

Left–right dissociation of hippocampal memory processes in mice

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Left–right asymmetries have likely evolved to make optimal use of bilateral nervous systems; however, little is known about the synaptic and circuit mechanisms that support divergence of function between equivalent structures in each hemisphere. Here we examined whether lateralized hippocampal memory processing is present in mice, where hemispheric asymmetry at the CA3–CA1 pyramidal neuron synapse has recently been demonstrated, with different spine morphology, glutamate receptor content, and synaptic plasticity, depending on whether afferents originate in the left or right CA3. To address this question, we used optogenetics to acutely silence CA3 pyramidal neurons in either the left or right dorsal hippocampus while mice performed hippocampus-dependent memory tasks. We found that unilateral silencing of either the left or right CA3 was sufficient to impair short-term memory. However, a striking asymmetry emerged in long-term memory, wherein only left CA3 silencing impaired performance on an associative spatial long-term memory task, whereas right CA3 silencing had no effect. To explore whether synaptic properties intrinsic to the hippocampus might contribute to this left–right behavioral asymmetry, we investigated the expression of hippocampal long-term potentiation. Following the induction of long-term potentiation by high-frequency electrical stimulation, synapses between CA3 and CA1 pyramidal neurons were strengthened only when presynaptic input originated in the left CA3, confirming an asymmetry in synaptic properties. The dissociation of hippocampal long-term memory function between hemispheres suggests that memory is routed via distinct left–right pathways within the mouse hippocampus, and provides a promising approach to help elucidate the synaptic basis of long-term memory.

Unilateral specializations may facilitate greater processing power in bilateral brain structures by using the available neuronal circuitry more effectively. Nevertheless, the nature of the mechanisms that can act within the confines of duplicate neural structures to support different cognitive functions in each hemisphere remains elusive.

The hippocampus is essential for certain forms of learning and memory, both in humans (1) and in rodents (2, 3), and also plays an important role in navigation (4). The left and right mammalian hippocampi comprise the same anatomical areas and directional connectivity, and yet in the human hippocampus, task-related activity may be localized to only one hemisphere (5). This lateralization may enable the left and right hippocampus to support complementary functions in human episodic memory, with left hippocampal activity associated with an egocentric, sequential representation of space but greater activity in the right hippocampus when an allocentric representation is used (6). It has been suggested that human hippocampal asymmetry is primarily dictated by external asymmetry—namely, the left hemispheric involvement in language processing and the stronger contribution of the right hemisphere to visuospatial attention (7), supported by observations of left hippocampal dominance when semantic information is most task-relevant, compared with right hippocampal dominance when spatial information becomes

more pertinent (8). However, a seminal discovery in the mouse brain suggests that left–right asymmetry may actually be a fundamental property of the mammalian hippocampus: it was found that the postsynaptic spine morphology and receptor distribution in CA1 pyramidal neurons is determined by whether the presynaptic input originates in the left or right CA3 (9, 10). Specifically, apical CA1 postsynaptic spines receiving input from the left CA3 are primarily thin and rich in GluN2B subunit-containing NMDA receptors (NMDARs); in contrast, there is a higher proportion of mushroom-shaped spines receiving right CA3 projection, and these larger spines have a lower density of GluN2B subunit-containing NMDARs (9, 10). Interestingly, synaptic plasticity also shows hemispheric asymmetry: irrespective of the hemispheric location of the CA1 neuron, GluN2B NMDAR-requiring spike timing-dependent long-term potentiation (LTP) was induced at synapses where presynaptic input originates in the left CA3, but not in the right CA3 (11).

These left–right synaptic differences raise the question as to whether memory processing in mice, as in humans, might differ between the left and right hippocampus. Therefore, in this study, we asked whether acutely inactivating one part of the asymmetric CA3–CA1 network unilaterally would affect learning and memory differentially between hemispheres. To test this, we silenced excitatory cells of CA3 in either the left or the right hippocampus, and consequently also both their ipsilateral and

Significance

The hippocampus is implicated in memory and spatial navigation. In rodents, in which this bilateral brain structure has been studied extensively, the left and right hippocampi have generally been considered functionally equivalent. However, recent work has revealed unexpected asymmetries in the molecular and morphological characteristics of neuronal connections according to brain hemisphere. To investigate whether this left–right difference has implications for hippocampal function, we acutely inhibited activity in an area-specific and genetically-defined population of hippocampal neurons during various behavioral tasks. We found that silencing the CA3 area of the left hippocampus impaired associative spatial long-term memory, whereas the equivalent manipulation in the right hippocampus did not. Thus, our data show that hippocampal long-term memory processing is lateralized in mice.

Author contributions: O.A.S., K.D., D.M.B., O.P., and M.M.K. designed research; O.A.S., M.E., J.A.S., and M.M.K. performed research; K.D. contributed new reagents/analytic tools; O.A.S., D.M.B., and M.M.K. analyzed data; and O.A.S., D.M.B., O.P., and M.M.K. wrote the paper.

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effect of hemisphere: $F_{(1,82)} = 5.37$; $P = 0.023$, but no transgene by hemisphere interaction: $P = 0.23$].

