			2-5	2-6	3-4	1-4	
Total cells	33	21	25			34	20	17	22	

Fig. 4c: sEPSC AMPLITUDE (pA)

	Nested one-way ANOVA ^a		Nested one-way ANOVA ^a
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Table 1 (continued)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	F, DFn, DFd p-value
Mean ± SD	-8.1 ± 2.1	-11.5 ± 2.5	-12.6 ± 3.0	19.20, 2, 15 <0.0001	-6.7 ± 1.3	-8.7 ± 1.9	-10.1 ± 4.1	-8.5 ± 1.8	4.280, 3, 23 0.0154
No. of animals	7	5	6		9	5	5	8	
No. cells/animal	3-6	4-5	2-7		2-5	2-6	3-4	1-4	
Total cells	33	21	25		34	20	17	22	

Fig. 4d: sEPSC TOTAL CHARGE (pA/ms)

	Control	<i>Rheb^{Y35L}</i>	<i>mTOR^{S2215Y}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value	Control	<i>Depdc5^{KO}</i>	<i>Pten^{KO}</i>	<i>Tsc1^{KO}</i>	Nested one-way ANOVA ^a F, DFn, DFd p-value
Mean ± SD	0.20 ± 0.12	0.26 ± 0.08	0.43 ± 0.22	8.300, 2, 15 0.0037	0.20 ± 0.10	0.35 ± 0.14	0.41 ± 0.21	0.38 ± 0.20	9.273, 3, 89 <0.0001
No. of animals	7	5	6		9	5	5	8	
No. cells/animal	3-6	4-5	2-7		2-5	2-6	3-4	1-4	
Total cells	33	21	25		34	20	17	22	

^aThe nested one-way ANOVA fits a mixed-effects model wherein the main factor is treated as a fixed factor and the nested factor is treated as a random factor.

^bPost-hoc analyses were performed using Holm-Šidák multiple comparison test. Significant post-hoc results (p<0.05) are denoted with symbols (*, #, ¥) on the graphs, with the number of symbols 1-4 denoting the significant levels p<0.05, <0.01, <0.001, and <0.0001, respectively. For all two-way repeated measured and mixed-effects model ANOVA, all significant results (p<0.05) are denoted with one symbol regardless of the significant level for clearness on the graphs.

Table 1 (continued)

Expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} universally leads to decreased depolarization-induced excitability, but only *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Tsc1*^{KO} expression leads to depolarized resting membrane potential

To elucidate the contribution of each experimental condition to the function of cortical neurons, we obtained whole-cell patch clamp recordings of layer 2/3 pyramidal neurons at P26-P51 (Fig. 2a). The *Rheb*^{Y35L} and *mTOR*^{S2215Y} conditions were compared to a control group expressing fluorescent proteins under the same CAG promoter. The *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} conditions were compared to a CRISPR/Cas9 empty vector control. Recordings of control and experimental conditions were alternated to match the animal ages.

Consistent with the changes in soma size (Fig. 1c, e), recorded neurons displayed increased membrane capacitance in all experimental conditions (Fig. 2b, Table 1, Fig. S3a). Neurons expressing the *mTOR*^{S2215Y} variant had a larger capacitance increase than those expressing the *Rheb*^{Y35L} variant. *Pten*^{KO} and *Tsc1*^{KO} neurons had similar increases in capacitance that were both larger than that of the *Dedpdc5*^{KO} neurons. All neurons across the experimental conditions also had increased resting membrane conductance in a pattern that followed that of the capacitance (Fig. 2c, Table 1, Fig. S3b). However, while *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Tsc1*^{KO} expression led to depolarized resting membrane potential (RMP), *Dedpdc5*^{KO} and *Pten*^{KO} expression did not significantly affect the RMP (Fig. 2d, Table 1, Fig. S3c). To assess whether these changes impacted neuron intrinsic excitability, we examined the action potential (AP) firing response to depolarizing current injections. For all experimental conditions, neurons fired fewer APs for current injections above 100 pA compared to the respective control neurons (Fig. 2e, f, Table 1). This decrease in intrinsic excitability is reflected in the increased rheobase (i.e., the minimum current required to induce an AP) in all experimental conditions, with the *mTOR*^{S2215Y} and *Rheb*^{Y35L} conditions leading to the largest rheobase increases (Fig. 2g, Table 1, Fig. S3d). Collectively, these findings indicate that *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Tsc1*^{KO} neurons display a decreased ability to generate APs upon depolarization despite having depolarized RMPs. In terms of firing pattern, neurons in all groups displayed a regular-spiking pattern with spike-frequency adaptation (Fig. 2e). However, while an initial spike doublet (with an interspike interval of 10-15 ms) was observed in the majority of control neurons, consistent with the expected firing pattern for layer 2/3 mPFC pyramidal neurons²⁹, this was observed in a smaller fraction of neurons in the experimental conditions [number of neurons displaying spike doublets: *Rheb*^{Y35L}: 4/23 (17%), *mTOR*^{S2215Y}: 7/28 (25%), *Dedpdc5*^{KO}: 11/27 (41%), *Pten*^{KO}: 21/28 (75%) - notably, 6 of the 21 doublets are parts of triplets, *Tsc1*^{KO}: 7/28 (25%), control: 24/26 (92%)]. There were no differences in the AP threshold across the conditions (Fig. 2h, Table 1, Fig. S3e). The AP peak amplitude was decreased in the *mTOR*^{S2215Y} and *Tsc1*^{KO} conditions (Fig. 2i, Table 1, Fig. S3f), while the AP half-width was decreased in the *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Pten*^{KO} conditions (Fig. 2j, Table 1, Fig. S3g). Taken together, these findings show that various genetic conditions that activate the mTORC1 pathway universally lead to decreased depolarization-induced excitability in layer 2/3 pyramidal neurons, with gene-dependent changes in RMP and several AP properties.

Expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} leads to the abnormal presence of HCN4 channels with variations in functional expression

We recently reported that neurons expressing *Rheb*^{S16H}, an mTOR activating variant of Rheb, display abnormal expression of HCN4 channels^{30,31}. These channels give rise to a hyperpolarization-activated cation current (*I*_h) that is normally absent in layer 2/3 pyramidal neurons^{30,31}. The aberrant *I*_h, which has implications for neuronal excitability, preceded

seizure onset and was detected by P8-12 in mice³⁰. Rapamycin treatment starting at P1 and expression of constitutive active 4E-BP1, a translational repressor downstream of mTORC1, prevented and alleviated the aberrant HCN4 channel expression, respectively^{30,31}. These findings suggest that the abnormal HCN4 channel expression is mTORC1-dependent. Given that all the experimental conditions in the present study led to increased mTORC1 activity, we investigated whether they also resulted in abnormal HCN4 channel expression. Immunostaining for HCN4 channels using previously validated antibodies³⁰ in brain sections from P28-43 mice revealed significantly increased HCN4 staining intensity in the electroporated neurons in all experimental conditions compared to the respective controls, which exhibited no HCN4 staining (**Fig 3a, b**, **Table 1**, **Fig. S4a**). The increased staining was evident in the ipsilateral cortex containing *mTOR*^{S2215Y} electroporated neurons and absent in the non-electroporated contralateral cortex (**Fig. S5a**). These data indicate the presence of aberrant HCN4 channel expression following *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Depdc5*^{KO}, *Pten*^{KO}, or *Tsc1*^{KO} expression in layer 2/3 pyramidal neurons.

To examine the functional impacts of the aberrant HCN4 channel expression, we examined I_h amplitudes in the various experimental conditions. To evoke I_h , we applied a series of 3 s-long hyperpolarizing voltage steps from -120 mV to -40 mV. Consistent with previous findings in *Rheb*^{S16H} neurons^{30,31}, hyperpolarizing voltage pulses elicited significantly larger inward currents in all experimental conditions compared to their respective controls (**Fig. 3c, d**, **Table 1**). The *mTOR*^{S2215Y} condition displayed larger inward currents than the *Rheb*^{Y35L} condition, while the *Pten*^{KO} condition displayed the largest inward currents compared to the *Depdc5*^{KO} and *Tsc1*^{KO} conditions (**Fig. 3d**). These data were proportional to the changes in neuron soma size (**Fig. 1e, 2b**). The inward currents in *Rheb*^{S16H} neurons are thought to result from the activation of both inward-rectifier K⁺ (Kir) channels and HCN channels³⁰. Kir-mediated currents activate fast whereas HCN-mediated currents, i.e., I_h , activate slowly during hyperpolarizing steps; therefore, to assess I_h amplitudes, we measured the difference between the instantaneous and steady-state currents at the beginning and end of the voltage pulses, respectively (i.e., ΔI)³². The resulting ΔI -voltage (V) curve revealed significantly larger I_h amplitudes in all experimental conditions (**Fig. 3e**, **Table 1**). To further isolate the I_h from Kir-mediated currents, we measured I_h amplitudes at -90 mV, near the reversal potential of Kir channels to eliminate Kir-mediated current contamination. At -90 mV, I_h amplitudes were significantly higher in the *mTOR*^{S2215Y} and *Tsc1*^{KO} conditions compared to controls (**Fig. 3f**, **Table 1**, **Fig. S4b**). Of note, although the *Depdc5*^{KO} and *Pten*^{KO} conditions did not display a significant increase in I_h amplitudes at -90 mV, 1 out of 28 *Depdc5*^{KO} neurons and 4 out of 27 *Pten*^{KO} neurons had I_h amplitudes that were 2-fold greater than the mean I_h amplitude of the *Tsc1*^{KO} condition. 6 out of 24 *Rheb*^{Y35L} neurons also had I_h amplitudes 2-fold greater than this value (**Fig. 3f**). These data suggest that I_h currents are present in a subset of *Rheb*^{Y35L}, *Depdc5*^{KO}, and *Pten*^{KO} neurons, and most *mTOR*^{S2215Y} and *Tsc1*^{KO} neurons.

