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BRIEF COMMUNICATION

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A genetically encoded near-infrared fluorescent calcium ion indicator

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We report an intensiometric, near-infrared fluorescent, genetically encoded calcium ion (Ca^{2+}) indicator (GECI) with excitation and emission maxima at 678 and 704 nm, respectively. This GECI, designated NIR-GECO1, enables imaging of Ca^{2+} transients in cultured mammalian cells and brain tissue with sensitivity comparable to that of currently available visible-wavelength GECIs. We demonstrate that NIR-GECO1 opens up new vistas for multicolor Ca^{2+} imaging in combination with other optogenetic indicators and actuators.

GECIs are often used together with optogenetic actuators for simultaneous recording and control of biological processes with high spatiotemporal resolution. However, substantial spectral overlap among currently available GECIs, optogenetic actuators and other genetically encoded indicators limits the possibilities for multiplexing. Most genetically encoded fluorophores fall into two classes: visibly fluorescent β-barrel fluorescent proteins that are homologs of the *Aequorea* green fluorescent protein[1], and far-red to near-infrared (NIR) fluorescent biliverdin-binding fluorescent proteins (BV-FPs) derived from bacteriophytochromes (BphPs)[2] or other biliverdin-binding proteins[3]. Fluorescent proteins have emission peaks in the visible range (~450–670 nm), and BV-FPs have emission peaks in the NIR range (~670–720 nm)[4]. While many GECIs and other indicators have been engineered from fluorescent proteins, examples of BV-FP-based indicators are limited. Examples include BV-FPs as donors and acceptors in fluorescence resonance energy transfer (FRET)-based indicators, and the use of split BV-FPs in protein complementation assays[5].

To expand the range of GECI colors into the NIR range, we have engineered an intensiometric GECI on the basis of the monomeric BV-FP, mIFP[6]. We pursued a design with a Ca^{2+}-binding domain (calmodulin (CaM)-RS20), inserted into mIFP such that Ca^{2+} binding would modulate the biliverdin chromophore environment and fluorescence intensity (Supplementary Note 1). We chose four potential insertion sites (between residues 9/10, 57/58, 138/139 and 170/176) based on inspection of the X-ray crystal structure of *Deinococcus radiodurans* BphP (PDB ID: 2O9B)[7], which has 35% sequence identity with mIFP[6]. Only the replacement of residues 171–175 with CaM-RS20 yielded a protein with a Ca^{2+}-dependent change in fluorescence in vitro (a twofold decrease) (Fig. 1a,b and Supplementary Fig. 1). To improve the indicator properties, we systematically optimized the insertion site (leading to deletion of mIFP residues 176 and 177) and the N- and C-terminal linkers (ultimately the sequences GAL and RRHD, respectively) connecting CaM-RS20 to mIFP.

To facilitate iterative rounds of improvement on the basis of fluorescence screening of randomly mutated variants in bacterial colonies followed by functional tests in mammalian cells, we created a vector (*pcDuEx2*) for expression in both *Escherichia coli* and mammalian cells (Supplementary Fig. 2a). Following 12 rounds of library expression and screening (Supplementary Figs. 2b and 3), we designated our best variant as NIR genetically encoded Ca^{2+} indicator for optical imaging (NIR-GECO1; Supplementary Figs. 2c and 4). A parallel effort to engineer a GECI from the smURFP[3] BV-FP was not successful (Supplementary Fig. 5). NIR-GECO1 has absorbance and emission peaks at 678 and 704 nm, respectively, and undergoes a 90% decrease in fluorescence intensity upon binding Ca^{2+} (K_d = 215 nm) (Fig. 1c–e and Supplementary Fig. 6). The fluorescence change and K_d are comparable to those of GCaMP3 (F_{max}/F_{min} = 13.6; K_d = 405 nm), which was the first broadly useful single-fluorescent-protein-based GECI[8]. Key differences include the opposite directions of the responses to Ca^{2+} and NIR-GECO1's lower Hill coefficient (n = 1.03). As an inverse response indicator, NIR-GECO1 is in its more brightly fluorescent form in resting cells (low Ca^{2+}), and is therefore more susceptible to photobleaching under continuous illumination. In addition, excitation of resting cells above and below the imaging plane will contribute to an increased background signal. As expected when comparing an FP to a BV-FP, the Ca^{2+}-bound state of GCaMP3 is approximately sixfold brighter than the Ca^{2+}-free state of NIR-GECO1 (Supplementary Table 1)[8].

To evaluate the performance of NIR-GECO1 in cultured neurons, we compared intracellular fluorescence brightness and photostability to those of the spectrally similar BV-FPs, iRFP682[9] and miRFP[10] (Supplementary Table 1). All three BV-FPs distributed evenly within the cytosol, dendrites and nucleus of neurons, with no apparent puncta or localized accumulations (Fig. 1f). NIR-GECO1 baseline intracellular brightness was similar to that of miRFP and

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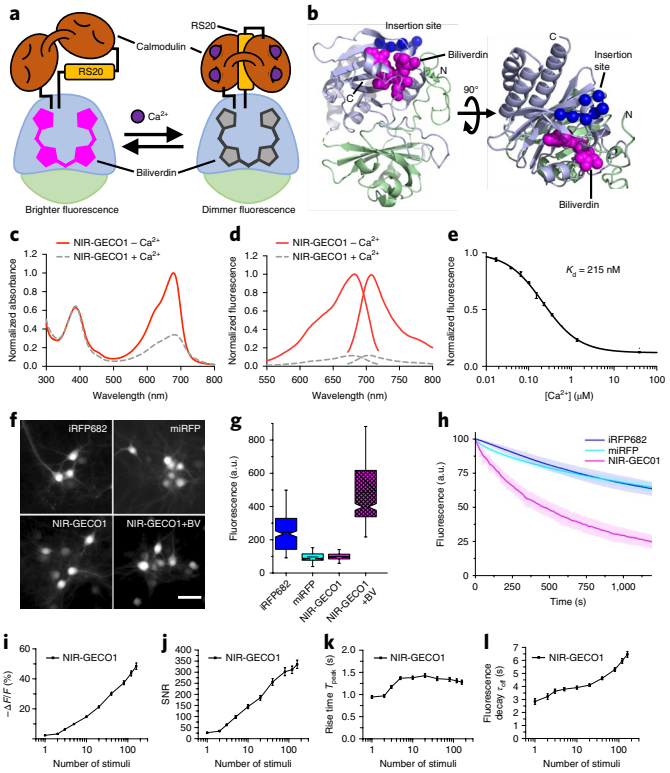