We also tested mice on a different short-term memory task, the spatial novelty preference Y-maze task, in which extramaze spatial cues are important to generate novel arm preference (Fig. 2C) (15). The effect of light delivery was similar to that in the spontaneous alternation short-term memory task, with an impairment arising from unilateral CA3 silencing irrespective of whether it was the left or right CA3 that was silenced [Fig. 2D; left-NpHR = 6 mice, right-NpHR = 5 mice, left-YFP = 7 mice, right-YFP = 4 mice; two-way ANOVA; main effect of transgene: $F_{(1,18)} = 14.91$; $P = 0.001$].

Overall, these results show that a unilateral manipulation can impair hippocampus-dependent short-term memory, and that silencing of either the left or the right CA3 reduces performance on short-term memory tasks.

Acute Silencing of Left CA3 Impairs Hippocampus-Dependent Long-Term Memory, but Silencing the Right CA3 Has No Effect. We next wanted to investigate whether unilateral dorsal CA3 silencing could also impair hippocampus-dependent long-term memory. We tested the same mice on an appetitively motivated task where they had to learn which arm of an elevated Y-maze was rewarded using extramaze spatial cues. The rewarded location remained constant for each mouse across consecutive days of testing. We verified that this task generated a long-term memory of the rewarded arm because a separate cohort of mice showed stable performance upon retesting 1 wk after the end of the acquisition period with no exposure to the apparatus in the intervening period (83% correct choices on both last trial before and first trial after the 7-d retention interval; $n = 12$), which extended to the whole trial block ($85 \pm 6\%$ correct arm choices on final block before retention interval and $85 \pm 5\%$ after retention interval; $n = 12$). A pseudorandom order of arm starts and periodic maze rotation between trials meant that intramaze cues provided no information that mice could use to perform the task successfully (Fig. 3A) (13, 16). Short-term memory errors could affect the acquisition of a spatial long-term memory task, but preventing arm reentry during a single trial removes this contribution to learning deficits (17). Therefore, to isolate long-term memory in this experiment, mice were only allowed to make one arm choice per trial and thus could not self-correct. Mice received blocks of 10 trials a day for 11 consecutive days, with five starts from the arm to the left of the designated rewarded arm, and 5 from the right in a pseudorandom order. Light was delivered for all mice during every trial, and was limited to the trial duration (10–40 s). To confirm that mice were not using olfactory cues from the reward to solve the task, the food was delivered after the arm choice was made on the final day of testing; this postchoice baiting did not cause performance to deteriorate.

Mice in the two control groups (left-YFP and right-YFP) acquired the task over the course of testing, reaching 90–100% accuracy. The right-NpHR group performed equivalent to the control mice. Strikingly, however, silencing the left CA3 did impair performance on this long-term memory task, and the deficit was not overcome even by the end of testing [Fig. 3B and C; left-NpHR = 21 mice, right-NpHR = 19 mice, left-YFP = 18 mice, right-YFP = 22 mice; two-way ANOVA; main effect of transgene (NpHR/YFP): $F_{(1,76)} = 6.01$, $P = 0.017$; transgene by hemisphere interaction: $F_{(1,76)} = 11.46$, $P = 0.001$; analysis of simple main effects showed a significant effect of transgene on the left hemisphere: $F_{(1,76)} = 16.62$, $P < 0.001$ and a significant effect of hemisphere for NpHR: $F_{(1,76)} = 13.29$, $P < 0.001$]. The absence of an effect on task performance by silencing the right CA3 indicates that this network is dispensable for associative spatial long-term memory. Moreover, the acute nature of the manipulation, which limits compensatory changes associated with longer-term manipulations (18), further suggests the right CA3 is