Considering that the *mTOR*^{S2215Y} condition led to the largest I_h , we examined the impact of the selective HCN channel blocker zatebradine on hyperpolarization-induced inward currents in *mTOR*^{S2215Y} neurons to further confirm the identity of ΔI as I_h . Application of 40 μ M zatebradine reduced the overall inward currents (**Fig. 3g, h**, **Table 1**) and ΔI (**Fig. 3i**, **Table 1**). At -90 mV, ΔI was significantly decreased from -167.7 ± 54.2 pA to 0.75 ± 8.2 pA ($\pm$ SD) (**Fig. 3i**, arrow). Subtraction of the post-from the pre-zatebradine current traces isolated zatebradine-sensitive inward currents which reversed near -50 mV, as previously reported for HCN4 channel reversal potentials³³ (**Fig. 3j, k**, **Table 1**). These experiments verified the identity of ΔI as I_h . In comparison, application of the Kir channel blocker barium chloride (BaCl₂) substantially reduced the overall inward currents but had no effects on ΔI (i.e., I_h) in *Tsc1*^{KO} neurons (**Fig. S6a-i**). Consistent with the function of I_h in maintaining RMP at depolarized levels^{34–38}, application of zatebradine hyperpolarized RMP in *mTOR*^{S2215Y} neurons but did not affect the RMP of control neurons that exhibited no I_h (**Fig. 3l**, **Table 1**). Collectively, these findings suggest that *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Depdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} expression in layer 2/3 pyramidal neurons lead to the abnormal presence of HCN4 channels with variations in functional expression.

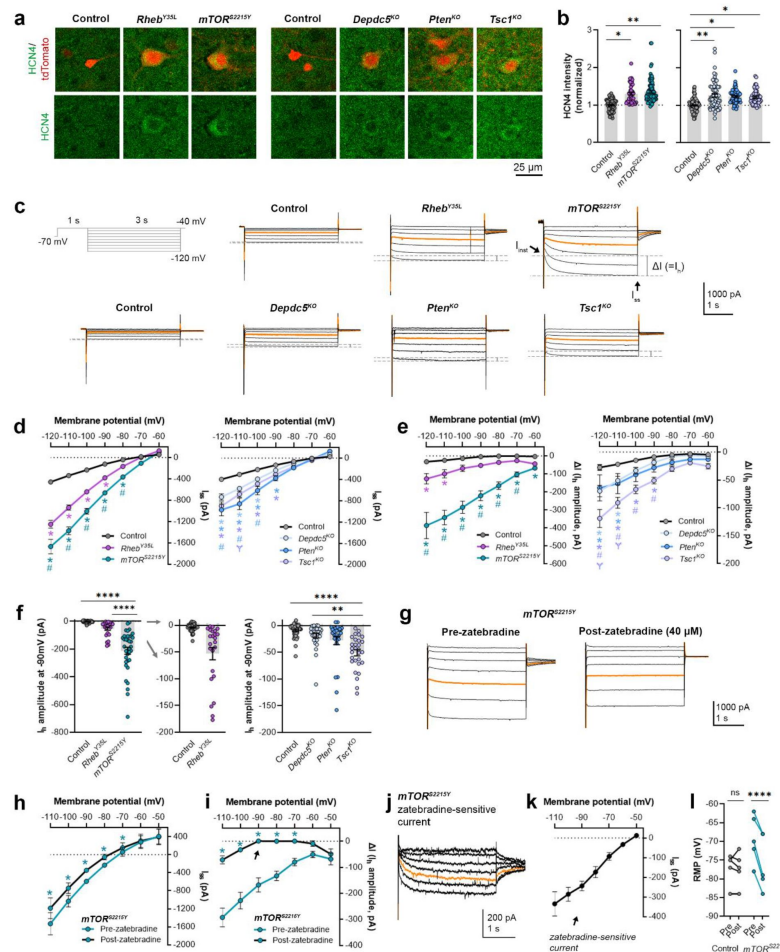


Figure 3

Expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} leads to the abnormal presence of HCN4 channels with variations in functional expression.

(a) Representative images of tdTomato+ cells (red) and HCN4 staining (green) in mouse mPFC at P28-43. (b) Quantification of HCN4 intensity (normalized to the mean control) in tdTomato+ neurons. (c) Representative current traces in response to a series of 3 s-long hyperpolarizing voltage steps from -120 to -40 mV, with a holding potential of -70 mV. Current traces from the -40 and -50 mV steps were not included due to contamination from unclamped Na⁺ spikes. Orange lines denote the current traces at -90 mV. (d) IV curve obtained from I_{SS} amplitudes. (e) ΔI IV curve obtained from I_h amplitudes (i.e., ΔI , where $\Delta I = I_{SS} - I_{inst}$). (f) Graphs of I_h amplitudes at -90 mV. (g) Representative current traces in response to a series of 3-s long hyperpolarizing voltage steps from -110 mV to -50 mV in the *mTOR*^{S2215Y} condition pre- and post-zatebradine application. Orange lines denote the current traces at -90 mV. (h) IV curve obtained from I_{SS} amplitudes in the *mTOR*^{S2215Y} condition pre- and post-zatebradine application. (i) ΔI IV curve obtained from I_h amplitudes (i.e., ΔI) in the *mTOR*^{S2215Y} condition pre- and post-zatebradine application. Arrow points to the post-zatebradine I_h amplitude at -90 mV. (j) Representative traces of the zatebradine-sensitive current obtained after subtraction of the post-from the pre-zatebradine current traces in response to -110 mV to -50 mV voltage steps. Orange lines denote the current traces at -90 mV. (k) IV curve of the zatebradine-sensitive current obtained after subtraction of the post-from the pre-zatebradine current traces. (l) Graph of RMP in the control and *mTOR*^{S2215Y} conditions pre- and post-zatebradine application. Connecting lines denote paired values from the same neuron. For graph b: n = 4-8 mice per group, with 4-15 cells analyzed per animal. For graphs d, e, f: n = 5-10 mice per group, with 24-47 cells analyzed per animal. For graphs h, i, k, l: n = 4-6 neurons (paired). Statistical comparisons were performed using (b, f) nested ANOVA (fitted to a mixed-effects model) to account for correlated data within individual animals, (d, e) mixed-effects ANOVA accounting for repeated measures, or (h, i, l) two-way repeated measures ANOVA. Post-hoc analyses were performed using Holm-Šidák multiple comparison test. *p<0.05, **p<0.01, ***p<0.0001, for the IV curves in d, e, h, i: *p<0.05 (vs. control), #p<0.05 (vs. *Rheb*^{Y35L} or *Dedpdc5*^{KO}), †p<0.05 (vs. *Pten*^{KO}). All data are reported as the mean of all neurons in each group ± SEM.

Expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} leads to different impacts on excitatory synaptic activity

As part of examining neuron excitability, we recorded spontaneous excitatory postsynaptic currents (sEPSCs) in all the gene conditions. The frequency of sEPSCs was unchanged in all experimental conditions except for the *Tsc1*^{KO} condition, in which the frequency was significantly increased (Fig. 4a, b, Table 1, Fig. S7a). Unlike the other experimental conditions, the *Rheb*^{Y35L} condition displayed a slight decrease in sEPSC frequency, consistent with previous findings in *Rheb*^{S16H} neurons; however, this did not reach statistical significance (Fig. 4b). The amplitude of sEPSCs was larger in the *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Pten*^{KO} conditions (Fig. 4a, c, Table 1, Fig. S7b). Although the amplitudes were slightly larger in the *Dedpdc5*^{KO} and *Tsc1*^{KO} conditions, these changes were not significant (Fig. 4c). Thus, *Tsc1*^{KO} neurons display increased sEPSC frequency but unchanged amplitude, while *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Pten*^{KO} neurons display increased sEPSC amplitude but unchanged frequency. Finally, there was an increase in the sEPSC total charge in all experimental conditions except for the *Rheb*^{Y35L} condition (Fig. 4d, Table 1, Fig. S7c). Collectively, these findings suggest all experimental conditions, except for *Rheb*^{Y35L}, lead to increased synaptic excitability, with variable impact on sEPSC frequency and amplitude.

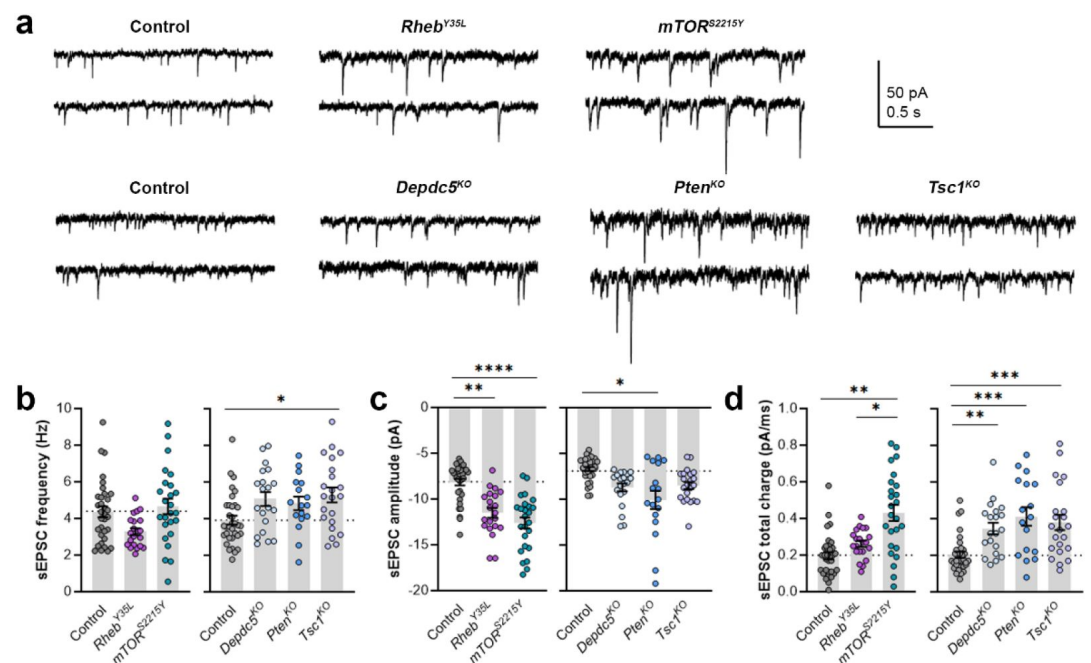


Figure 4:

Expression of *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Dedpdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} leads to different impacts on sEPSC properties.