Fig. 1 | Structure and characterization of NIR-GECO1. a, Schematic representation of NIR-GECO1 and its mechanism of response to Ca^{2+}. The PAS domain is colored light green, and the biliverdin-binding GAF domain is colored light blue. RS20 is the CaM-binding peptide of smooth muscle myosin light chain kinase. **b**, Orthogonal views of the structure of *Dr*BphP (PDB 2O9B)[7], a close homolog of mIFP. The PAS and GAF domains are colored as in **a**, biliverdin is shown as magenta spheres, and the Cα atoms of the seven residues that were replaced with CaM-RS20 are shown as blue spheres. **c**, Absorbance spectra in the presence (39 μM) and absence of Ca^{2+}. **d**, Fluorescence excitation and emission spectra in the presence (39 μM) and absence of Ca^{2+}. **e**, Fluorescence of NIR-GECO1 as a function of Ca^{2+} concentration. Center values are the mean, and error bars are s.d. $n=3$ independent experiments. **f**, Representative wide-field fluorescence images (631/28 nm excitation (Ex) at 38 mW mm^{-2} and 664LP emission (Em)) of mouse neurons expressing iRFP682, miRFP, NIR-GECO1 and NIR-GECO1 supplemented with exogenous biliverdin (25 μM) ($n=263$, 326, 367 and 473 neurons for iRFP682, miRFP, NIR-GECO1 and NIR-GECO1 + biliverdin, respectively, from two cultures). The dynamic ranges of these images have been normalized to facilitate visual comparison of protein localization. Fluorescence brightness quantification provided in **g**. Scale bar, 50 μm. **g**, Relative fluorescence intensity for neurons shown in **f** (BV, biliverdin). Box plots with notches are used. The narrow part of notch is the median; the top and bottom of the notch denote the 95% confidence interval of the median; the horizontal line is the mean; the top and bottom horizontal lines are the 25th and 75th percentiles for the data; and the whiskers extend 1×1.5 the interquartile range from the 25th and 75th percentiles. **h**, Photobleaching curves for iRFP682, miRFP and NIR-GECO1 ($n=84$, 69 and 88 neurons, respectively, from two cultures; 631/28 nm Ex at 38 mW mm^{-2}; solid lines represent mean value, shaded areas represent s.d.). **i**–**l**, NIR-GECO1 response amplitude (**i**), signal-to-noise ratio (SNR) (**j**), rise time (actually a fluorescence decrease) for Ca^{2+} binding (**k**) and decay time (actually a fluorescence increase) for Ca^{2+} dissociation (**l**), as a function of the number of field stimulation-induced action potentials. Center values are the mean, and error bars are s.e.m. $n=55$ neurons.

2.5-fold lower than that of iRFP682 (Fig. 1g). Administration of 25 μM exogenous biliverdin for 3 h resulted in an approximately fivefold increase in the NIR-GECO1 baseline fluorescence (Fig. 1g), indicating that ~80% of NIR-GECO1 was not bound to biliverdin. The addition of biliverdin also resulted in a slight increase in the mean value of the NIR-GECO1 fluorescence changes during spontaneous activity (16 ± 6% versus 20 ± 8% $-\Delta F/F_0$ for NIR-GECO1 and NIR-GECO1 + biliverdin, respectively; mean ± s.d. throughout; Supplementary Fig. 7a,b). This biliverdin-free fraction is not fluorescent but presumably participates in contra-productive Ca^{2+} buffering. Coexpression of heme-oxygenase 1 (HO1) with NIR-GECO1[6] resulted in only a 1.4-fold enhancement of fluorescence intensity (Supplementary Fig. 7c,d). Under continuous wide-field illumination at 38 mW mm^{-2} (about two to four times higher than typically used for NIR-GECO1 imaging), the photobleaching rate of NIR-GECO1 was approximately fourfold higher than those of miRFP and iRFP682 (Fig. 1h and Supplementary Table 1).

To characterize the fluorescence response of NIR-GECO1 to electric field stimulation-evoked action potentials, we delivered field stimuli (50 V, 83 Hz, 1 ms) in trains of 1, 2, 3, 5, 10, 20, 40, 80, 120 and 160 to transfected neurons (Supplementary Fig. 8a). The resulting fluorescence changes, recorded from cell bodies, revealed that $-\Delta F/F_0$, SNR, rise time and decay time all increased with the number of stimuli (Fig. 1i–l). Relative to GCaMP3, NIR-GECO1 has similar $-\Delta F/F_{min}$ for 1–10 action potentials and an approximately twofold higher SNR, but these values are around tenfold lower than those for GCaMP6s (Supplementary Fig. 9a–d). The near-linear stimulus response over the range of approximately 2–40 stimuli is consistent with the near-unity Hill coefficient[11]. In cells, the rise and decay times of NIR-GECO1 appeared substantially slower than those of GCaMP6s. This observation is inconsistent with the fast Ca^{2+}-dissociation kinetics measured in vitro (Ca^{2+}-dissociation kinetic constant $k_{off}=1.93\ s^{-1}$ for NIR-GECO1 versus 1.08 s^{-1} for GCaMP6s; Supplementary Fig. 6b). With no targeting sequence attached, NIR-GECO1 distributes throughout the cytoplasm and nucleus. Measuring from the cell body, we found that nuclear-excluded NIR-GECO1 (NES-NIR-GECO1) exhibited similar kinetics as NIR-GECO1, ruling out slow Ca^{2+} diffusion in and out of the nucleus as an explanation for slower response kinetics (Supplementary Fig. 9c,d). When coexpressed in cultured neurons, NIR-GECO1 and GCaMP6s both reported spontaneous oscillations in Ca^{2+} concentration with opposite fluorescence changes (Supplementary Fig. 9e,f).

To evaluate in vivo expression of NIR-GECO1, we induced expression of the gene in layer 2/3 (L2/3) of mouse motor cortex via in utero electroporation (IUE). Imaging of brain slices revealed fluorescence through neuronal cell bodies and processes (Fig. 2a and Supplementary Fig. 8b) and no punctate structures. Stimulation of action potentials with whole-cell patch-clamp electrophysiology gave $-\Delta F/F_0$ of 7.2 ± 2.8%, 13.4 ± 3.8% and 27.6 ± 2.8% for 5, 10 and 20 action potentials, respectively (Fig. 2b, Supplementary Fig. 8c). Stimulation of neuronal activity with 4-aminopyridine resulted in mean maximal $-\Delta F/F_0$ of ~20% and mean averaged $-\Delta F/F_0$ of ~10% (Fig. 2c,d). To determine whether NIR-GECO1 could be used for one-photon in vivo imaging, we injected adeno-associated virus (AAV) carrying the NIR-GECO1 gene (AAV2/9-hSyn1-NIR-GECO1) in the sensorimotor cortex of mice. Mesoscale fluorescence imaging through the intact skin (hair removed) and skull of anesthetized mice during two paradigms of paw stimuli revealed transient stimuli- and NIR-GECO1-dependent fluorescence changes (decreases) of approximately 0.3% (Fig. 2e–g, Supplementary Figs. 10 and 11 and Supplementary Videos 1 and 2). Under similar conditions, GCaMP6s exhibited approximately tenfold greater fluorescence changes (increases). We attribute the better performance of GCaMP6s to its inherently larger Ca^{2+}-dependent fluorescence response (×30 versus ×8 under identical conditions; Supplementary Table 1), its higher Hill coefficient (2.4 versus 1.0) and lower K_d (144 versus 215 nm) that has been empirically optimized for neuronal activity imaging.