Hippocampus-dependent long-term memory

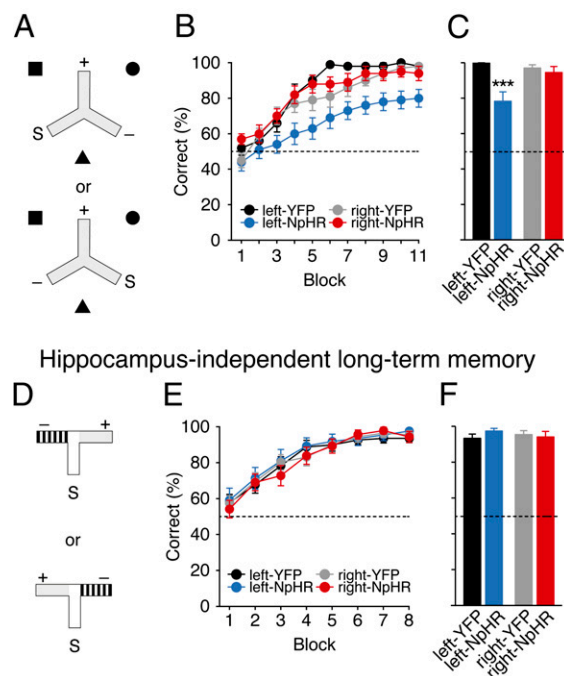


Fig. 3. Hippocampus-dependent associative spatial long-term memory uniquely requires the left CA3. (A) Mice were trained on a hippocampus-dependent long-term memory task where they had to associate a reward location that was fixed with respect to allocentric extramaze spatial cues (black square, circle, and triangle), and remained constant for each mouse across consecutive days of testing. Mice received arm starts (S) to the left or the right of the rewarded arm (+) in a pseudorandom order. Mice entering the nonrewarded arm (–) were not allowed to self-correct. (B) Light delivery in mice expressing eNpHR3.0 in the left CA3 (left-NpHR, blue) impairs but does not affect learning in right-NpHR mice (red) and control groups (left-YFP: black, right-YFP: gray) in this hippocampus-dependent long-term memory task. (C) Average performance on penultimate day. (D) Mice were trained on a hippocampus-independent visual-discrimination long-term memory task where they had to associate arm floor and wall color (gray vs. black-and-white stripes) with a reward; this was fixed for each mouse across consecutive days of testing. Rewarded (+) and nonrewarded (–) arms were pseudorandomly interchanged so that reward location was learnt independent of the spatial position of the arms of the maze. (E) Mice in all groups successfully learned this task at an equivalent rate. (F) Average performance on penultimate day. In both tasks, on the last day of testing, reward was delivered after the animal had chosen to control for the possibility of mice smelling the milk (postchoice baiting). Broken lines represent chance performance. Mean percentage correct choices \pm SEM. *** $P < 0.001$.

not required even under normal learning conditions. In contrast, the left CA3 appears to form an important part of the network that supports associative spatial long-term memory performance.

Acute Silencing of Either Left or Right CA3 Does Not Affect Performance on a Hippocampus-Independent Visual (Nonspatial) Long-Term Memory Task. To ensure that unilateral optogenetic silencing does not cause a generalized sensorimotor or motivational behavioral impairment that could account for the deficit in the left-NpHR group on the spatial long-term memory task, a subset of the same mice, as well as a group of experimentally naive mice, were trained on an associative, nonspatial visual discrimination T-maze task (16, 19) with trial-limited light delivery, as before (10–40 s). Mice had to learn to associate either a gray or a black/white-striped goal arm with reward (Fig. 3D). As with the previous long-term memory task, mice received training over consecutive days with 10 trials per block and were prevented from self-correcting within

a trial. However, in contrast to the associative spatial Y-maze task, the positions of the target arms were interchanged in a pseudo-random order so that, within each block, mice received a total of five starts with the rewarded arm to the left of the start arm and five starts with it to the right (Fig. 3D). Consequently, there was no extramaze spatial information that could be used to solve the task.

In contrast to the asymmetric effect of silencing on the spatial long-term memory task, all four groups of mice learnt this nonspatial control task successfully (90–100% correct) and at an equivalent rate [Fig. 3E and F; left-NpHR = 15 mice, right-NpHR = 16 mice, left-YFP = 17 mice, right-YFP = 17 mice; two-way ANOVA; main effect of block: $F_{(7,427)} = 80.27$, $P < 0.001$, but no main effect of hemisphere: $F_{(1,161)} = 0.43$, $P = 0.51$, no main effect of transgene: $F_{(1,161)} = 0.09$, $P = 0.76$, no hemisphere by transgene interaction: $F_{(1,161)} = 0.43$, $P = 0.51$; and also no interaction between block and transgene $F_{(7,427)} = 0.19$, $P = 0.99$, nor between block and hemisphere: $F_{(7,427)} = 1.14$, $P = 0.34$ and no triple interaction: $F_{(7,427)} = 0.36$, $P = 0.93$]. Thus, the effect of optogenetic manipulation of the CA3 is limited to hippocampus-dependent tasks; furthermore, it implies that the impairment in the left-NpHR group during the associative spatial long-term memory task was not due a gross asymmetric disruption of sensorimotor or motivational aspects of task performance as a result of silencing of the left CA3.

High Frequency Stimulation-Induced LTP Is Present at CA3–CA1 Synapses Where Afferents Originate in the Left CA3, but Not in the Right CA3. Although their precise roles are debated, NMDAR-dependent synaptic plasticity processes are likely to be involved during performance on hippocampus-dependent spatial memory tasks (20–23). It has previously been reported that there is an asymmetry in the induction of hippocampal spike timing-dependent LTP (tLTP), such that tLTP can only be induced in CA3–CA1 synapses where the presynaptic input originates in the left CA3 via a GluN2B-dependent mechanism (11). However, conventional high-frequency stimulation (HFS)-induced LTP is not blocked by pharmacological GluN2B antagonism (24). Here we investigated whether the expression of HFS-LTP might also be asymmetric. Because hippocampal pyramidal neurons could not be driven at 100 Hz with optogenetic tools, we induced LTP

with nonselective electrical HFS and sampled the left and right CA3–CA1 synapses selectively with optical stimulation to monitor any changes in synaptic weights.