(a) Representative sEPSC traces recorded at a holding voltage of -70 mV. Top and bottom traces are from the same neuron. (b-d) Graphs of sEPSC frequency, amplitude, and total charge. For all graphs: n = 5-9 mice per group, with 17-34 cells analyzed per animal. Statistical comparisons were performed using a nested ANOVA (fitted to a mixed effects model) to account for correlated data within individual animals. Post-hoc analyses were performed using Holm-Šidák multiple comparison test. *p<0.05, **p<0.01, ***p<0.001, ****p<0.0001. All data are reported as the mean of all neurons in each group ± SEM.

In this unprecedented comparison study, we examined the impacts of several distinct epilepsy-associated mTORC1 pathway gene mutations on cortical pyramidal neuron development and their electrophysiological properties and synaptic integration in the mouse mPFC. Through a combination of IUE to model the genetic mosaicism of FMCDs, histological analyses, and patch-clamp electrophysiological recordings, we found that activation of either *Rheb* or *mTOR* or biallelic inactivation *Depdc5*, *Tsc1*, or *Pten*, all of which increase mTORC1 activity, largely leads to similar alterations in neuron morphology and membrane excitability but differentially impacts excitatory synaptic transmission. These findings have significant implications for understanding the mechanisms leading to cortical hyperexcitability and seizures in mTORC1-driven FMCDs and highlight the utility of personalized medicine dictated by patient gene variants.

Several histological phenotypes associated with mTORC1 hyperactivation were anticipated and confirmed in our studies. We found increased neuron soma size across all gene conditions, consistent with previous reports^{24,26,27,39,42}. Additionally, all conditions, except for *Pten*^{KO}, resulted in neuronal mispositioning in the mPFC, with *Rheb*^{Y35L} and *mTOR*^{S2215Y} conditions being the most severe. Interestingly, *Pten*^{KO} neurons were correctly placed in layer 2/3, despite having one of the largest soma size increases, suggesting that cell positioning is independent of cell size. The lack of mispositioning of *Pten*^{KO} neurons was surprising as it is thought that increased mTORC1 activity leads to neuronal misplacement, and aberrant migration of *Pten*^{KO} neurons has been reported in the hippocampus⁴³. Given that PTEN has a long half-life, with a reported range of 5 to 20 hours or more depending on the cell type^{44–51}, it is possible that following knockout at E15, the decreases in existing protein levels lagged behind the time window to affect neuronal migration. However, TSC1 also has a long half-life of ~22 hours^{52,53}, and knockout of *Tsc1* at the same time point was sufficient to affect neuronal positioning. Mispositioning of neurons following *Pten* knockout in E15 rats was reported by one study, but this was a very mild phenotype compared to findings in the other gene conditions³⁹. Therefore, these data suggest that PTEN has gene-specific biological mechanisms that contribute to the lack of severe neuronal mispositioning in the developing cortex. *mTOR*^{S2215Y} exhibited the strongest phenotypes in terms of neuron size and positioning, which is perhaps not surprising as the mTOR protein itself forms the catalytic subunit of mTORC1. *Depdc5*^{KO} exhibited the mildest changes in these parameters. Unlike PTEN, TSC1, RHEB, and mTOR, which regulate mTORC1 via the canonical PI3K-mTORC1 pathway in response to growth factor stimulation, DEPDC5 regulates mTORC1 via the GATOR1 complex in response to changes in cellular amino acid levels⁵⁴. The different modes of mTORC1 regulation by DEPDC5 may contribute to the differences in the severity of the phenotypes.

To assess the impact of RHEB, mTOR, DEPDC5, PTEN, and TSC1 disruption on cortical neuron excitability, we examined the intrinsic biophysical and synaptic properties of layer 2/3 pyramidal neurons in the mPFC. We found that all gene manipulations led to increased membrane conductance but decreased AP firing upon membrane depolarization, consistent with previous reports in the somatosensory cortex^{26,39,42,55–58} and in the mPFC for the *Rheb*^{S16H} condition^{30,31}. Neurons in these conditions required a larger depolarization to generate an AP (increased rheobase), likely due to their enlarged cell size. These findings seem to contradict the theory that seizure initiation originates from these neurons. However, inhibiting firing in cortical pyramidal neurons expressing the mTORC1-activating *Rheb*^{S16H} mutation via co-expression with Kir2.1 channels (to hyperpolarize neurons) has been shown to prevent seizures, supporting a cell-autonomous mechanism³⁰. This discrepancy may be reconciled by the identification of abnormal HCN4 channel expression in the *Rheb*^{S16H} neurons, which was shown to contribute to increased excitability by depolarizing RMPs, bringing neurons closer to the AP threshold, and conferring firing sensitivity to cyclic AMP³⁰. The abnormal HCN4 channel expression has been verified in resected human FCDII and HME tissue (of unknown genetic etiology)³⁰. Here, we found that *Rheb*^{Y35L}, *mTOR*^{S2215Y}, *Depdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO} cortical

neurons also display aberrant HCN4 channel expression, which is consistent with the rapamycin- and 4E-BP1-dependent mode of expression in *Rheb*^{S16H} neurons^{30,31}. The functional expression of these channels was variable, and the corresponding changes in I_h did not reach statistical significance for *Rheb*^{Y35L}, *Depdc5*^{KO}, and *Pten*^{KO} neurons. Nonetheless, consistent with the function of HCN4 channels in maintaining the RMP at depolarized levels³⁸, *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Tsc1*^{KO} neurons exhibited depolarized RMPs. Interestingly, the RMP was unchanged in *Pten*^{KO} and *Depdc5*^{KO} neurons. The lack of RMP changes may be explained by the milder HCN4 phenotype or the presence of different ion channel complements in these neurons. In addition to HCN4 channels, it is thought that increased Kir channels, which are well-known to hyperpolarize RMPs, contribute to the enlarged inward currents in all the conditions we investigated. This was confirmed in the *Tsc1*^{KO} neurons where application of BaCl₂ to block Kir channels reduced the overall inward current and depolarized RMPs. Since *Pten*^{KO} neurons have a larger overall inward current but a smaller I_h compared to *Tsc1*^{KO} neurons, we postulate that *Pten*^{KO} neurons have a higher expression of Kir channels neurons that could counteract the HCN4 channels' depolarizing effect on RMP. The mechanisms and functional significance of the Kir channel increases in these neurons are yet to be validated. Nevertheless, our data suggest that abnormal HCN4 channel expression is a conserved mechanism across these gene conditions and warrant further investigation of HCN-mediated excitability in mTORC1-related epilepsy.

While membrane excitability was largely similar across all gene conditions, the excitatory synaptic properties were more variable. All conditions, except for *Rheb*^{Y35L}, led to increased excitatory synaptic activity, with variable impact on sEPSC frequency and amplitude. *Tsc1*^{KO} neurons were the only investigated condition that displayed increased sEPSC frequency. This finding corroborates a previous study showing increased sEPSC frequency with no sEPSC amplitude changes in layer 2/3 cortical pyramidal neurons from 4-week-old *Tsc1* conditional KO mice⁵⁸. Interestingly, as previously reported for *Rheb*^{S16H} neurons⁵⁹, the sEPSC frequency in *Rheb*^{Y35L} neurons was reduced by 25% but this did not reach statistical significance, possibly due to a generally weaker effect of the Y35L mutation compared to the S16H mutation. *Rheb*^{Y35L}, *mTOR*^{S2215Y}, and *Pten*^{KO} neurons exhibited increased sEPSC amplitudes. We found no changes in the sEPSC amplitude of *Depdc5*^{KO} neurons, which differs from a previous study reporting increased sEPSC amplitude in these neurons²⁶. This discrepancy may likely be explained by the differences in the age of the animals examined in their study (P20-24) versus ours (P26-43), given that dynamic changes in synaptic properties are still ongoing past P21⁶⁰. Despite the above differences in sEPSC frequencies and amplitudes, the total charge was increased in almost all conditions except for in *Rheb*^{Y35L}, suggesting enhanced synaptic drive and connectivity. These excitatory synaptic changes may counteract the increases in rheobase (i.e., decreased membrane excitability) and thereby impact circuit hyperexcitability and seizure vulnerability. Overall, the changes in synaptic activity for the *Rheb*^{Y35L} condition are in stark contrast to the other gene conditions. These observations suggest a *Rheb*-specific impact on synaptic activity that differs from the other mTORC1 pathway genes. Thus, despite impinging on mTORC1 signaling, different mTORC1 pathway gene mutations can affect synaptic activity, and thereby, excitability differently. The mechanisms accounting for the observed differences are not clear, but it is increasingly acknowledged that additional pathways beyond mTORC1 are activated by each gene condition that could contribute to the differential impacts on synaptic activity¹³. One limitation of this study is that we did not examine inhibitory synaptic properties and the impact on excitatory-inhibitory balance. These changes could potentially contribute to gene-specific mechanisms of cortical hyperexcitability and should be the subject of another study.