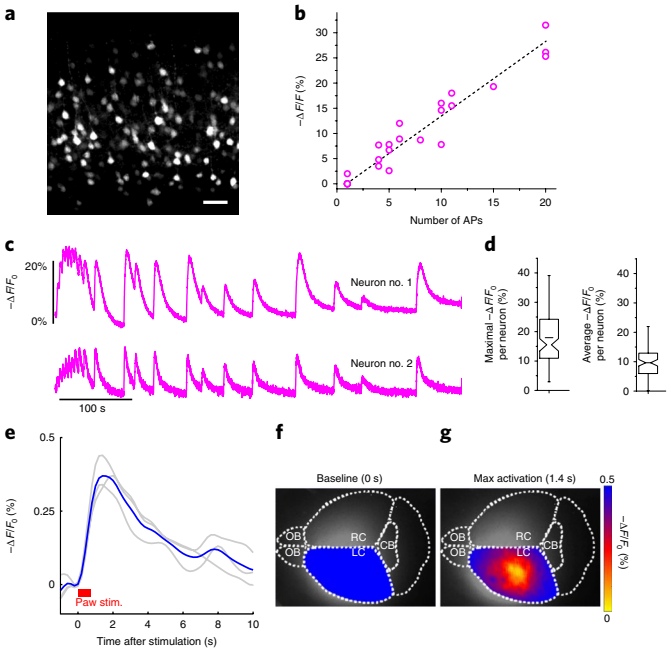

Fig. 2 | Imaging of in vivo expressed NIR-GECO1. a, Representative confocal image of live brain slice expressing NIR-GECO1 (641 nm Ex; 664LP Em; $n = 4$ slices from two mice at P11–22). Scale bar, 50 µm. **b**, NIR-GECO1 fluorescence responses to action potential (AP) trains evoked by current injections ($n = 6$ neurons from four mice at P11–22; dashed line indicates linear regression). **c**, Single-trial wide-field imaging of 4-aminopyridine (1 mM final concentration) evoked neuronal activity from the cell bodies of two representative neurons (631/28 nm Ex and 664LP Em; acquisition rate 20 Hz; $n = 129$ neurons from two slices from one mouse). **d**, Maximal (left) and average (right) $-\Delta F/F_0$ for the experiment of **c**. Box plots are used as described in Fig. 1g. For experiments in **a–d**, NIR-GECO1 was expressed in vivo by IUE at E15.5. **e–g**, In vivo mesoscale imaging of foot-shock responses in mouse sensorimotor cortex. Three mice (4 weeks old) were injected with AVV2/9-hSyn1-NIR-GECO1 in either the right or the left side of the brain and imaged (671 nm Ex; 721/42 nm Em) 10–21 d later. **e**, Response to a paw stimulation paradigm of ten pulses in 700 ms (0.5 mA, 20 ms on and 50 ms off). Each gray line represents the averaged response of a mouse across 19 cycles, and the blue line represents the mean response from all three mice ($n = 3$; that is, 57 cycles). **f**, Activation map of mouse brain, injected in left cortex, before stimulation. Diffuse fluorescence in the right cortex is attributed to diffusion of viral particles and light scattering. **g**, Activation map of mouse brain at max activation 1.4 s after stimulation. Scale bar, 2 mm. OB, olfactory bulb; CB, cerebellum; L/RC, left or right cortex.

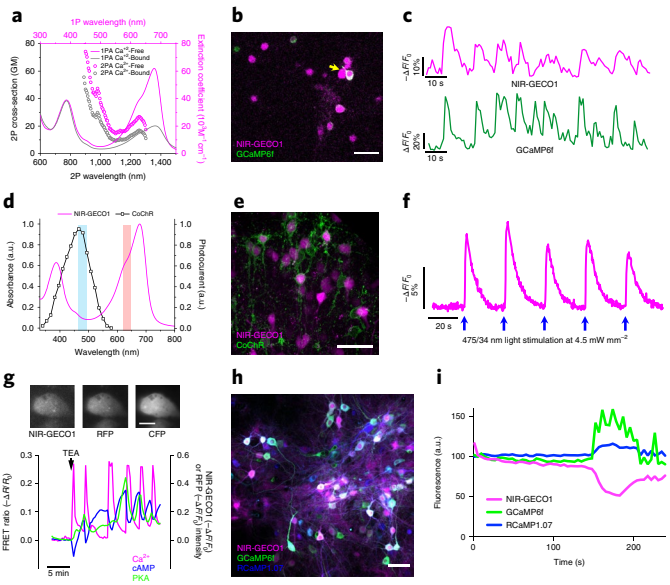

Fig. 3 | Spectral multiplexing of NIR-GECO1 with optogenetic indicators and actuators. a, One-photon (solid line; identical to Fig. 1c) and two-photon (open circles) absorption spectra of NIR-GECO1 in the presence and absence of Ca^{2+}. Two-photon absorption spectra are presented versus laser wavelength used for excitation. GM, Goeppert–Mayer units. **b**, Representative fluorescence image of cultured neurons expressing NIR-GECO1 (magenta) and GCaMP6f (green) acquired under two-photon excitation (imaging condition: NIR-GECO1 1,250 nm Ex, 705/90 nm Em; GCaMP6f 920 nm Ex, 518/45 nm Em; $n = 2$ cultures). Scale bar, 50 µm. **c**, Representative single-trial fluorescence recording of 4-aminopyridine (1 mM final concentration) evoked neuronal activity using NIR-GECO1 and GCaMP6f under imaging conditions as in **b** ($n = 32$ neurons from two cultures; yellow arrow indicates the neuron the fluorescence traces were obtained from; image acquisition rate, 1 Hz). **d**, Action spectrum of channelrhodopsin from *Chloromonas oogama* (CoChR) (black line; adapted with permission from ref. [12]) and NIR-GECO1 absorbance spectrum (magenta line; identical to Fig. 1c with no free Ca^{2+}) with wavelengths used for CoChR activation (475/34 nm; cyan bar) and NIR-GECO1 excitation (638/14 nm; orange bar). **e**, Representative confocal images of neurons in L2/3 of motor cortex coexpressing NIR-GECO1 (magenta) and CoChR-mTagBFP2-Kv2.2$_{motif}$ (green) targeted by IUE at E15.5 (imaging conditions: NIR-GECO1 641 nm Ex, 664LP Em; CoChR-mTagBFP2-Kv2.2$_{motif}$ 405 nm Ex and 452/45 nm Em). Scale bar, 50 µm. **f**, Single-trial wide-field imaging of NIR-GECO1 responses to CoChR activation (fluorescence excitation and activation as in **d**; 664LP Em; blue arrows, CoChR stimulation with 200 ms light pulses; image acquisition rate 5 Hz). Similar results were obtained with CheRiff[20] (Supplementary Fig. 13d,e). **g**, Top, representative fluorescence images of MIN6 β-cell coexpressing AKAR4 (left, 420/20 nm Ex and 475/40 nm Em for CFP and 535/25 nm Em for YFP), *NIR-GECO1* (middle, 640/30 nm Ex and 700/75 nm Em) and Pink Flamindo[16] (right, 555/25 nm Ex and 605/52 nm Em). Scale bar, 10 µM. Bottom, simultaneous visualization of Ca^{2+} (*NIR-GECO1*; $-\Delta F/F_0$, magenta line), cyclic AMP (Pink Flamindo; $\Delta F/F_0$, blue line), and PKA (AKAR4; FRET emission ratio $\Delta R/R_0$, green line) in a MIN6 cell treated with 20 mM tetraethylammonium chloride (TEA) at $t = 0$ (arrow). Traces for four additional representative cells are provided in Supplementary Fig. 14. **h**, Representative overlaid fluorescence image of dissociated neurons coexpressing NIR-GECO1, GCaMP6f and RCaMP1.07. **i**, Simultaneous detection of spontaneous neuronal activity reported by GCaMP6f, RCaMP1.07 and NIR-GECO1, in a single cell as in **h**. The percentage of responding cells (during a 3-min imaging session) was 92% for GCaMP6f ($n = 271$ neurons), 79% for RCaMP1.07 ($n = 178$ neurons) and 59% for NIR-GECO1 ($n = 331$ neurons).