Adult male wild-type mice were injected in the CA3 of one hemisphere with a viral construct containing channelrhodopsin-2 (hChR2) under control of the CaMKII α promoter [AAV5-CaMKII α -hChR2(E123T/T159C)-eYFP; Fig. 4A]. At 4–6 wk later, coronal slices were prepared for plasticity experiments, which were performed blind to injection side. We performed field recordings from CA1 with one electrically and one optically stimulated input pathway, and maximized the overlap between these two pathways by electrode and optical fiber placement (Fig. 4A). We recorded a stable baseline of both optically and electrically stimulated field excitatory postsynaptic potentials (fEPSPs), then induced LTP with high-frequency electrical stimulation (100 stimuli at 100 Hz). Following this induction protocol, we monitored the optical and electrical pathways to determine whether there was a difference in the response of synapses receiving input from either the left or right CA3. Despite equivalent potentiation in the electrical pathway in both left- and right-injected mice (left: $154 \pm 6\%$, $n = 14$; right: $149 \pm 6\%$, $n = 11$; $P = 0.50$), the optical pathway showed a significant increase in synaptic strength only in left-injected mice, irrespective of whether the slice was ipsilateral or contralateral to the injection side, and the fEPSP increase was significantly greater in left-injected compared with right-injected mice (Fig. 4B and C; left: $145 \pm 7\%$; right: $113 \pm 7\%$; $P = 0.004$). This result held when the change in the optical pathway was normalized to the magnitude of electrical LTP (left: $84 \pm 11\%$ of electrical; right: $19 \pm 15\%$; $P = 0.002$). Thus, the expression of HFS-LTP depends on whether the input originates in the left or right CA3; this suggests that these two inputs may perform different functions in vivo and provides one possible mechanistic explanation for the observed functional lateralization in long-term memory.

Discussion

Using trial-limited optogenetic silencing of excitatory neurons in either the left or right CA3, we have found a left–right functional dissociation in hippocampal memory performance in the mouse. Silencing of the left CA3 alone impairs performance on

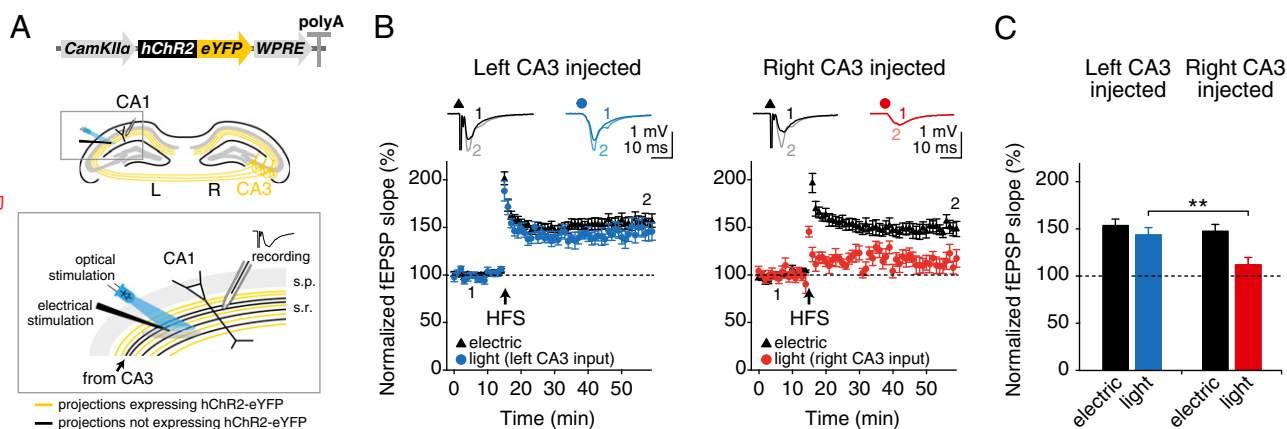


Fig. 4. High-frequency stimulation-induced LTP is asymmetrically expressed at the CA3–CA1 pyramidal cell synapse. (A, Upper) Adeno-associated virus containing hChR2-eYFP construct under the control of a CaMKII α promoter was unilaterally injected into the dorsal CA3 area of C57BL/6J mice. (Lower) An electrode to deliver nonselective electrical stimulation was placed in the stratum radiatum and a high-power 470-nm LED was arranged to recruit an overlapping population of projections. Optical stimulation only recruits projections originating in the CA3 of the injected hemisphere (yellow), whereas electrical stimulation is nonselective (black and yellow). Electrical stimulation was used to deliver the high-frequency LTP induction protocol and the effects were monitored via field recording of EPSPs evoked by electrical or optical stimulation. (B) HFS produces robust LTP in the electrical pathway (black triangles), but LTP is only expressed in the optical pathway (circles) when projections originate in the left CA3. (Insets) Representative field EPSPs at the indicated time points (1, 2). (C) Significantly more LTP is observed in left-injected mice than in right-injected mice in the optical pathway. Broken lines represent baseline. Error bars represent SEM. $**P < 0.01$, Student's t test.

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Supporting Information

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SI Materials and Methods

Behavioral Experiments. Animals and adeno-associated virus vectors.

All experiments were performed in accordance with UK Home Office Regulations and under personal and project licenses held by the authors. Male C57BL/6J mice (Charles River Laboratories or Harlan) were housed in polycarbonate cages of 5–10 mice on a 12-h light/dark cycle (7:00 AM–7:00 PM), and had access to food and water ad libitum, except when on food restriction during appetitively motivated behavioral tests. eNpHR3.0 was fused in-frame to enhanced YFP (eYFP) and driven by a CaMKII α promoter (1). Adeno-associated viral (AAV) particles of serotype 5 were produced by the Vector Core Facility at The University of North Carolina at Chapel Hill (titers detailed below).