In summary, we have shown that mutations affecting different mTORC1 pathway genes have similar and dissimilar consequences on cortical pyramidal neuron development and function, which may affect how neurons behave in cortical circuits. Our findings suggest that cortical neurons harboring different mTORC1 pathway gene mutations may differentially affect how

neurons receive and process cortical inputs, which have implications for the mechanisms of cortical hyperexcitability and seizures in FMCDs, and potentially affect how neurons and their networks respond to therapeutic intervention.

Author contribution

LN: conceptualization, investigation, analysis, visualization, writing-original draft, review & editing, YX: investigation, analysis, MN: analysis, AB: conceptualization, writing-original draft, review & editing.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding authors upon reasonable request.

Competing interest

AB is an inventor on a patent application “Methods of treating and diagnosing epilepsy” (Pub. no. US2022/0143219 A1).

Grant funding

National Institutes of Health (NIH) F32 HD095567 (LHN), R01 NS111980 (AB)

Acknowledgements

We thank Drs. Stéphanie Baulac (Paris Brain Institute, France) for providing the pX330-*Depdc5* plasmid and Dr. Joseph LoTurco (University of Connecticut) for insightful discussions and advice on the pX330-*Tsc1* plasmid.

Methods

Animals

All animal procedures were performed in accordance with Yale University Institutional Animal Care and Use Committee’s regulations. All experiments were performed on male and female CD-1 mice (Charles River Laboratories).

Plasmid DNA

Information on the plasmids used in this study is listed in **Table 2** [↗](#). Concentrations of plasmids used for each control and experimental condition are listed in **Table 3** [↗](#).

Plasmid name	Plasmid source/generation
pCAG-tdTomato	Addgene plasmid #83029; this plasmid was previously generated by our lab
pCAG-GFP	Addgene plasmid #11150; deposited by Dr. Connie Cepko
pCAG-tagBFP	Gift from Dr. Joshua Breunig ⁶⁴
pCAG- <i>Rheb</i> ^{Y35L} -T2A-tdTomato	The <i>Rheb</i> insert was synthesized and subcloned into a pCAG-Kir2.1Mut-T2A-tdTomato construct (Addgene plasmid #60644) via SmaI and BamHI sites, after excision of Kir2.1. <i>Rheb</i> insert sequence: NM_053075.3 (<i>mus musculus</i>), mutation: Y35L
pCAG- <i>mTOR</i> ^{S2215Y}	The <i>mTOR</i> insert was subcloned from a pcDNA3-FLAG-mTOR-SS2215Y construct (Addgene plasmid #69013) into a pCAG-tdTomato construct (Addgene plasmid #83029) via 5' AgeI and 3' NotI sites, after excision of tdTomato. <i>mTOR</i> insert sequence: NM_004958 (<i>homo sapiens</i>), mutation: S2215Y
pX330-Control (i.e., pX330-empty)	Addgene plasmid #42230; deposited by Dr. Feng Zhang
pX330- <i>Depdc5</i>	Gift from Dr. Stéphanie Baulac. The gRNA sequence (gRNA1) was originally validated by Ribierre <i>et al</i>²⁶. gRNA sequence (5' to 3'): GTCTGTGGTGATCACGC (17 nt) The gRNA targets exon 16 of <i>Depdc5</i> (NM_001025426, <i>mus musculus</i>), resulting in deleterious indels and inactivation of the gene
pX330- <i>Pten</i>	Addgene plasmid #59909; deposited by Dr. Tyler Jacks. The gRNA sequence (gRNA1) was originally validated by Xue <i>et al</i>²⁸. gRNA sequence (5' to 3'): AGATCGTTAGCAGAAACAAA (20 nt) The gRNA targets <i>Pten</i> (NM_008960, <i>mus musculus</i>), resulting in deleterious indels and inactivation of the gene
pX330- <i>Tsc1</i>	The gRNA sequence was synthesized based on published sequences²⁷ and subcloned into a pX330-empty vector. The specificity of the gRNA (gRNA T4) was originally described and validated by Lim <i>et al</i>²⁷. gRNA sequence (5' to 3'): CAGTGTGGAGGAGTCCAGCA (20 nt) The gRNA targets exon 3 of <i>Tsc1</i> (NM_001289575, <i>mus musculus</i>), resulting in deleterious indels and inactivation of the gene

Table 2

Plasmid DNA information

Group	Plasmid name	Plasmid concentration (μg/μl) ^a
Control (for <i>Rheb</i> ^{Y35L} littermates) ^b	pCAG-tdTomato	3.5
Control (for <i>mTOR</i> ^{S2215Y} littermates) ^b	pCAG-GFP	2.5
	pCAG-tdTomato	1.0
<i>Rheb</i> ^{Y35L}	pCAG- <i>Rheb</i> ^{Y35L} -T2A-tdTomato	2.5
	pCAG-GFP	1.0
<i>mTOR</i> ^{S2215Y}	pCAG- <i>mTOR</i> ^{S2215Y}	2.5
	pCAG-tdTomato	1.0
Control	pX330-Control	2.5
	pCAG-tdTomato	1.0
	pCAG-tagBFP ^c	0.5
<i>Depdc5</i> ^{KO}	pX330- <i>Depdc5</i>	2.5
	pCAG-tdTomato	1.0
	pCAG-GFP ^c	0.5
<i>Pten</i> ^{KO}	pX330- <i>Pten</i>	2.5
	pCAG-tdTomato	1.0
	pCAG-GFP ^c	0.5
<i>Tsc1</i> ^{KO}	pX330- <i>Tsc1</i>	2.5
	pCAG-tdTomato	1.0
	pCAG-GFP ^c	0.5

^aWorking plasmid solutions were diluted in water and contained 0.03% Fast Green dye to visualize the injection. For each embryo, 1.5 μl of the plasmid mixture was injected into the right ventricle.

^bControl groups for *Rheb*^{Y35L} and *mTOR*^{S2215Y} contained pCAG tdTomato and pCAG-GFP+pCAG-tdTomato, respectively, to distinguish between control and experimental animals for each litter. The total plasmid concentration was kept equal between the two control groups. No differences were observed between the two groups, and therefore, they were combined into one control group.

^cEqual concentrations of pCAG-tagBFP and pCAG-GFP were added into the control and experimental (*Depdc5*^{KO}, *Pten*^{KO}, and *Tsc1*^{KO}) groups, respectively, to distinguish the control and experimental animals for each litter.

Table 3

Plasmid concentrations for control and experimental conditions

***In utero* electroporation (IUE)**

Timed-pregnant embryonic day (E) 15.5 mice were anesthetized with isoflurane, and a midline laparotomy was performed to expose the uterine horns. A DNA plasmid solution was injected into the right lateral ventricle of each embryo using a glass pipette. For each litter, half of the embryos received plasmids for the experimental condition and the other half received plasmids for the respective control condition. A 5 mm tweezer electrode was positioned on the embryo head and 6 x 42V, 50 ms pulses at 950 ms intervals were applied using a pulse generator (ECM830, BTX) to electroporate the plasmids into neural progenitor cells. Electrodes were positioned to target expression in the mPFC. The embryos were returned to the abdominal cavity and allowed to continue with development. At P0, mice were screened under a fluorescence stereomicroscope to ensure electroporation success, as defined by fluorescence in the targeted brain region, before proceeding with downstream experiments

Brain fixation and immunofluorescent staining

P7-9 (neonates) and P28-43 (young adults) mice were deeply anesthetized with isoflurane and sodium pentobarbital (85 mg/kg i.p. injection) and perfused with ice-cold phosphate buffered saline (PBS) followed by ice-cold 4% PFA. Whole brains were dissected and post-fixed in 4% PFA for 2 hours and then cryoprotected in 30% sucrose for 24-48 hours at 4°C until they sank to the bottom of the tubes. Brains were serially cut into 50 µm-thick coronal sections using a freezing microtome and stored in PBS + 0.05% sodium azide at 4°C until use.

For immunofluorescence staining, free-floating brain sections were washed in PBS + 0.1% triton X-100 (PBS-T) for 2x10 min and permeabilized in PBS + 0.3% triton X-100 for 20-30 min. Sections were then incubated in blocking buffer (10% normal goat serum + 0.3% BSA + 0.3% triton X-100 in PBS) for 1 hour at room temperature and in primary antibodies [anti-p-S6 S240/244 (Cell Signaling Technology #5364, 1:1000) or anti-HCN4 (Alomone Labs APC-052, 1:500), diluted in 5% normal goat serum + 0.3% BSA + 0.1% triton X-100 in PBS] for 2 days at 4°C. Sections were then washed in PBS-T for 3x10 min, incubated in secondary antibodies [goat anti-rabbit IgG Alexa Fluor Plus 647 (Invitrogen #A32733, 1:500)] for 2 hours at room temperature, and again washed in PBS-T for 3x10 min. All sections were mounted onto microscope glass slides and coverslipped with ProLong Diamond Antifade Mountant (Invitrogen) for imaging. The specificity of the HCN4 antibodies was previously validated in our lab³⁰. Additionally, a no primary antibody control was included to confirm the specificity of the secondary antibodies (Fig. S5b).

Confocal microscopy and image analysis

Images were acquired using a Zeiss LSM 880 confocal microscope. All image analyses were done using ImageJ software (NIH) and were performed blinded to experimental groups. Data were quantified using grayscale images of single optical sections. Representative images were prepared using Adobe Photoshop CC. All quantified images meant for direct comparison were taken with the same settings and uniformly processed.