Owing to its spectrally distinct fluorescence, NIR-GECO1 should be particularly useful for in vitro imaging in combination with optogenetic actuators and fluorescent-protein-based indicators. To explore such applications, we attempted two-photon imaging of NIR-GECO1 and GCaMP6f. NIR-GECO1 two-photon brightness at both 1,250 nm and 880 nm excitation is sufficient to image neurons in culture and in mouse brain tissue ex vivo and in vivo (Fig. 3a,b and Supplementary Fig. 12). With 1,250-nm excitation we observed neuronal-activity-dependent changes in NIR-GECO1 fluorescence in cultured neurons, as confirmed by coexpression of GCaMP6f, with average $-\Delta F/F_0$ of 48 ± 28% ($n = 37$ neurons from one culture; Fig. 3c). With two-photon excitation at 880 nm (11.4 mW of total light power), both the intracellular brightness and the photostability of NIR-GECO1 ($t_{1/2} = 20$ s) were slightly higher than those of miRFP, but lower than those of iRFP682 (Supplementary

Fig. 12a,b). However, when we used 880-nm excitation, we did not observe characteristic fluorescence changes of NIR-GECO1 associated with neuronal Ca^{2+} dynamics in neurons either in culture or in live brain slices (Supplementary Fig. 12c). We have not succeeded in demonstrating in vivo imaging of neuronal activity using NIR-GECO1 with either 880-nm or 1,250-nm two-photon excitation.

To explore the combined use of NIR-GECO1 and an optogenetic actuator, we prepared live brain slices expressing NIR-GECO1 and the high-photocurrent channelrhodopsin CoChR[12,13] (Fig. 3d). Activation of CoChR with cyan-colored light produced Ca^{2+} transients that were reliably reported by NIR-GECO1 (Fig. 3e,f), and there was no evidence of photophysical artifacts attributable to the illumination conditions (Supplementary Fig. 13a–c)[14].

To demonstrate NIR-GECO1's utility for use with fluorescent-protein-based indicators, we performed three-indicator (four-color) imaging using NIR-GECO1, the cyan- and yellow-fluorescent-protein-based protein kinase A indicator AKAR4[15] and the red-fluorescent-protein-based cAMP indicator Pink Flamindo[16]. Pharmacological stimulation of Ca^{2+} oscillations in MIN6 β-cells in vitro led to rapid and synchronous oscillations in Ca^{2+}, cAMP and PKA activity (Fig. 3g, Supplementary Fig. 14 and Supplementary Video 3). Coexpression of NIR-GECO1 with GCaMP6f[17] and RCaMP1.07[18] enabled three-color in vitro imaging of spontaneous neuronal activity (Fig. 3h,i and Supplementary Video 4).

We have demonstrated that NIR-GECO1 is a useful new addition to the GECI palette. As a first-generation indicator, NIR-GECO1 falls short of the most extensively optimized fluorescent-protein-based GECIs in several critical performance parameters. Accordingly, NIR-GECO1 is not generally useful for in vivo imaging of neuronal activity. However, NIR-GECO1 does provide a robust inverse response to Ca^{2+} concentration changes in cultured cells, primary neurons and acute slices roughly on par with GCaMP3. In addition, because of its highly red-shifted excitation maximum, it is the preferred Ca^{2+} indicator for pairing with blue-light-activated optogenetic actuators, to minimize actuator activation during imaging[19]. Finally, it creates a multitude of new opportunities for multiparameter imaging in conjunction with multiple fluorescent-protein-based intensiometric or ratiometric FRET-based indicators.

As with many BV-FPs, NIR-GECO1 is substantially dimmer than state-of-the-art fluorescent-protein-derived GECIs such as GCaMP6s (10.7 times brighter)[17] and jRGECO1a (three times brighter)[19]. To enable general utility for in vivo imaging, future iterations of NIR-GECO1 should be optimized for brighter fluorescence (for example, improved biliverdin-binding efficiency could provide up to an approximately fivefold increase), increased affinity for Ca^{2+}, increased photostability and faster kinetics. We expect NIR-GECO1 to be just as amenable to further improvements as the GCaMP series, and for these advancements to be soon realized through protein-engineering efforts.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41592-018-0294-6.

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Author contributions

Y.Q. developed NIR-GECO1 and performed in vitro characterization. Y.Q., K.D.P., A.S.A. and M.H.M. performed characterization in hippocampal neurons. K.D.P. and M.H.M. characterized NIR-GECO1 in intact brain slices. B.M.L. and S.G. performed in vivo mesoscale imaging. S.M. performed live-cell imaging in MIN6 β-cells. R.S.M. and M.D. measured two-photon spectra. W.Z. built the pcDuEx2 vector. Y.C. and J.W. worked on development of the smURFP-based GECI. M.D., T.E.H., J.Z., E.R.S., S.S., D.R., E.S.B. and R.E.C. supervised research. All authors were involved in data analysis. Y.Q., K.D.P. and R.E.C. wrote the manuscript.

Competing interests

The University of Alberta has non-exclusively licensed NIR-GECO1 to LumiSTAR Biotechnology.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41592-018-0294-6.

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Methods

General methods and materials. Synthetic DNA oligonucleotides were purchased from Integrated DNA Technologies. Q5 high-fidelity DNA polymerase (New England Biolabs) was used for routine PCR amplifications, and Taq DNA polymerase (New England Biolabs) was used for error-prone PCR. The QuikChange mutagenesis kit (Agilent Technologies) was used for site-directed mutagenesis. Restriction endonucleases, rapid DNA ligation kits and GeneJET miniprep kits were from Thermo Fisher Scientific. PCR products and products of restriction digests were purified using agarose gel electrophoresis and the GeneJET gel extraction kit (Thermo Fisher Scientific). All DNA sequences were confirmed using the BigDye Terminator v.3.1 cycle sequencing kit (Applied Biosystems). Reactions were analyzed at the University of Alberta Molecular Biology Service Unit. Absorbance measurements were made with a DU-800 UV-visible spectrophotometer (Beckman), and fluorescence spectra were recorded on a Safire2 platereader (Tecan).

Engineering of NIR-GECO1. The gene encoding mIFP (a gift from Michael Davidson and Xiaokun Shu; Addgene plasmid no. 54,620)[6] was inserted between BamH1 and EcoR1 of a pBAD vector (Life Technologies) that expressed cyanobacteria *Synechocystis* HO-1 to convert an endogenous heme in bacteria into biliverdin, as previously described[3,21].