Surgery and light delivery. Mice (10–12 wk old) were anesthetized with 2–4% (vol/vol) isoflurane at 0.6–1.4 L·min⁻¹, placed on a heating pad to aid body temperature maintenance and their head fixed in a stereotactic apparatus (Kopf Instruments). The head was leveled and three small craniotomies were made above either the left or right dorsal hippocampus. At sites 1 and 3 [site 1: anterior-posterior (AP): -1.46 mm, mediolateral (ML): \pm 1.25 mm, dorsoventral (DV): -2.00 mm; site 3: AP: -2.46 mm, ML: \pm 2.40 mm, DV: -2.30, all coordinates from skull surface at bregma], 0.75- μ L virus suspension (AAV5-CaMKII α -eNpHR3.0-eYFP-WPREpA, 4×10^{12} viral molecules per milliliter for experimental mice and AAV5-CaMKII α -eYFP, 6×10^{12} viral molecules per milliliter for control mice; University of North Carolina Vector Core) was delivered at a rate of 0.1 μ L·min⁻¹ through a 33-gauge needle using a Hamilton Microliter syringe. Following a 6-min wait after bolus injection, the needle was retracted by 0.20 mm and after another 4-min wait slowly retracted fully. At site 2 (AP: -1.94 mm, ML: \pm 2.00 mm), a fiber optic cannula [200 μ m diameter, 0.22 N.A. (Doric Lenses)] was lowered to DV -1.80 mm (from bregma) and secured to the skull using dental cement (C&B Metabond; Prestige Dental and Simplex). The scalp incision was sutured, and anti-inflammatory and analgesic drugs (2 mg·kg⁻¹ meloxicam; 0.1 mg·kg⁻¹ buprenorphine) were administered s.c. to aid recovery.

Green laser light from a solid-state laser diode (532 nm, 24 \pm 3 mW at fiber tip; Laser 2000) was collimated into an aperture-matched fiberoptic patch cord (Doric Lenses) that was connected to the fiberoptic implants.

To ensure strong eNpHR3.0 expression in an area of cells 0.5 mm away from each injection site, a relatively large quantity of virus was injected into each site in the CA3c subfield (0.75 μ L, at a titer of $4\text{--}6 \times 10^{12}$ viral molecules per milliliter); this also produced virus expression in the dentate gyrus (DG), but additional specificity was achieved through the use of a low numerical aperture (0.22 N.A.) optical fiber to restrict light spread and manipulate a volume of cells between the two injection sites. The efficacy of this approach is illustrated by the restricted area of YFP photobleaching below the optical fiber (Fig. S1). A similar principle of limiting optogenetic silencing by spatially restricted light delivery has been used previously (2).

To provide a quantitative estimate of the degree of specificity of our optogenetic manipulation in the CA3 compared with DG, we used available experimental values from Yizhar et al. (3) for transmission of 594-nm wavelength light from a 0.37-N.A. fiber through brain tissue; this provided an upper limit of transmission because we used a lower wavelength light for behavior (532 nm), which penetrates less through tissue and also a lower N.A. fiber (0.22) that will cause a more restricted light cone (full acceptance angle is 25° for 0.22 N.A. compared with 46°

for 0.37 N.A.). We determined the location of implants in each mouse (*Immunohistochemistry*; Fig. S2) and used these placements and the light spread data to estimate the proportion of light at 1%, 5%, 10%, and 50% (isobar lines) of the maximum light power (24 \pm 3 mW at tip in our experiments) that reached the DG (Fig. S1) and calculated values of (mean \pm SEM): 13 \pm 3% DG overlap for 50% of total laser power; 16 \pm 3% overlap for 10% total power; 15 \pm 3% overlap for 5% total power; and 17 \pm 2% for 1% of total power (n = 86).

To confirm that differences in implant placement, and hence the region exposed to light, between behavioral groups could not account for the difference in silencing left compared with right CA3 in spatial long-term memory, we recorded the average position of the tip of each fiber optic implant (mean \pm SEM) shown in Fig. S2 (left-NpHR = 22 mice, right-NpHR = 21 mice, left-YFP = 21 mice, right-YFP = 22 mice): left-NpHR: AP: -2.11 ± 0.04 mm, ML: 1.98 ± 0.03 mm, DV: -1.64 ± 0.05 mm; right-NpHR: AP: -2.12 ± 0.07 mm, ML: 1.87 ± 0.06 mm, DV: -1.65 ± 0.04 mm; left-YFP: AP: -2.06 ± 0.06 mm, ML: 1.94 ± 0.05 mm, DV: -1.63 ± 0.06 mm; right-YFP: AP: -2.21 ± 0.07 mm, ML: 2.01 ± 0.06 mm, DV: -1.75 ± 0.04 mm.

There were no significant differences between the NpHR experimental groups in average optical fiber placement in any spatial dimension that could explain the asymmetry in long-term memory [left-NpHR = 22 mice, right-NpHR = 21 mice; two-way ANOVA with spatial dimension (AP, ML, DV) as a within-subjects factor and hemisphere as a between-subjects factor: no main effect of hemisphere $F_{(1,41)} = 2.26$, $P = 0.141$; and no hemisphere by spatial dimension interaction $F_{(2,82)} = 0.503$, $P = 0.607$].