P28-43 neuron soma size and p-S6 staining intensity were quantified from 20x magnification images of p-S6 stained brain sections by tracing the soma of randomly selected tdTomato+ cells and measuring the area and p-S6 intensity (mean gray value) within the same cell, respectively. HCN4 staining intensity was quantified from 20x magnification images by tracing the soma of randomly selected tdTomato+ cells and measuring HCN4 intensity (mean gray value). Staining intensities were normalized to the mean control. 15 cells from 2 brain sections per animal were analyzed for each of the parameters. Neuron positioning (% cells in layer 2/3) was quantified by counting the number of tdTomato+ cells within an 800 µm x 800 µm region of interest (ROI) on the electroporated cortex. Cells within 300 µm from the pial surface were considered correctly located in layer 2/3 whereas cells outside that boundary were considered misplaced^{31,41,61}. The distribution of neurons in the cortex was further quantified by dividing the 800 µm x 800 µm ROI into 10 evenly spaced bins (bin width = 80 µm) parallel to the pial surface and counting the

number of tdTomato⁺ cells in each bin. Only cells within the gray matter of the cortex were quantified. Data are shown as % of total tdTomato⁺ cell count. One brain section per animal was analyzed. P7-9 neuron soma size (supplemental data) was quantified from 10x magnification images of unstained brain sections by tracing the soma of randomly selected tdTomato⁺ cells and measuring the area. 30 cells from 2 sections per animal were analyzed.

Acute brain slice preparation, patch clamp recording, and analysis

P26-P51 mice were deeply anesthetized by carbon dioxide inhalation and sacrificed by decapitation. Whole brains were rapidly removed and immersed in ice-cold oxygenated (95% O₂/5%CO₂) high-sucrose cutting solution (in mM: 213 sucrose, 2.6 KCl, 1.25 NaH₂PO₄, 3 MgSO₄, 26 NaHCO₃, 10 Dextrose, 1 CaCl₂, 0.4 ascorbate, 4 Na-Lactate, 2 Na-Pyruvate, pH 7.4 with NaOH). 300 µm-thick coronal brain slices containing the mPFC were cut using a vibratome (Leica VT1000) and allowed to recover in a holding chamber with oxygenated artificial cerebrospinal fluid (aCSF, in mM: 118 NaCl, 3 KCl, 1.25 NaH₂PO₄, 1 MgSO₄, 26 NaHCO₃, 10 Dextrose, 2 CaCl₂, 0.4 ascorbate, 4 Na-Lactate, 2 Na-Pyruvate, 300 mOsm/kg, pH 7.4 with NaOH) for 30 min at 32°C before returning to room temperature (22°C) where they were kept for 6-8 hours during the experiment.

Whole-cell current- and voltage-clamp recordings were performed in a recording chamber at room temperature using pulled borosilicate glass pipettes (4-7 MΩ resistance, Sutter Instrument) filled with internal solution (in mM: 125 K-gluconate, 4 KCl, 10 HEPES, 1 EGTA, 0.2 CaCl₂, 10 di-tris-phosphocreatine, 4 Mg-ATP, 0.3 Na-GTP, 280 mOsm/kg, pH 7.3 with KOH). Fluorescent (i.e., electroporated) neurons in the mPFC were visualized using epifluorescence on an Olympus BX51WI microscope with a 40X water immersion objective. Recordings were performed on neurons in layer 2/3. Data were acquired using Axopatch 200B amplifier and pClamp 10 software (Molecular Devices) and filtered (at 5 kHz) and digitized using Digidata 1320 (Molecular Devices). All data analysis was performed offline using pClamp 10 software (Clampfit) and exported to GraphPad Prism 9 software for graphing and statistical analysis.

The RMP was recorded within the first 10 s after achieving whole-cell configuration at 0 pA in current-clamp mode. The membrane capacitance was measured in voltage-clamp mode and calculated by dividing the average membrane time constant by the average input resistance obtained from the current response to a 500-ms long (±5 mV) voltage step from -70 mV holding potential. The membrane time constant was determined from the biexponential curve best fitting the decay phase of the current; the slower component of the biexponential fit was used for the membrane time constant. The resting membrane conductance was measured in current-clamp mode and calculated using the membrane potential change induced by -500 pA hyperpolarizing current injections from rest. The AP input-output curve was generated by injecting 500 ms-long depolarizing currents steps from 0 to 400 pA in 20 pA increments from the RMP of each condition in current-clamp mode. The number of elicited APs was counted using the threshold search algorithm in Clampfit (pClamp). To determine the minimum amount of current needed to induce the first AP, i.e. rheobase, 5 ms-long depolarizing current steps in increments of 20 pA were applied every 3 s until an AP was elicited. The AP threshold, peak amplitude, and half-widths were analyzed from averaged traces of 5-10 consecutive APs induced by the rheobase +10 pA. The AP threshold was defined as the membrane potential at which the first derivative of an evoked AP achieved 10% of its peak velocity (dV/dt). The AP peak amplitude was defined as the difference between the peak and baseline. The AP half-width was defined as the duration of the AP at the voltage halfway between the peak and baseline. I_h was evoked by a series of 3 s-long hyperpolarizing voltage steps from -120 mV to -40 mV in 10 mV increments., with a holding potential of -70 mV. The I_h amplitudes (ΔI) were measured as the difference between the instantaneous current immediately following each test potential (I_{inst}) and the steady-state current at the end of each test potential (I_{ss})³².

Zatebradine (40 μ M, Toris Bioscience) and BaCl₂ (200 μ M, Sigma-Aldrich) were applied locally to the recorded neurons via a large-tip (350 μ M diameter) flow pipe. When no drugs were applied, a continuous flow of aCSF was supplied from the flow pipe. The IV curve, Δ IV curve, and RMP were measured before and after drug application as described above. The zatebradine-sensitive and BaCl₂-sensitive currents were obtained by subtracting the current traces obtained after from before drug application. The IV curve for the zatebradine-sensitive current was obtained by measuring the steady-state of the resulting current, and the IV curve for the BaCl₂-sensitive current was obtained by measuring the peak of the resulting current.

sEPSCs were recorded at a holding potential of -70 mV. Synaptic currents were recorded for a period of 2–5 min and analyzed by using the template search algorithm in Clampfit. The template was constructed by averaging 5–10 synaptic events, and the template match threshold parameter was adjusted to minimize false positives. All synaptic events identified by the program were manually inspected and non-synaptic currents (based on the fast-rising time) were discarded. The total charge (pA/ms) was calculated as area of sEPSC events (pA/ms) x frequency (Hz)/1000 for each neuron.

Statistical analysis

All statistical analyses were performed using GraphPad Prism 9 software with the significance level set at $p < 0.05$. Data were analyzed using nested t-test or nested one-way ANOVA (obtained by fitting a mixed-effects model wherein the main factor is treated as a fixed factor and the nested factor is treated as a random factor; to account for correlated data within individual animals within groups^{62,63}), one-way ANOVA, two-way repeated measure ANOVA, or mixed-effects ANOVA (fitted to a mixed-effects model for when values were missing values in repeated measures analyses), as appropriate. For all nested statistics, the distribution of data among individual animals is shown in **Supplemental Figs. S1**, **S3**, **S4**, and **S7**. All post-hoc analyses were performed using Holm-Šidák's multiple comparison test. The specific tests applied for each dataset, test results, and sample size (n, number of animals or neurons) are summarized in **Tables 1** and **S1** and described in the figure legends. All data are reported as the mean of all neurons or brain sections in each group $\pm$ standard error of the mean (SEM).

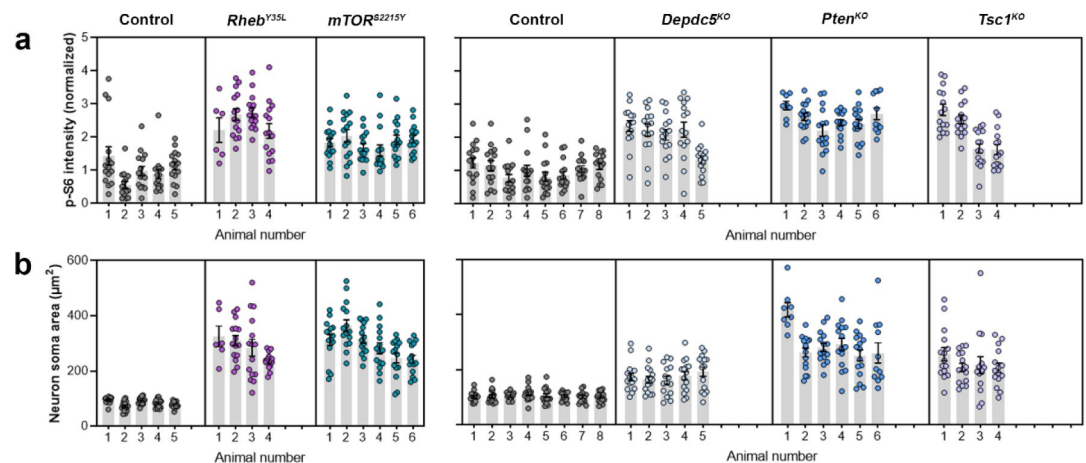


Figure S1:

Distribution of p-S6 staining intensity and neuron soma size among individual animals P28-43.

(a) Distribution of p-S6 staining intensity among individual animals. (b) Distribution of neuron soma size among individual animals.