The DNA sequence encoding CaM and RS20 (a peptide that corresponds to the CaM-binding peptide of smooth muscle myosin light chain kinase; VDSSRRKWNKAGHAVRAIGRLSS) portions of REX-GECO1 (ref. [22]), with mutations Q306D and M339F borrowed from jRGECO1a[19], were genetically fused by overlap extension PCR using a DNA sequence that encodes for the flexible peptide linker GGGGS[23].

For each site (X) of mIFP targeted for CaM-RS20 insertion, the full-length gene (encoding $mIFP_{1\ to\ X}$-CaM-RS20-$mIFP_{X+1\ to\ 320}$) was assembled by overlap extension PCR and then inserted into the pBAD vector. Variants were expressed in *E. coli* strain DH10B (Thermo Fisher Scientific) in LB media supplemented with 100 μg ml^{-1} ampicillin and 0.0016% L-arabinose. Proteins were extracted using B-PER bacterial protein extraction reagent (Thermo Fisher Scientific) and tested for fluorescence brightness and Ca^{2+}-dependent response.

The most promising variant was subjected to an iterative process of library generation and screening in *E. coli*. The pBAD vector was used in the first three rounds. From the fourth round, pcDuEx2 was used to enable expression in both *E. coli* and mammalian cells. Libraries were generated by error-prone PCR of the whole gene[24] or site-directed mutagenesis using Quikchange (Agilent Technologies) and degenerate codons at the targeted positions.

For libraries generated by random mutagenesis, approximately 10,000 colonies were screened in a given round. For libraries generated by randomization of one or more codons, a number of colonies that was approximately threefold the theoretical number of gene variants were screened. For each round, the top 2% of colonies with high fluorescence intensity were picked, cultured and tested on 396-well plates. Approximately 25% of those picked variants were further screened in HeLa cells on the basis of fluorescence. In a given round, screening was stopped when a substantially improved variant was identified. There were 12 rounds of screening before NIR-GECO1 was identified.

NIR-GECO1 expression vectors. pcDuEx2 was constructed based on the pcDNA3.1 backbone. The Tac promoter and a gene sequence containing Kpn2I and XbaI sites was inserted immediately after the CMV promoter by overlap extension PCR. A DNA fragment containing the T7 promoter, the gene encoding NIR-GECO1 and the gene encoding HO-1 was amplified from the pBAD vector and inserted into the Kpn2I and XbaI sites.

For HeLa cell expression, the pcDuEx2 vector was used. For expression in dissociated neurons, either an AAV2 vector or a lentivirus containing NIR-GECO1 was used. For AAV2 vector preparation, NIR-GECO1 was cloned from pcDuEx2 into BamHI and HindIII sites of an AAV2 vector (a gift from Roger Tsien; Addgene plasmid no. 50970)[25]. To create lentivirus expressing NIR-GECO1, the gene for NIR-GECO1 or NIR-GECO1-T2A-HO1 was cloned into the BamHI and EcoRI sites of FCK lentivirus vector (Addgene plasmid no. 22217). HEK293FT cells at 80% confluency in 35-mm cell-culture dishes (Corning) were transfected with 1.5 μg of FCK-CMV-NIR-GECO1 or FCK-CMV-NIR-GECO1-T2A-HO1, 1.0 μg of psPAX2 (a gift from D. Trono; Addgene plasmid no. 12,260), 0.5 μg of pMD2.G (a gift from D. Trono; Addgene plasmid no. 12,259) and 0.2 μg of pAdvantage (Promega), with 9 μl of Turbofect transfection reagent in 2 ml of Opti-MEM medium (Thermo Fisher Scientific). Opti-MEM medium containing Turbofect and DNA mix were replaced with 2 ml of complete cell-culture medium containing 110 mg ml^{-1} sodium pyruvate at 24 h post-transfection. At 48 h post-transfection, the virus-containing supernatant was collected, spun at 400*g* (relative centrifugal force) for 5 min and filtered through a 0.45-μm PVDF syringe filter unit (EMD Millipore) to get rid of pellet cellular debris. Dissociated neurons in 24-well plates were transduced with 2 ml of virus-containing supernatant.

Protein purification and in vitro characterization. The gene encoding NIR-GECO1, with a poly-histidine tag on the C terminus, was expressed from the pBAD vector. Bacteria were lysed with a cell disruptor (Constant Systems Ltd) and then centrifuged at 15,000*g* for 30 min, and proteins were purified by Ni-NTA affinity chromatography (Agarose Bead Technologies). The buffer was typically exchanged to 10 mM MOPS, 100 mM KCl (pH 7.2) with centrifugal concentrators (GE Healthcare Life Sciences). We determined extinction coefficients by comparing the absorbance value at 678 nm to the absorbance value at the 391 nm and assuming an extinction coefficient of 39,900 $M^{-1}cm^{-1}$ at 391 nm[2,6]. For determination of quantum yields (Φ), purified mIFP (Φ = 0.08) was used as a standard. The concentration of NIR-GECO1 (Ca^{2+}-free), NIR-GECO1 (Ca^{2+}-saturated) and mIFP was adjusted to have absorbance of 0.2–0.6 at 650 nm. A series of dilutions, with absorbance ranging from 0.01 to 0.05, were prepared, and integrated emission intensity versus absorbance was plotted. Quantum yields were determined from the slopes (*S*) of each line using the equation $\Phi_{protein} = \Phi_{standard} \times (S_{protein}/S_{standard})$. We carried out pH titrations by diluting protein into buffers (pH from 2 to 11) containing 30 mM trisodium citrate, 30 mM sodium borate and either 10 mM $CaCl_2$ or 10 mM EGTA. Fluorescence intensities as a function of pH were then fitted by a sigmoidal binding function to determine the apparent pK_a. Ca^{2+} titrations were carried out using EGTA-buffered Ca^{2+} solutions (Calcium Calibration Buffer Kit no. 1, Life Technologies). We prepared buffers by mixing a CaEGTA buffer (30 mM MOPS, 100 mM KCl, 10 mM EGTA, 10 mM $CaCl_2$) and an EGTA buffer (30 mM MOPS, 100 mM KCl, 10 mM EGTA) to give free Ca^{2+} concentrations ranging from 0 nm to 39 μM at 25 °C. Fluorescence intensities were plotted against Ca^{2+} concentrations and fitted by a sigmoidal binding function to determine the Hill coefficient and K_d. To determine k_{off}, we used an SX20 stopped-flow spectrometer (Applied Photophysics). Briefly, protein samples with 10 μM $CaCl_2$ (30 mM MOPS, 100 mM KCl, pH 7.2) were rapidly mixed with 10 mM EGTA (30 mM MOPS, 100 mM KCl, pH 7.2) at room temperature, and an absorption growth curve was measured and fitted by a single exponential equation.

Two-photon spectra and cross-sections were measured using femtosecond excitation as described in Supplementary Note 2.

Animal care. For experiments performed at Massachusetts Institute of Technology (MIT), all methods for animal care and use were approved by the MIT Committee on Animal Care and were in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals. Four time pregnant Swiss Webster mice (Taconic) were used for this study, as were five C57BL/6 mice (Taconic), ages 4–12 weeks. Mice were used without regard to gender.