Optrode recordings. Adult male mice received dual injections of AAV5-CaMKII α -driven eNpHR3.0 at sites 1 and 3 as described above, but without the fiberoptic implant. Following at least 8 wk for expression to develop, mice were anesthetized with i.p. injections of urethane (1.2 g·kg⁻¹), ketamine (100 mg·kg⁻¹), and xylazine (10 mg·kg⁻¹). Simultaneous optical stimulation and electrical recording in CA3 were carried out as described previously (4) using an optrode consisting of an extracellular parylene-C insulated tungsten microelectrode (127- μ m diameter, 1 M Ω ; A-M Systems) tightly bundled with an optical fiber (200 μ m, 0.22 N.A.; Thorlabs), with the tip of the electrode protruding 0.5–0.7 mm beyond the fiber end to ensure illumination of the recorded neurons. The optical fiber was coupled to the laser and light output adjusted to 20–25 mW at the fiber tip. The optrode was initially placed above CA3 (AP: -1.94 mm, ML: \pm 2.00 mm, DV: -1.80 mm; equivalent to the implant coordinates) and gradually lowered in 0.1-mm increments. Signals were recorded and bandpass-filtered between 300 Hz and 5 kHz using a microelectrode amplifier (1800 Microelectrode AC Amplifier; A-M Systems) and recorded with Spike2 (Cambridge Electronic Design). A baseline of 1 min was recorded when clear spikes were detected, followed by 30-s continuous laser light illumination and then at least 1 min recording without light. This process was then repeated up to four times.

Behavioral testing. Following at least 8 wk for expression of eNpHR3.0-eYFP or eYFP to develop after surgery, mice were handled to habituate them to the experimenter and accustom them to connection of the implant to the fiber-optic cable. All behavioral testing was done during the light phase of the light/dark cycle and with the experimenter blind to condition. All mice were used first in the spontaneous alternation T-maze task and then in the appetitive Y-maze task. The last batch of 36 mice was additionally used in the visual discrimination T-maze task and

supplemented by a group of experimentally naïve mice. The latter group of mice then went on to be tested in the novelty preference Y-maze task. Any mice that lost implants during testing were perfused (*Immunohistochemistry*) and excluded from any tasks they did not complete.

Spontaneous alternation short-term memory T-maze task. The T-maze was black painted wood and had two sliding doors to enclose the two choice arms (30 × 10 cm, 20-cm high walls) and a removable central barrier (extending 5 cm into central arm). During each trial, the floor was covered with wood chipping litter. Mice received two self-contained trials each day, one in the morning and one in the afternoon. Mice were started in a pseudorandom order within the cage, which varied across trials. Before the start of each trial, the implant was connected to the laser. For “light on” trials, the illumination was started before the mouse was placed in the maze and light was then on continuously during the trial; light was turned off once the mouse was removed from the maze at the end of the trial. “Light off” trials were pseudorandomly interleaved, during which mice were still connected to the laser but no light was delivered. Mice were started facing outward and given a free choice of arm. The central barrier was in position so mice received sensory input from only the chosen side before they could enter the arm. Once they had entered an arm, a black painted wooden block was positioned so they experienced a 30-s exploratory period in their chosen arm. The central barrier was removed, and then the mouse was removed from the explored arm and immediately replaced in the start arm facing outward. The subsequent arm choice was recorded, and if it was the novel one, this was scored as a correct alternation. Because it has been reported that delay times can affect performance on short-term memory tasks (5), if mice had not made an arm decision after 20 s in the second phase of the trial, the trial was aborted.

Spatial novelty preference short-term memory Y-maze task. The novelty preference Y-maze consisted of three transparent colorless Perspex arms (8 cm wide and 25 cm tall) mounted onto a painted white wooden board. During each trial, the floor was covered with wood chipping litter. Each arm could be closed off with a block made of opaque Perspex. Mice were assigned a novel arm and a start arm (in relation to fixed extramaze cues). Arm designations were counterbalanced such that approximately equal proportions of each experimental group were assigned to each novel arm. During the first exploration phase of the trial, the novel arm was blocked off. Mice were placed facing outward in the start arm, and were given 5 min to explore the start and other arms. Timing was started once the mouse left the start arm. Before being placed in the maze, the implant was connected to the laser and illumination started; light was then on continuously during the first part of the trial. The light was turned off once the mouse was removed from the maze and the implant disconnected. Mice were then placed back in their home cage for 1 min. The arm block was then removed and wood chipping shuffled. Mice were reconnected to the laser and illumination started, light was then on continuously during the second part of the trial. Mice were then placed back in the start arm facing outward and given 2 min to explore all three arms; the time spent in each arm was recorded. Timing started once the mouse left the start arm. Mice received two separate novelty preference tests, 2–4 d apart, each in a different room.

Spatial long-term memory Y-maze task. The elevated Y-maze was constructed of gray painted wooden arms (50 × 13 cm bordered by 1-cm-high white plastic walls), extending from a central triangular platform. Metal food wells (1.5 cm high) were positioned 5 cm from the distal end of the arms. The maze was elevated 82 cm from the floor. Mice were put on a restricted feeding schedule, allowing them to maintain at least 85% of their free-feeding body weight. Mice were introduced to the food reward (0.1 mL of sweetened condensed milk diluted 50:50 with water)