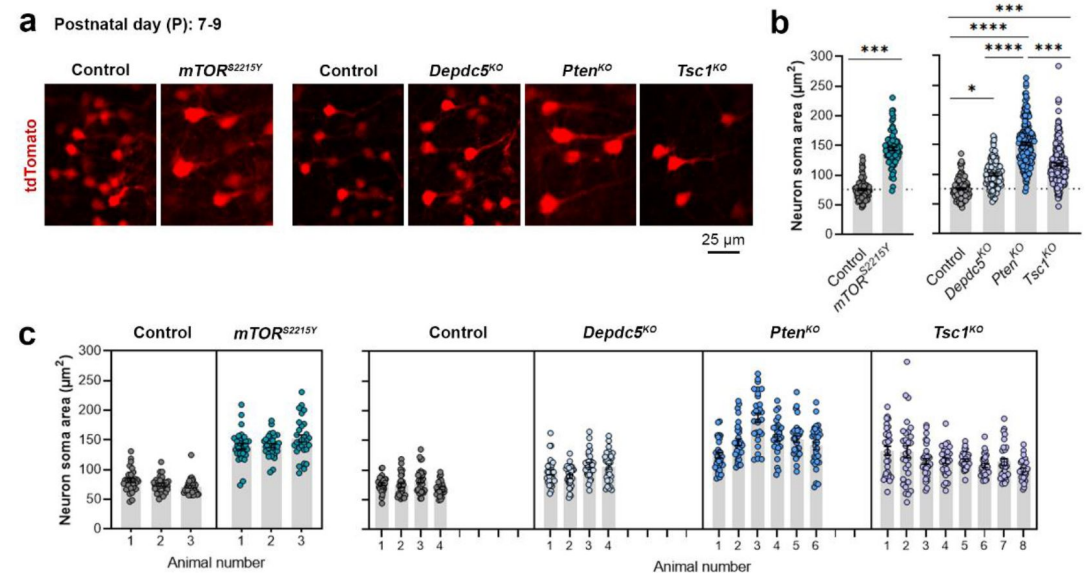


Figure S2:

Neuron soma sizes at P7-9.

(a) Representative images of tdTomato+ cells (red) in mouse mPFC at P7-9. (b) Quantification of tdTomato+ neuron soma size. (c) Graph showing the distribution of neuron soma size among individual animals in each group. $n = 3-8$ mice per group, with 30 cells analyzed per animal. Statistical comparisons were performed using a nested t-test (control vs. $mTOR^{S2215Y}$) or nested one-way ANOVA (control vs. $Depdc5^{KO}$ vs. $Pten^{KO}$, vs. $Tsc1^{KO}$) (fitted to a mixed-effects model) to account for correlated data within individual animals. Post-hoc analyses were performed using Holm-Šidák multiple comparison test. * $p < 0.05$, *** $p < 0.001$, **** $p < 0.0001$. Data are reported as the mean of all neurons in each group $\pm$ SEM.

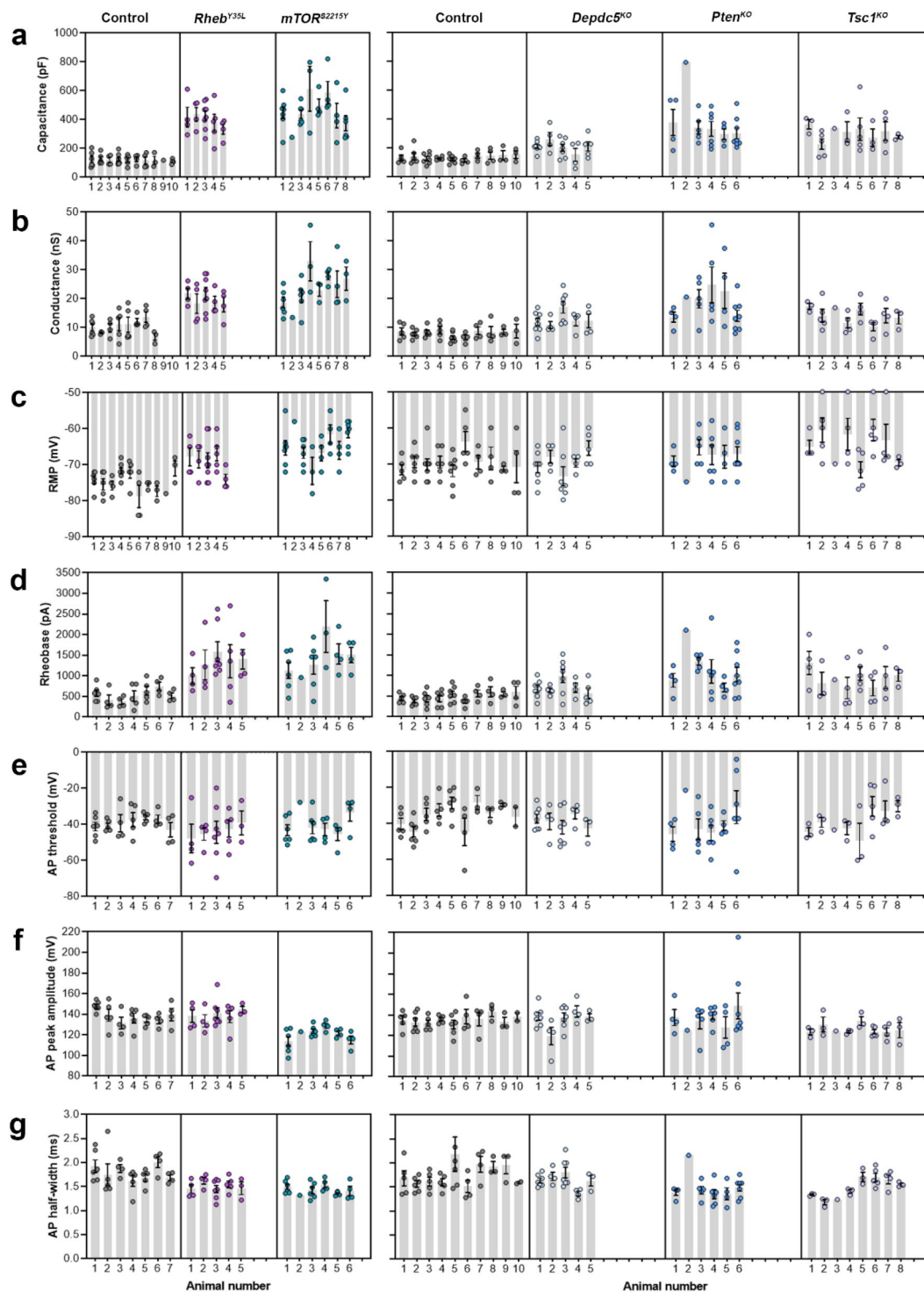


Figure S3

Distribution of membrane and AP properties among individual animals P26-51. (a-c)

Distribution of membrane capacitance, conductance, and RMP among individual animals. (d-g) Distribution of rheobase, AP threshold, AP peak amplitude, and AP half-width among individual animals.

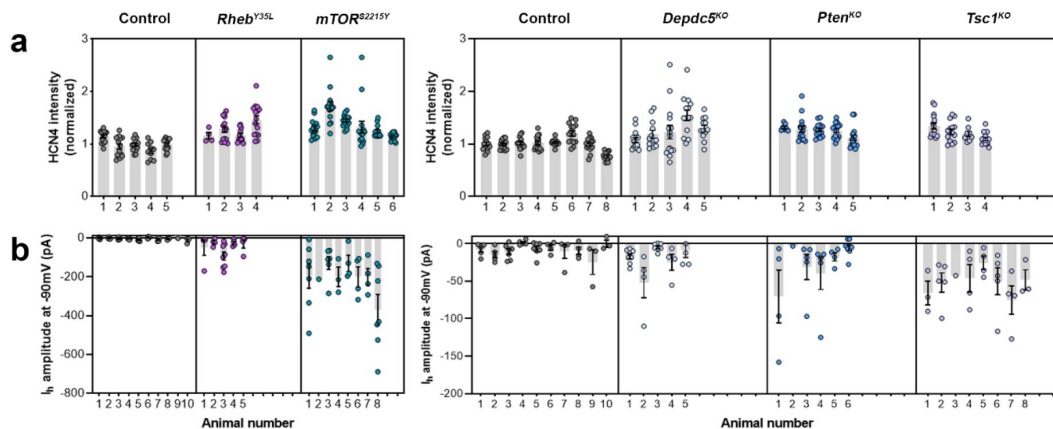


Figure S4

Distribution of HCN4 staining intensity and *I*_h amplitudes (at -90 mV) among individual animals at P28-43 and P26-51, respectively.

(a) Distribution of HCN4 staining intensity among individual animals. (d-g) Distribution of *I*_h amplitudes (at -90 mV) among individual animals.

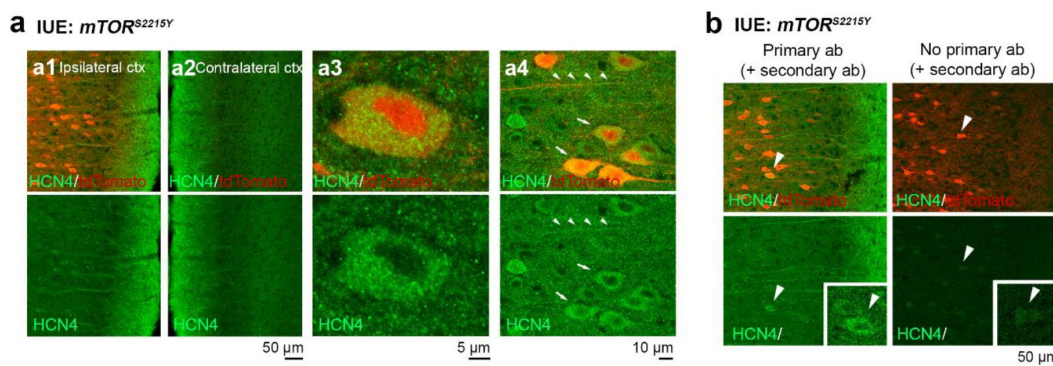


Figure S5

Additional images of HCN4 staining in mPFC sections from P28-43 mice expressing *mTOR*^{S2215Y}.

(a) Representative images of tdTomato+ cells (red) and HCN4 staining (green). Top panels show overlay images. Bottom panels show HCN4 single-channel images. **a1** and **a2** show the ipsilateral and contralateral cortex, respectively. **a3** and **a4** are high-magnification images demonstrating HCN4 staining within the cell. (b) Representative images of immunostaining with (left) or without (right) HCN4 primary antibodies (control for secondary antibody specificity).