For experiments performed at Technical University of Munich, all animal in vivo experimentation was done in full compliance with the institutional guidelines of the Institute for Biological and Medical Imaging and with approval from the Government District of Upper Bavaria. A total of 12 mice were used for these experiments: 3 female FOXN1 nude mice that were injected with the NIR-GECO1 virus, 3 female FOXN1 nude mice that were injected with the miRFP virus, 3 female Black6 (C57BL/6J) transgenic mice expressing GCaMP6s, and 3 mice (2 female FOXN1 and 1 female Black6) that were injected with PBS as negative controls.

All experiments at University of Alberta for obtaining the cortical neurons were approved by the University of Alberta Animal Care and Use Committee and carried out in compliance with guidelines of the Canadian Council for Animal Care and the Society for Neuroscience's Policies on the Use of Animals and Humans in Neuroscience Research.

For experiments at HHMI Janelia Research Campus, all surgical and experimental procedures were in accordance with protocols approved by the HHMI Janelia Research Campus Institutional Animal Care and Use Committee and Institutional Biosafety Committee.

Imaging of NIR-GECO1 in HeLa cells and dissociated neuron cultures. HeLa cells (40–60% confluent) in 24-well glass-bottom plates (Cellvis) were transfected with 0.5 μg of the NIR-GECO1-pcDuEx2 plasmid and 2 μl of TurboFect (Thermo Fisher Scientific) in Dulbecco's modified Eagle's medium (DMEM; Gibco Fisher Scientific). Following 2 h of incubation, the media was changed to DMEM supplemented with 10% fetal bovine serum (FBS; Sigma-Aldrich), 2 mM GlutaMax (Thermo Fisher Scientific) and 1% penicillin–streptomycin (Gibco). The cells were then incubated for 48 h at 37 °C in a CO_2 incubator. Before imaging, culture medium was changed to Hanks' Balanced Salt Solution (HBSS).

For dissociated hippocampal mouse neuron culture preparation, postnatal day 0 or 1 Swiss Webster mice (Taconic Biosciences) were used as previously described[10]. Briefly, dissected hippocampal tissue was digested with 50 units of papain (Worthington Biochem) for 6–8 min at 37 °C, and the digestion was stopped by incubation with ovomucoid trypsin inhibitor (Worthington Biochem) for 4 min at 37 °C. Tissue was gently dissociated with Pasteur pipettes, and dissociated neurons were plated at a density of 20,000–30,000 per glass coverslip coated with Matrigel (BD Biosciences). Neurons were seeded in 100 μl of plating medium containing MEM (Life Technologies), glucose (33 mM; Sigma), transferrin (0.01%; Sigma), HEPES (10 mM; Sigma), Glutagro (2 mM; Corning), insulin (0.13%; Millipore), B27 supplement (2%; Gibco) and heat-inactivated FBS (7.5%; Corning). After cell adhesion, additional plating medium was added. AraC (0.002 mM; Sigma) was added when glia density was 50–70% of confluence. Neurons were grown at 37 °C and 5% CO_2 in a humidified atmosphere. We

transduced cultured neurons at 4–5 days in vitro (DIV) by administering ~10^{10} viral particles of rAAV8-hSyn-iRFP682, rAAV8-hSyn-miRFP (both from Vector Core, University of North Carolina) or rAAV9-hSyn-NIR-GECO1 (Department of Biochemistry and Microbiology, University of Laval) per well (the rAAV genome titer was determined by dot blot). For coexpression of the GECIs, the rAAV8-hSyn-GCaMP6f, rAAV8-hSyn-RCaMP1.07 (both from Vector Core, University of North Carolina) and rAAV9-hSyn-NIR-GECO1 viral particles were added in a 1/1/3 ratio, respectively. A biliverdin hydrochloride (Sigma-Aldrich) solution in dimethylsulfoxide (25 mM) was used as a 1,000× stock (25 µM final concentration) for the experiments shown in Fig. 1g and Supplementary Fig. 7a,b. All measurements on neurons were taken after DIV 16.

For dissociated rat cortical neuron culture preparation, postnatal day 0 or 1 Sprague Dawley rats were used. Dissected cortices were digested in Papain solution (50 units; Sigma) for 10 min at 37 °C and then incubated with DNase (0.15 mg ml^{-1}; Sigma) for 5 min at 37 °C. After washing the tissue with FBS (Sigma) and removing supernatant, we added neurobasal B27 (Thermo Fisher Scientific) to tissue. Tissue was then gently dissociated with Pasteur pipettes, and dissociated neurons were plated at a density of ~1.5×10^5 on collagen-coated 24-well glass-bottom dishes containing NbActiv4 culture medium (BrainBits LLC) supplemented with 2% FBS, penicillin-G potassium salt (50 units per ml), and streptomycin sulfate (50 mg ml^{-1}). Half of the culture media was replaced every 4–5 d. Neuronal cells were infected using the NIR-GECO1 lentivirus on day 8. Before imaging, the culture medium was changed to HBSS.

Wide-field fluorescence imaging of cultured neurons was performed using an epifluorescence inverted microscope (Eclipse Ti-E, Nikon) equipped with a Photometrics QuantEM 512SC camera and a 75-W Nikon xenon lamp or a Zyla5.5 sCMOS (scientific complementary metal-oxide semiconductor) camera (Andor) and a SPECTRA X light engine (Lumencor). NIS-Elements Advanced Research (Nikon) was used for automated microscope and camera control. Cells were imaged with 60×/1.49-NA (numerical aperture) oil or 20×/0.75-NA air objective lenses (Nikon) at room temperature. For dual-color imaging with GCaMP6s, NIR (650/60 nm Ex and 720/50 nm Em) and green (490/15 nm Ex and 525/50 nm Em) filter sets were rotated into the emission light path. Three-color Ca imaging with GCaMP6f and RCaMP1.07 was performed using an inverted Nikon Eclipse Ti microscope equipped with a spinning disk sCSUW1 confocal scanner unit (Yokogawa), 488-, 561- and 642-nm solid state lasers, 525/25-nm, 579/34-nm and 664LP emission filters, a 20×/0.75-NA air objective lens (Nikon) and a 4.2 PLUS Zyla camera (Andor), controlled by NIS-Elements AR software. One cautionary note for confocal imaging is that gallium-arsenide-phosphide photomultiplier tube detectors have poor sensitivity at wavelengths greater than 700 nm.

Two-photon imaging (as shown in Fig. 3b,c and Supplementary Fig. 12c) was performed using an Olympus FVMPE-RS equipped with two lasers for fluorescence excitation. An InSight X3 laser (Spectra-Physics) tuned to 1,250 nm at 8.0% transmissivity was used to excite NIR-GECO1, and a Mai-Tai HP Ti:Sapphire laser (Spectra-Physics) tuned to 920 nm at 17.4% transmissivity was used to excite GCaMP6f. The laser beams were focused by a 25×/1.05-NA water-immersion objective lens (Olympus). NIR-GECO1 emission was separated using a 660–750-nm filter, GCaMP6f emission was separated using a 495–540-nm filter, and signals were collected onto separate photomultiplier tubes. Imaging was performed at a sampling speed of 2.0 µs per pixel with one-way galvano scanning. Raw scanner data were converted to an image z-stack using ImageJ (NIH).