in their home cages to overcome neophobia and then pretrained on the elevated Y-maze in a room different to where behavioral testing would occur until they were highly motivated to search for food and running freely on the Y-maze (reaching the food reward in under 15 s for three consecutive trials). Mice were assigned a rewarded target arm (designated A, B, or C according to its fixed position relative to allocentric extramaze spatial cues). Target arm designations were counterbalanced such that approximately equal proportions of each experimental group were assigned to each arm. Mice were started facing outward in either the left or right arm relative to the target arm and received 10 trials per day for 11 consecutive days. On each day, mice had five starts from the left of the target arm and five starts from the right in a pseudorandom order with no more than three consecutive starts from the left or right. Mice were started in a pseudorandom order within the cage, which varied across trials, and the intertrial interval (ITI) was ~15 min. Before being placed on the maze, the implant was connected to the laser and illumination started; light was then on continuously during the trial and was turned off once the mouse was removed from the maze (trial duration 10–40 s). If a mouse made the correct choice, it was allowed to consume the reward, but the trial was ended if mice chose the incorrect arm and after they had seen the empty food well (i.e., they were not allowed to self-correct). The maze was pseudorandomly rotated either clockwise or anticlockwise between trials to ensure that olfactory, tactile, or visual cues on the maze itself (intramaze cues) did not provide information that could be used to solve the task. On the last day of testing, food was only delivered once the mouse reached the food well to check that mice did not use reward odor to solve the task (postchoice baiting). When not performing the task, mice were kept behind a screen to minimize exposure to the testing room and cues in the absence of laser light. A subset of mice was tested for longer-term memory recall for the goal location. These mice were trained in the Y-maze task for 11 d, as described above; they then received a 7-d period with no testing, before receiving a further block of 10 trials. These 10 trials were conducted on one day in the same room as previously, with identical cues and the same arm being rewarded.

Visual discrimination long-term memory T-maze task. The visual T-maze consisted of two painted wooden interchangeable arms, one gray and one black-and-white striped (30 × 10 cm, 30-cm-high walls). The starting arm, central area, and back wall were all brown. Mice were put on a restricted feeding schedule, allowing them to maintain at least 85% of their free-feeding body weight, and were reintroduced to the food reward (0.1 mL of sweetened condensed milk diluted 50:50 with water). Mice were assigned a target arm (with numbers trained to the gray or striped arm counterbalanced across each experimental group). Before testing commenced, mice received four forced pretrials to overcome any potential neophobia to the goal arms. In these forced trials, one arm was blocked off so that they experienced each possible combination across the four trials (gray-left, gray-right, striped-left, and striped-right), and the reward contingencies applied as they would for the rest of the experiment. For training, mice received 10 trials per day for 8 consecutive days and were always started facing outward in the central arm, which remained in a fixed position. To ensure that there was no spatial solution to the task, the gray and the striped arm were interchanged such that each day mice received five trials where the rewarded arm was on the left and five where it was on the right. Reward arm location was in a pseudorandom order with no more than three consecutive positions of the rewarded arm being the same. Mice were started in a pseudorandom order within the cage, which varied across trials, and the ITI was ~15 min. Before being placed in the maze, the implant was connected to the laser and illumination started; light was then on continuously during the trial. The light was turned off once the mouse was removed

from the maze. If a mouse made the correct choice, it was allowed to consume the reward, but if an incorrect choice was made the mouse was removed from the maze immediately after they had seen the empty food well, analogous to the appetitive Y-maze task. On the last day of testing, food was only delivered once the mouse reached the food well to check that mice did not use reward odor to solve the task (postchoice baiting).

Immunohistochemistry. Mice were anesthetized by i.p. injection of pentobarbital (533 mg·kg⁻¹) and then transcardially perfused with cold PBS (pH 7.4) followed by 4% (wt/vol) paraformaldehyde (PFA) in PBS. Brains were postfixed for 36 h at 4 °C in PFA in PBS, then rinsed and subsequently infiltrated with 30% (wt/vol) sucrose in PBS for at least 48 h. Coronal sections of 40-μm thickness along the entire dorsal–ventral axis of the hippocampus were cut using a microtome (Spencer Lens Co.) and divided into three series. The first series was immunostained to visualize expression of the YFP tag. Sections were rinsed for 3 × 10 min in PBS and incubated for 1 h in PBS with 0.2% (wt/vol) Triton X-100 (PBS-T) containing 1% (wt/vol) bovine serum (Sigma); they were then incubated for 15 h at 4 °C in PBS-T containing 1% bovine serum and anti-GFP (goat, 1:1,000; Abcam, ab5450). The sections were then rinsed for 3 × 10 min in PBS and incubated in PBS-T containing 1% bovine serum and Alexa 488-labeled secondary antibody (donkey anti-goat; 1:1,000; Invitrogen, A11055) for 90 min at room temperature. After three 10-min rinses in PBS, slices were mounted in VectaShield (Vector Labs). Fluorescence images (Zeiss Axioskop 2 microscope) were taken either following the protocol for YFP immunostaining described above (first batch of mice) or using the intrinsic fluorescence of YFP (subsequent batches) and scored blindly for the presence of expression. Brightfield images (Zeiss Axioskop 2 microscope) were also taken and scored blindly for implant location (Fig. S2).

Data analysis. Optrode recording data were analyzed using Spike2; a voltage threshold was set and spike templates were produced during the baseline in Spike2 and counted. Data were then binned (5 s) and normalized to a 30-s baseline. The normalized means during silencing were compared with 100% using a one-sample *t* test. The behavioral results were analyzed by two-way ANOVA with between-subjects factors of transgene (NpHR vs. YFP) and hemisphere (left vs. right), and also a within-subjects factor of block for the long-term memory tests. Significant interactions were explored by analysis of simple main effects. *N* numbers (unless otherwise stated) refer to the number of mice.