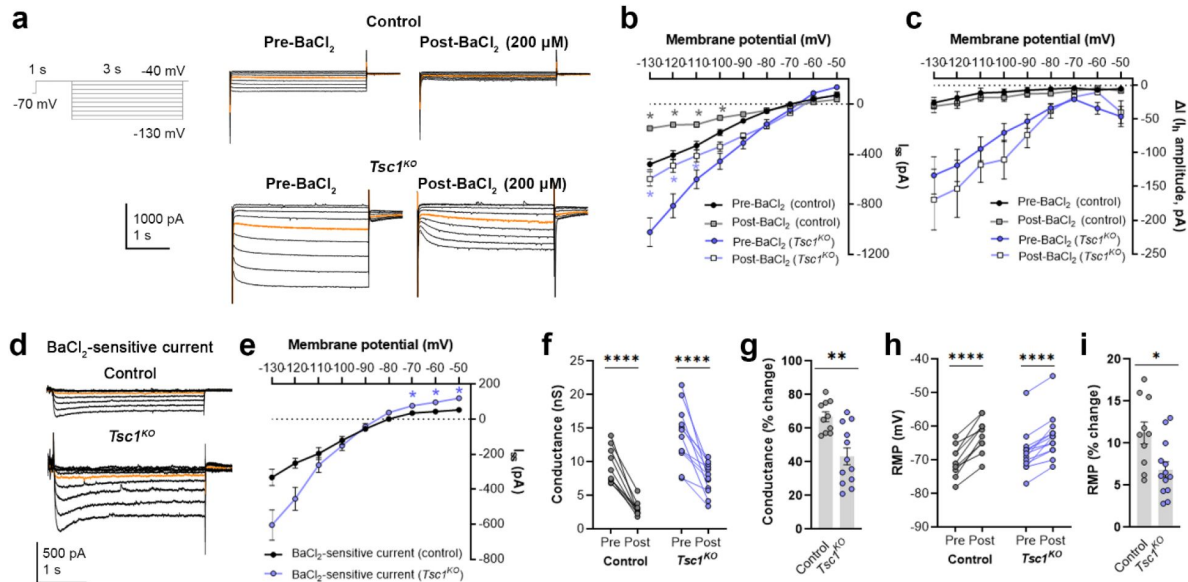


Figure S6

BaCl₂ application decreases overall inward currents without affecting I_h in *Tsc1*^{KO} neurons.

(a) Representative current traces in response to a series of 3-s long hyperpolarizing voltage steps from -130 mV to -40 mV in the *Tsc1*^{KO} condition pre- and post-BaCl₂ application. Orange lines denote the current traces at -90 mV. (b) IV curve obtained from I_{SS} amplitudes in the *Tsc1*^{KO} condition pre- and post-BaCl₂ application. (c) IV curve obtained from I_h amplitudes (i.e., ΔI , where $\Delta I = I_{SS} - I_{inst}$) in the *Tsc1*^{KO} condition pre- and post-BaCl₂ application. (d) Representative traces of the BaCl₂-sensitive current obtained after subtraction of the post-from the pre-BaCl₂ current traces. Orange lines denote the current traces at -90 mV. (e) IV curve of the BaCl₂-sensitive current obtained after subtraction of the post-from the pre-BaCl₂ current traces. The isolated BaCl₂-sensitive current reversed near -80 mV. (f) Graph of conductances (at -500 pA) in the control and *Tsc1*^{KO} conditions pre- and post-BaCl₂ application. Connecting lines denote paired values from the same neuron. (g) Graph of % change in conductances pre- and post-BaCl₂ application in the control and *Tsc1*^{KO} conditions. (h) Graph of RMP in the control and *Tsc1*^{KO} conditions pre- and post-BaCl₂ application. Connecting lines denote paired values from the same neuron. (i) Graph of % change in RMP pre- and post-BaCl₂ application in the control and *Tsc1*^{KO} conditions. For all graphs: n = 10-13 neurons per group. Statistical comparisons were performed using (b, c, e) mixed-effects ANOVA, (f, h) two-way repeated measures ANOVA, or (g, i) unpaired t-test. Post-hoc analyses were performed using Holm-Šidák multiple comparison test. *p<0.05, **p<0.01, ***p<0.0001. All data are reported as the mean of all neurons or brain sections in each group ± SEM.

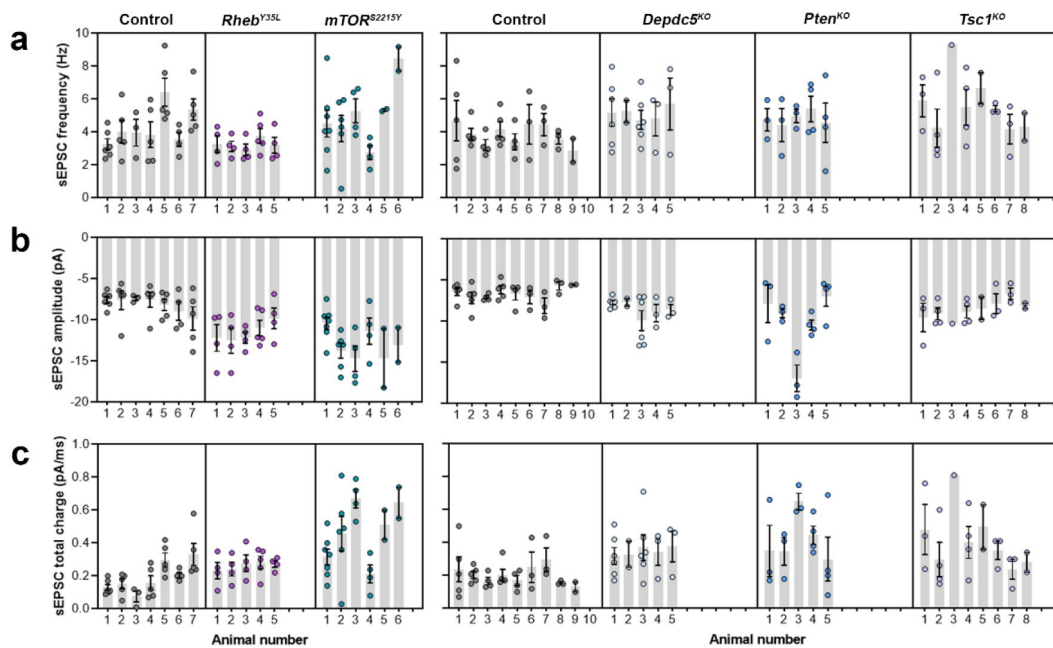


Figure S7

Distribution of sEPSC properties among individual animals at P26-51. (a-c)

Distribution of sEPSC properties among individual animals.

Fig. S2b: NEURON SOMA SIZE (P7-9)

			Nested t-test ^a					Nested one-way ANOVA ^a			
	Control	<i>mTOR</i> ^{S2215Y}	t, df	F, DFn, DFd	p-value		Control	<i>Depdc5</i> ^{KO}	<i>Pten</i> ^{KO}	<i>Tsc1</i> ^{KO}	F, DFn, DFd, p-value
Mean ± SD	76.2 ± 1.7	144.4 ± 2.9	13.22, 4	174.8, 1, 4	0.0002		75.9 ± 1.5	100.1 ± 2.1	151.7 ± 2.8	116.7 ± 2.1	26.87, <0.0001, 3, 18
No. of animals	3	3					4	4	6	8	
No. cells/ animal	30	30					30	30	30	30	
Total cells	90	90					120	120	180	240	

Fig. S6b: IV CURVE (BaCl₂)

Mixed-effects ANOVA			
Fixed effects			
No. of neurons (type III)		F (DFn, DFd)	p-value
Pre-BaCl ₂ (control) 10	Voltage step	F (8, 72) = 201.6	<0.0001
Post-BaCl ₂ (control) 10	Group	F (1, 9) = 46.18	<0.0001
	Voltage step x group	F (8, 55) = 45.52	<0.0001
Pre BaCl ₂ (<i>Tsc1</i> ^{KO}) 13	Voltage step	F (8, 96) = 81.41	<0.0001
Post-BaCl ₂ (<i>Tsc1</i> ^{KO}) 13	Group	F (1, 12) = 12.46	0.0041
	Voltage step x group	F (8, 64) = 20.46	<0.0001

Fig. S6c: ΔIV CURVE (BaCl₂)

Mixed-effects ANOVA			
Fixed effects			
No. of neurons (type III)		F (DFn, DFd)	p-value
Pre-BaCl ₂ (control) 10	Voltage step	F (8, 72) = 4.337	0.0003
Post-BaCl ₂ (control) 10	Group	F (1, 9) = 2.310	0.1629
	Voltage step x group	F (8, 56) = 0.3825	0.9255
Pre BaCl ₂ (<i>Tsc1</i> ^{KO}) 13	Voltage step	F (8, 96) = 12.53	<0.0001
Post-BaCl ₂ (<i>Tsc1</i> ^{KO}) 13	Group	F (1, 12) = 0.7970	0.3895
	Voltage step x group	F (8, 64) = 2.306	0.0307

Fig. S6e: IV CURVE (BaCl₂-sensitive current)

Mixed-effects ANOVA			
Fixed effects			
No. of neurons (type III)		F (DFn, DFd)	p-value
Control 10	Voltage step	F (1.252, 19.41) = 92.62	<0.0001
<i>Tsc1</i> ^{KO} 13	Group	F (1, 21) = 1.036	0.3204
	Voltage step x group	F (8, 124) = 7.724	<0.0001

Fig. S6f: CONDUCTANCE (nS, BaCl₂)

No. of neurons Two-way repeated measures ANOVA			
		F (DFn, DFd)	p value
Control 10	Group	F (1, 20) = 20.04	0.0002
<i>Tsc1</i> ^{KO} 12	Treatment	F (1, 20) = 82.05	<0.0001
	Group x treatment	F (1, 20) = 0.0002453	0.9877

Fig. S6g: CONDUCTANCE (% change, BaCl₂)

No. of neurons Unpaired t-test			
	t, df	p-value	
Control 10	t=3.841, df=20	0.0010	
<i>Tsc1</i> ^{KO} 12			

Fig. S6h: RMP (mV, BaCl₂)

No. of neurons Two-way repeated measures ANOVA			
--	--	--	--

Table S1

Statistical results (for supplemental figures)

			F (DFn, DFd)	p value	
Control	10	Group	F (1, 21) = 0.2692	0.6093	
<i>Tsc1</i>^{KO}	13	Treatment	F (1, 21) = 134.7	0.0001	
		Group x treatment	F (1, 21) = 9.281	0.0061	

Fig. S6i: RMP (% change, BaCl₂)

	No. of neurons	Unpaired t-test		
		t, df	p-value	
Control	10	t=2.810, df=21	0.0105	
<i>Tsc1</i>^{KO}	13			

^aThe nested t-test and ANOVA fit a mixed-effects model wherein the main factor is treated as a fixed factor and the nested factor is treated as a random factor.