Two-photon imaging for Supplementary Fig. 12a,b,d–f was performed using a two-photon laser scanning microscope (Ultima IV, Prairie Technologies) with a mode-locked Ti-Sapphire laser (Mai-Tai, Spectra-Physics) and a 16×/0.8-NA water-immersion objective (CFI75 LWD 16; Nikon). For image acquisition, the laser was set to emit 880 nm at a total light power of 11.4 mW, and 535/50-nm and 731/137-nm emission filters (Semrock) were used. The microscope was operated using the ScanImage 3.8 software package[26].

Electrophysiology and Ca^{2+} imaging in dissociated hippocampal neurons. The genes encoding NIR-GECO1 and GCaMP6s were expressed under the control of a synapsin promoter in cultured rat hippocampal neurons. Neurons were stimulated using a custom-built field stimulator using a stimulus isolator (A385, World Precision Instruments) with platinum wires. Field stimuli (50 V, 83 Hz, 1 ms) were delivered in trains of 1, 2, 3, 5, 10, 20, 40, 80, 120 and 160 to the cultured neurons. Neurons were imaged using a Nikon Eclipse Ti2 inverted microscope equipped with a 40×/1.4-NA objective (Nikon). A quad bandpass filter (set number, 89,000; Chroma) was used along with a 480-nm light-emmitting diode (LED) (Spectra X light engine, Lumencor) or a 640-nm LED (Spectra X light engine, Lumencor) to image GCaMP6s or NIR-GECO1, respectively. Fluorescence was collected using an sCMOS camera (Orca-Flash4.0, Hamamatsu) at 34 Hz. For GCaMP6s, the response amplitude ($\Delta F/F_{min}$) was quantified as the change in fluorescence divided by baseline fluorescence over the 0.5-s period preceding the stimulus. For NIR-GECO1, the response amplitude was quantified as the change in fluorescence divided by peak fluorescence during the stimulus ($-\Delta F/F_{min}$). SNR was quantified as the peak change in fluorescence over the s.d. of the signal over the 0.5-s period preceding stimulation.

Multiplexed live-cell imaging with NIR-GECO1 in MIN6 β-cells. MIN6 pancreatic β-cells were cultured in DMEM containing 4.5 g l^{-1} glucose, supplemented with 10% (v/v) FBS, 1% (v/v) Pen-Strep and 50 µM β-mercaptoethanol, and maintained at 37 °C with a 5% CO_2 atmosphere. Cells were plated onto 35-mm glass-bottom dishes, grown to 40–60% confluence and then transfected with 0.5 µg each of plasmids encoding AKAR4[15], Pink Flamindo[16] and NIR-GECO1 using Lipofectamine 2000 (Invitrogen). After 48 h, cells were washed twice with HBSS (Gibco) and imaged in HBSS at 37 °C using a Zeiss AxioObserver Z1 inverted epifluorescence microscope (Carl Zeiss) equipped with a 40×/1.3-NA objective, a Lambda 10–2 filter-changer (Sutter Instruments) and a Photometrics Evolve 512 EMCCD (electron-multiplying charge-coupled device) (Photometrics) controlled by METAFLUOR v.7.7 software (Molecular Devices). Filters for cyan/yellow emission ratio were a 420DF20 excitation filter, a 450DRLP dichroic mirror and two emission filters (475DF40 for CFP and 535DF25 for YFP). Filters for RFP were a 555DF25 excitation filter, a ZT568RDC dichroic mirror and a 605DF52 emission filter. Filters for NIR-GECO1 were a 640DF30 excitation filter, a 700DF75 excitation filter and a T660LPXR dichroic mirror. Exposure times ranged between 50 and 500 ms, with EM gain set from 10–50, and images were acquired every 20 s. Fluorescence intensities were corrected by background subtraction. The emission ratio change ($R - R_0$) or fluorescence intensity change ($F - F_0$) was divided by the initial ratio or intensity to obtain $\Delta R/R_0$ or $\Delta F/F_0$, with time zero defined as the time point immediately preceding drug addition. Graphs were plotted using GraphPad Prism 7 (GraphPad Software).

In utero electroporation. Embryonic day (E) 15.5 timed-pregnant female Swiss Webster (Taconic) mice were deeply anesthetized with 2% isoflurane. Uterine horns were exposed and periodically rinsed with warm sterile PBS. A plasmid encoding NIR-GECO1 or a mixture of plasmids encoding NIR-GECO1 and CoChR (pCAG-NIR-GECO1-WPRE, pCAG-CoChR-mTagBFP2-Kv2.2motif-WPRE; at a total DNA concentration of ~1–2 µg µl^{-1}) diluted with PBS were injected into the lateral ventricle of one cerebral hemisphere of an embryo. Five voltage pulses (50 V, 50-ms duration, 1 Hz) were delivered using round plate electrodes (ECM 830 electroporator, Harvard Apparatus). Injected embryos were placed back into the dam, and allowed to mature to delivery. The P0 pups were screened for corresponding fluorescence and negative pups were excluded for further experiments. All experimental manipulations were performed in accordance with protocols approved by the Massachusetts Institute of Technology Committee on Animal Care, following guidelines described in the US National Institutes of Health Guide for the Care and Use of Laboratory Animals.

Acute brain slice preparation. Acute brain slices were obtained from Swiss Webster (Taconic) mice at P11 to P22, using standard techniques. Mice were used without regard for sex. No statistical methods were used to estimate sample size for animal studies throughout. No randomization or blinding were used for animal studies throughout. Mice were anaesthetized by isoflurane inhalation, decapitated and cerebral hemispheres were quickly removed and placed in cold choline-based cutting solution consisting of (in mM): 110 choline chloride, 25 $NaHCO_3$, 2.5 KCl, 7 $MgCl_2$, 0.5 $CaCl_2$, 1.25 NaH_2PO_4, 25 glucose, 11.6 ascorbic acid and 3.1 pyruvic acid (339–341 mOsm per kg; pH 7.75 adjusted with NaOH) for 2 min, blocked and transferred into a slicing chamber containing ice-cold choline-based cutting solution. Coronal slices (300 µm thick) were cut with a Compresstome VF-300 slicing machine, transferred to a holding chamber with artificial cerebrospinal fluid (ACSF) containing (in mM) 125 NaCl, 2.5 KCl, 25 $NaHCO_3$, 2 $CaCl_2$, 1 $MgCl_2$, 1.25 NaH_2PO_4 and 11 glucose (300–310 mOsm per kg; pH 7.35 adjusted with NaOH) and recovered for 10 min at 34 °C followed by another 30 min at room temperature. Slices were subsequently maintained at room temperature until use. Both cutting solution and ACSF were constantly bubbled with 95% O_2 and 5% CO_2.