Electrophysiology Experiments. Animals and AAVs. All experiments were performed in accordance with UK Home Office Regulations and under personal and project licenses held by the authors. Male C57BL/6J mice (Charles River Laboratories) were housed in polycarbonate cages of 5–10 mice on a 12-h light/dark cycle, and had access to food and water ad libitum. hChR2(E123T/T159C) was

delivered at a rate of 0.1 μL·min⁻¹ 2.25 mm below the skull surface through a 33-gauge needle using a Hamilton Microliter syringe. Following a 5-min wait after bolus injection, the needle was retracted by 0.2 mm and after another 5-min wait slowly retracted fully. The scalp incision was sutured, and postinjection analgesic (0.03 mg·kg⁻¹ buprenorphine) was administered i.p. to aid recovery.

Slice preparation. Coronal hippocampal slices (350 μm) were prepared after decapitation under deep isoflurane-induced anesthesia. After dissection in ice-cold artificial cerebrospinal fluid (ACSF) containing (mM): NaCl 126; KCl 3; NaH₂PO₄ 1.25; MgSO₄ 2; CaCl₂ 2; NaHCO₃ 25; glucose 10; pH 7.2–7.4; bubbled with carbogen gas (95% O₂, 5% CO₂), slices were maintained at room temperature (22–25 °C) in a submerged-style holding chamber for at least 1 h. For recording, slices were transferred to an interface-style recording chamber maintained at 31–33 °C superfused with ACSF at a rate of 0.5 mL·min⁻¹; recording started at least 10 min after the slices were transferred.

Electrophysiological protocols and light delivery. Extracellular field recordings from CA1 were made with an Axoclamp-2A amplifier in bridge mode, and data acquired with an InstruTech ITC-16 A/D board (InstruTech Corp.) using Igor Pro software (WaveMetrics). Borosilicate glass recording electrodes were filled with ACSF. Recording and stimulation electrodes were positioned in the stratum radiatum of CA1. The optical fiber was also placed in the stratum radiatum, as close as possible to the stimulation electrode to ensure maximal overlap of fibers recruited. Synaptic efficacy was monitored by alternately stimulating the Schaffer collaterals at 0.2 Hz (50 μs, 30–150 μA) with a 2-MΩ monopolar tungsten electrode (A-M Systems) connected to a stimulus isolator unit (ISO-Flex; A.M.P.I.) for the electrical pathway and by stimulating at 0.2 Hz (5 ms, 0.5–1.2 A) using a 200-μm diameter, 0.39-N.A. optical fiber (Thorlabs) connected to a blue (470 nm) fiber-coupled high-power LED (Thorlabs) for the optical pathway. Stimulation strength was set to elicit a field excitatory postsynaptic potential (fEPSP) of half-maximal amplitude. fEPSP slopes were monitored for a baseline period of at least 15 min. If synaptic transmission was stable (<15% change in fEPSP slopes over 15 min), the Schaffer collateral pathway was stimulated with a single high-frequency tetanus (100 Hz for 1 s, 100 μs) in the electrical pathway. The level of overlap between the optical and the electrical pathways was estimated using linear summation. Linear summation (LS) was measured by stimulating the electrical and optical pathways independently at the stimulation strength used for the LTP recording. Both optical and electrical pathways were then triggered simultaneously and the amplitude of the resulting fEPSP measured. The degree of linear summation was quantified as

$$\frac{(\text{optical fEPSP amplitude} + \text{electrical fEPSP amplitude}) - \text{simultaneous fEPSP amplitude}}{\text{optical fEPSP amplitude}},$$

fused in-frame to eYFP and driven by a CaMKIIα promoter. Adeno-associated viral particles of serotype 5 were produced by the Vector Core Facility at the University of North Carolina at Chapel Hill.

Virus injections. Wild-type mice (14–16 wk old) were anesthetized with 2–4% (vol/vol) isoflurane at 0.6–1.4 L·min⁻¹. Using a stereotactic apparatus (Kopf Instruments), a small craniotomy was made 2.3 mm anterior and 2.2 mm lateral (either left or right) from bregma. Through a small durotomy, 0.6-μL virus suspension (AAV5-CaMKII-hChR2(E123T/T159C)-eYFP, 4 × 10¹² viral

whereby an overlap index of 0 would suggest no overlap, and 1 would suggest complete overlap. The optical fEPSP amplitude was used as the normalization factor to estimate the fraction of the optical fEPSP that was stimulated by the electrical pathway. This linear summation measure was found not to differ between right- and left-injected mice (LS left: 0.47 ± 0.10, *n* = 10; LS right: 0.40 ± 0.09, *n* = 11; *P* = 0.602, Student *t* test).

Data analysis. Changes in synaptic efficacy were estimated by using the mean fEPSP slopes of 30–45 min after tetanic stimulation



Fig. S2. Implant placement does not vary between behavioral groups. Posttesting, brains were fixed and sliced, and the placement of the deepest point of the implant was recorded for each mouse. (A) Representative brightfield image of implant site over left CA3. (B) The approximate locations of the fiber optic implant tip for each animal.