^bPost-hoc analyses were performed using Holm-Šidák multiple comparison test. Significant post-hoc results ($p < 0.05$) are denoted with symbols (*) on the graphs, with the number of symbols 1-4 denoting the significant levels $p < 0.05$, < 0.01 , < 0.001 , and < 0.0001 , respectively.

Table S1 (continued)

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Editors

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Reviewer #1 (Public Review):

Pathogenic mutations of mTOR pathway genes have been identified in patients with malformation of cortical development and intractable epilepsy. Nguyen et al., established an in vivo rodent model to investigate the impact of different mTOR pathway gene dysfunction on neuronal intrinsic membrane excitability and cortical network activity. The results demonstrate that activation of mTORC1 activators or inactivation of mTORC1 repressors leads to convergent mTOR pathway activation and alterations of neuronal morphology, the key pathological feature of human FCD and hemimegalencephaly. However, different mTOR pathway gene mutations also exhibited variations in modulating Ih current and synaptic

activity in rodent cortical neurons. These findings provide novel insights into the mechanism of seizure generation associated with cortical malformation.

1. The authors found differences in the initial spike doublet of action potentials between cortical neurons in experimental and control conditions (Figure 2e). The action potential firing frequency of the first two APs (instant firing frequency) of recorded neurons shall be quantified to investigate whether there are statistical differences between the action potential firing frequency in cortical neurons in different experimental groups versus control conditions.
2. The mTORS12215Y induced the largest changes in I_h current amplitudes in cortical neurons compared with other experimental conditions. Whether the HCN4 channel expression is regulated by mTOR pathway activation, or could there be possible interactions between the HCN channel and mTORS12215Y mutant protein?
3. A comparison of the electrophysiological characteristics of cortical neurons in different experimental conditions in the present study and pathological neurons in human FCD reported in previous literature could be interesting. Inducing pathological gene mutations or knocking out key genes in mTOR pathway in the rodent cortex - which approach could better model human FCD?

Reviewer #2 (Public Review):

Summary:

The study provides valuable and compelling evidence that while activation of the mTOR cascade confers some similarities in alterations in cell size, mTOR pathway activation, cortical lamination, baseline firing properties, and synaptic activity, there are distinctions that could account for clinical differences in seizure and epilepsy phenotypes in patients harboring these mutations. These findings could have important implications going forward as we design clinical therapeutic strategies to modulate mTOR activity in these individuals to treat seizures.

This study presents a valuable finding on the role that distinct mTOR pathway genes play in altered cell shape, cortical laminar migration, and cellular excitability in the mouse medial prefrontal cortex (mPFC). The evidence supporting the claims of the authors is solid, although analysis of the role of the mTORC2 pathway and consideration of distinct metabolic states i.e., amino acid levels would have strengthened the study. The work will be of interest to neuroscientists working on human epilepsy. These genes have each been assayed in previous independent studies and thus the direct comparison is what provides the innovation and interest.

The manuscript by Nguyen and colleagues attempts to define both the common and differential roles of mTOR pathway genes, both by gene knockout (KO) and activation, on cortical neuronal size, cortical lamination, and excitability. They focused on 5 genes that have been linked to human malformations of cortical development (MCD) and epilepsy: RhebY35L, mTORS2215Y, Dedpdc5KO, PtenKO, and Tsc1KO. The RhebY35L, mTORS2215Y are known and pathogenic human gain-of-function variants. Each of these genes is known to modulate the activity of mTORC1 and either KO or activation will lead to abnormal and persistent hyperactivation of mTOR activity. Using in utero electroporation they transfected plasmids containing these gene constructs into fetal mouse brains at E15.5 and then assessed neuronal shape and size, laminar positioning, spontaneous activity, synaptic activity, and expression of a novel voltage-gated potassium channel (HCN4) at varying time postnatally e.g., P7-9 (neonates) and P28-43 (young adults).

The study clearly achieves its stated aims i.e., that disruption of each of five distinct mTOR pathway genes, Rheb, mTOR, Depdc5, Pten, and Tsc1, individually impacts pyramidal neuron

development and electrophysiological function in the mouse mPFC. The data from each of the 5 genes provides strong support to the notion that mTOR pathway gene mutations yield the unifying clinical parcellation of mTORopathies, likely as a consequence of mTOR pathway activation. The data also provide interesting evidence that subtle or even overt differences in clinical phenotypes between RhebY35L, mTORS2215Y, Dedpdc5KO, PtenKO, and Tsc1KO in humans could be due to effects of these genes either on mTOR or on yet to be defined alternative pathways. Assuredly follow-up studies to examine how Rheb, mTOR, Dedpdc5, Pten, and Tsc1 engage with other protein binding partners or other pathways will be warranted in future studies.

Strengths:

The investigators demonstrate that gene KO or activation leads to common changes in cell size (enlargement) though with different effects across each gene subtype suggesting distinct genetic effects despite a common effect on mTOR signaling. The major effect was seen in forebrain neurons expressing mTORS2215Y. They also report gene-specific effects of each mTOR pathway gene on cortical lamination. For example, while RhebY35L, mTORS2215Y, Dedpdc5KO, and Tsc1KO significantly disrupted laminar positioning of neurons in layer 2/3, PtenKO had minimal effects on laminar positioning. This finding is intriguing since it means that simply activating mTOR during fetal brain development will not necessarily alter cortical lamination and that an increase in cell size by itself doesn't disrupt laminar fidelity. To verify that the expression of plasmids led to mTORC1 hyperactivation, phosphorylated levels of S6 (i.e., p-S6), a downstream substrate of mTORC1, were assayed by immunohistochemistry in P28-43 mice. Expression of the RhebY35L, mTORS2215Y, Dedpdc5KO, PtenKO, and Tsc1KO plasmids all led to significantly increased p-S6 staining intensity, supporting that the expression of each of these plasmids leads to increased mTORC1 signaling.

Whole-cell current- and voltage-clamp recordings were performed in P25-P51 mice in acute brain slice preparations. Expression of RhebY35L, mTORS2215Y, Dedpdc5KO, PtenKO, and Tsc1KO led to decreased depolarization-induced excitability, but only RhebY35L, mTORS2215Y, and Tsc1KO expression led to depolarized resting membrane potentials. Interestingly, expression of RhebY35L, mTORS2215Y, Dedpdc5KO, PtenKO, and Tsc1KO led to the abnormal presence of HCN4 channels with variations in functional expression suggesting a common cellular mechanism that could confer excitability. Treatment with rapamycin, an mTOR inhibitor, reversed the expression changes in HCN4. Expression of RhebY35L, mTORS2215Y, Dedpdc5KO, PtenKO, and Tsc1KO led to different impacts on sEPSC properties. Effects of treatment with the selective HCN channel blocker zatebradine on hyperpolarization-induced inward currents in mTORS2215Y neurons confirmed the identity of ΔI as I_h .

Overall the data presented provides a convincing and compelling direct comparison of the roles that select mTOR pathway genes play on brain development and network excitability. It is critical to directly compare these gene effects in mouse models because although these genes are part of the mTOR pathway and clearly cause augmentation of mTOR activation, there are mechanistic differences in how these genes modify mTOR and how they interact with other proteins and phenotypic differences in humans harboring mutations in these same genes.

Weaknesses:

There are a few limitations to an otherwise solid study. First, the authors postulate that all the findings are dependent on mTORC1-related effects but don't assess whether some of the differences could be due to effects on mTORC2 signaling. mTORC2 is an important and poorly understood alternative isoform of mTOR (due to rictor binding) that has effects on distinct cell signaling pathways and in particular actin polymerization. This doesn't diminish the effects of the current analysis of mTORC1 but could explain genotypic differences in each

variable. A few prior studies have assessed the role of mTORC2 in epileptogenesis and Cortical malformations (Chen et al., 2019)

Second, the slice recordings were performed in the usual recording aCSF buffer conditions but there is no assessment of the role of amino acids or nutrients in the bath. While it is clear that valuable and viable acute slice recordings can be made in aCSF, the role of the mTOR pathway is to modulate cell growth in response to nutrient conditions. Thus, one variable that could be manipulated and assessed currently in this study is the levels of amino acids i.e., leucine and arginine added to the bath since DEPDC5 and TSC1 are responsive to ambient amino acid levels.

Third, the analysis concedes that the role of somatic mutations in cortical malformations may depend not only on genotypic effects but also on allelic load and cellular subtype affected by the mutation. Thus, it would interesting to see if electroporation either at E14 or E16, thereby affecting a distinct pool of progenitors, would mitigate or accentuate differences between mTOR pathway genes.

Treatment with rapamycin and zatebradine in each condition would have added to the strength of the findings to determine the mTOR-dependence and reversibility of HCN4 effects.