Concurrent electrophysiology and Ca^{2+} imaging in acute brain slice. Slices were transferred to a recording chamber on an Olympus BX51WI upright microscope and superfused (2–3 ml min^{-1}) with ACSF at room temperature. Whole-cell patch-clamp recordings were acquired via an Axopatch 700B amplifier (Molecular Devices) and Digidata 1440 digitizer (Molecular Devices). For recordings, borosilicate glass pipettes (Warner Instruments) with an outer diameter of 1.2 mm and a wall thickness of 0.255 mm were pulled to a resistance of 3–5 MΩ with a P-97 Flaming/Brown micropipette puller (Sutter Instruments) and filled with a solution containing 155 mM K-gluconate, 8 mM NaCl, 0.1 mM $CaCl_2$, 0.6 mM $MgCl_2$, 10 mM HEPES, 4 mM Mg-ATP and 0.4 mM Na-GTP. The pipette solution pH was adjusted to 7.3 with KOH and the osmolarity was adjusted to 298 mOsm with sucrose. Cells were visualized through a 40×/0.8-NA water-immersion objective with epifluorescence. Whole-cell current-clamp recordings were obtained from NIR-GECO1-positive neurons in layer 2/3 of motor cortex. Fluorescence was excited by a SPECTRA X light engine (Lumencor) with 638/14-nm excitation filter (Semrock), fluorescence was collected through the same objective, passed through a 664 LP emission filter and imaged onto an Orca-Flash4.0 v.2 sCMOS camera (Hamamatsu) at 50-Hz acquisition frequency.

In vivo imaging of NIR-GECO1. Methods for in vivo two-photon imaging to acquire the image shown in Supplementary Fig. 12f are provided as Supplementary Note 3. Methods for in vivo mesoscale imaging to acquire data

and images shown in Fig. 2e–g and Supplementary Figs. 10 and 11 are provided as Supplementary Note 4.

Statistics and reproducibility. All data are expressed as mean ± s.d. or mean ± s.e.m., as specified in figure legends. Box plots with notches[27] are used for Figs. 1g and 2d and Supplementary Figs. 7b, 12a and 13c. In these plots, the narrow part of the notch is the median; the top and bottom of the notch denote the 95% confidence interval of the median; the horizontal line is the mean; the top and bottom horizontal lines are the 25th and 75th percentiles for the data; and the whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Sample sizes (n) are listed with each experiment. No samples were excluded from analysis and all experiments were reproducible. For experiments for which representative data are shown, the number of times each experiment was repeated independently with similar results is summarized in Supplementary Note 5. No randomization or blinding was used. All attempts at replication of the experiments were successful.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The NIR-GECO1 gene sequence is available through GenBank (submission no. MK134690). pDuEx2-NIR-GECO1 (plasmid no. 113,680) and pAAV-hSyn-NES-NIR-GECO1 (plasmid no. 113,683) are available via Addgene according to the terms of the Uniform Biological Material Transfer Agreement. Source data for Figs. 1–3 and Supplementary Figs. 5–14 are available online.

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When statistical analyses are reported, confirm that the following items are present in the relevant location (e.g. figure legend, table legend, main text, or Methods section).

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	An indication of whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
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☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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☐	☒	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

Our web collection on statistics for biologists may be useful.

Software and code

Policy information about availability of computer code

Data collection	Molecular Devices MetaMorph and MetaFluor 7.7, NIS-Elements AR software, LabView, Andor Solis 4.21, OLYMPUS FLUOView 3000
Data analysis	Graphpad Prism 6.0 and 7.0, Origin9, Microsoft Excel, Clampfit 10.7, MatLab2017b, ImageJ, MetaFluor 7.7

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

One page 15 of the Supplementary Material we state: "Data Availability. Gene sequence data will be deposited in GenBank with accession codes that are TBD. Plasmids will be distributed via Addgene according to the terms of the Uniform Biological Material Transfer Agreement. Source data for Figs. 1-2, and Supplementary Figs. 5-7, 9, 11 will be included in the final version of the paper."

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Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	On page 9 of Supplementary Material we state: "No statistical methods were used to estimate sample size for animal studies throughout. " As noted Dell et al ILAR. J (2002) and recommended by the NIH, "In experiments based on the success or failure of a desired goal, the number of animals required is difficult to estimate..." As noted in the aforementioned paper, "The number of animals required is usually estimated by experience instead of by any formal statistical calculation, although the procedures will be terminated [when the goal is achieved]." On page 15 of the Supplementary Material we include the following statement: "Statistical analysis. All data are expressed as mean ± s.d or mean ± s.e.m, as specified in figure legends. Box plots with notches19 are used for Figs. 1g, 2d, and Supplementary Figs. 7b, 12a and 13c. In these plots, the narrow part of notch is the median; the top and bottom of the notch is the 95% confidence interval of the median; the horizontal line is the mean; the top and bottom horizontal lines are the 25% and 75% percentiles for the data; and the whiskers extend 1.5× the interquartile range from the 25th and 75th percentiles. Sample sizes (n) are listed with each experiment. No samples were excluded from analysis and all experiments were reproducible. No randomization or blinding was used "
Data exclusions	P31. The P0 pups were screened for corresponding fluorescence, negative pups were excluded for further experiments.
Replication	P33. All attempts at replication were successful.
Randomization	P33. No randomization or blinding was used
Blinding	P33. No randomization or blinding was used

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study
☒	☐ Unique biological materials
☒	☐ Antibodies
☐	☒ Eukaryotic cell lines
☒	☐ Palaeontology
☐	☒ Animals and other organisms
☒	☐ Human research participants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Eukaryotic cell lines

Policy information about cell lines

Cell line source(s)	HeLa (ATCC), HEK293FT (Thermo Fisher Scientific), MIN6 (Miyazaki laboratory, Osaka University)
Authentication	Cell lines were not authenticated
Mycoplasma contamination	MIN6 cells were tested weekly for Mycoplasma using DNA staining. Other cell lines were not tested.
Commonly misidentified lines (See ICLAC register)	HEK293FT cells were used for production of lentivirus due to the following advantages: fast-growing, high transfection efficientcy and tolerance of high levels of proteins.

Animals and other organisms

Policy information about studies involving animals; ARRIVE guidelines recommended for reporting animal research

Laboratory animals	Pages 4 and 5 of Supplementary material. We state: "Animal care. For experiments performed at Massachusetts Institute of

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Technology (MIT), all methods for animal care and use were approved by the MIT Committee on Animal Care and were in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals. Four time pregnant Swiss Webster mice (Taconic) were used for this study, as were five C57BL/6 mice (Taconic), ages 4–12 weeks. Mice were used without regard to gender.
For experiments performed at Technical University of Munich, all animal in vivo experimentation was done in full compliance with the institutional guidelines of the Institute for Biological and Medical Imaging and with approval from the Government District of Upper Bavaria. A total of twelve mice were used for these experiments: three female FOXN1 nude mice that were injected with the NIR-GECO1 virus; three female FOXN1 nude mice that were injected with the miRFP virus; three female Black6 (C57BL/6J) transgenic mice expressing GCaMP6s and three mice (two female FOXN1 and one female Black6) that were injected with PBS as negative controls.
All experiments at University of Alberta for obtaining the cortical neurons were approved by the University of Alberta Animal Care and Use Committee and carried out in compliance with guidelines of the Canadian Council for Animal Care and the Society for Neuroscience's Policies on the Use of Animals and Humans in Neuroscience Research.
For experiments at HHMI Janelia Research Campus, all surgical and experimental procedures were in accordance with protocols approved by the HHMI Janelia Research Campus Institutional Animal Care and Use Committee and Institutional Biosafety Committee."

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The study did not involve wild animals.

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The study did not involve sample collected from the field.

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