Genetic disruption of the core circadian clock impairs hippocampus-dependent memory

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Perturbing the circadian system by electrolytically lesioning the suprachiasmatic nucleus (SCN) or varying the environmental light-dark schedule impairs memory, suggesting that memory depends on the circadian system. We used a genetic approach to evaluate the role of the molecular clock in memory. Bmal1−/− mice, which are arrhythmic under constant conditions, were examined for hippocampus-dependent memory, LTP at the Schaffer-collateral synapse, and signal transduction activity in the hippocampus. Bmal1−/− mice exhibit impaired contextual fear and spatial memory. Furthermore, LTP in hippocampal slices from Bmal1−/− mice is also significantly decreased relative to that from wild-type mice. Activation of Erk1,2 MAP kinase (MAPK) during training for contextual fear memory and diurnal oscillation of MAPK activity and cAMP in the hippocampus is also lost in Bmal1−/− mice, suggesting that the memory defects are due to reduction of the memory consolidation pathway in the hippocampus. We conclude that critical signaling events in the hippocampus required for memory depend on BMAL1.

Hippocampus-dependent learning and memory is initiated by a calcium influx mediated through NMDA receptors (Morris et al. 1986; Tsien et al. 1996) and leads to the activation of several signaling pathways, including the CAMP and Erk1,2 MAP kinase (MAPK) pathways (Adams and Sweatt 2002; Wang and Storm 2003). Activation of CaM-stimulated adenylyl cyclases and MAPK causes stimulation of CRE-mediated transcription (Imppey et al. 1998; Athes et al. 2002; Sindreu et al. 2007). Perturbing any of these signaling events disrupts memory consolidation (Bourchuladze et al. 1994; Atkins et al. 1998; Wong et al. 1999; Athes et al. 2002; Pittenger et al. 2002).

Despite the potential for memories to persist over the lifetime of an individual, the proteins that underlie strengthened synaptic connections degrade. Recurring rounds of transcription and protein synthesis may contribute to the persistence of memories (Beckinscellen et al. 2007; Eckel-Mahan et al. 2008). Specifically, Eckel-Mahan et al. (2008) showed that the CAMP/MAPK/CREB transcriptional pathway undergoes a circadian oscillation in the hippocampus that, when blocked, inhibits the maintenance of contextual fear memory in mice. The mammalian circadian system may provide the signal to coordinate returning rounds of transcription important for memory maintenance.

Previous research has established that time of day can influence learning and memory of fear conditioning under both light:dark entrained and free-running conditions (Chaudhury and Colwell 2002; Eckel-Mahan et al. 2008). Hippocampal LTP also depends on time of day under light:dark entrained conditions (Chaudhury et al. 2005). This time-of-day influence on memory and LTP suggests involvement of the circadian system. Perturbing the circadian system through environmental disruption of lighting conditions or lesioning the master circadian regulator can impair memory (Tapp and Holloway 1981; Devan et al. 2001; Lyons et al. 2006; Ruby et al. 2008; Loh et al. 2010; Phan et al. 2011).

The suprachiasmatic nucleus (SCN) is the master regulatory clock in mammals. The SCN receives light input from the environment via the retinohypothalamic pathway and synchronizes peripheral oscillators via synaptic connection or diffusible factors (Antle and Silver 2005). A molecular clock comprised of positively and negatively regulated transcriptional/translational loops drives the oscillations in central and peripheral sites with a period of about 24 h (Ko and Takahashi 2006). BMAL1 and CLOCK heterodimerize and bind to E-box elements to promote the transcription of circadian-regulated genes, including the heterodimer’s negative regulators, Period and Cryptochrome. PERIOD and CRYPTOCHROME dimerize and translocate to the nucleus to inhibit the activity of the BMAL1:CLOCK heterodimer. A second loop involving the competitive binding of REV-ERBα and RORα at RORE binding sites in the Bmal1 promoter regulates BMAL1 levels.

Only the Bmal1−/− mouse is completely arrhythmic in constant conditions and exhibits impaired entrainment to a light:dark cycle (Bunger et al. 2000). Other molecular clock knockout mouse strains retain some rhythmicity due to compensatory functional isoforms and present with subtle or no memory deficits (Garcia et al. 2000; Debruyne et al. 2006; Zueng et al. 2006; Van der Zee et al. 2008). Bmal1−/− mice exhibit a circadian arrhythmicity that may be a consequence of a second loop involving the competitive binding of REV-ERBα and RORα at RORE binding sites in the Bmal1 promoter regulates BMAL1 levels.

We hypothesize that the molecular clock is required for the diurnal oscillation of signaling activity in the hippocampus and hippocampus-dependent memory. Here, we report that Bmal1−/− mice have impaired contextual fear memory, deficits in learning and spatial memory, impaired LTP at the Schaffer-collateral synapse, as well as no diurnal change in cAMP and MAPK activity.

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Results

*Bmal1*<sup><small>−/−</small></sup> mice exhibit impaired hippocampus-dependent learning and memory

Consistent with previous reports (Bunger et al. 2000), *Bmal1*<sup><small>−/−</small></sup> mice are arrhythmic under dark-dark (DD) conditions while *Bmal1*<sup><small>+/+</small></sup> littermates exhibit an expected \( \tau \) close to 24 h (Fig. 1C,D). *Bmal1*<sup><small>−/−</small></sup> mice also exhibit difficulties entraining to a 12-h light-dark (LD) cycle (Fig. 1A,B), thus all experiments were performed under diurnal conditions.

*Bmal1*<sup><small>−/−</small></sup> and *Bmal1*<sup><small>+/+</small></sup> mice were trained and tested for contextual fear conditioning from ZT3 (3 h after light onset) to ZT8. Throughout this training, *Bmal1*<sup><small>−/−</small></sup> mice consistently took longer to find the hidden platform compared to their wild-type littermates (Bonferroni post-hoc test) (Fig. 2C). Two-way ANOVA revealed a significant effect of genotype (\( F(1,45) = 34.25, P < 0.0001 \)) and day of training (\( F(7,98) = 9.043, P < 0.001 \)). When the platform was removed during the probe trial, *Bmal1*<sup><small>−/−</small></sup> littermates spent significantly more time in the quadrant where the platform was during training compared to *Bmal1*<sup><small>+/+</small></sup> mice, 45.4 ± 3.9% vs. 20.3 ± 0.5% of probe trial (\( F(3,52) = 4.080, P < 0.01 \), two-way ANOVA with Bonferroni post-hoc test) (Fig. 2D). Furthermore, *Bmal1*<sup><small>+/+</small></sup> mice crossed the platform’s previous location more frequently than *Bmal1*<sup><small>−/−</small></sup> mice, 3.9 ± 0.8 vs. 0.8 ± 0.4 crossings (\( t(13) = 2.964, P = 0.0110 \), two-tailed unpaired t-test).

While *Bmal1*<sup><small>−/−</small></sup> mice showed impairment in contextual fear conditioning and the Morris water maze, they demonstrated no deficit in the novel object recognition task. Mice were exposed to object A for 5 min, three times. Both *Bmal1*<sup><small>+/+</small></sup> and *Bmal1*<sup><small>−/−</small></sup> mice spent more time exploring novel object B 30 min after training (\( F(3,22) = 18.12, P < 0.001 \), one-way ANOVA, Tukey post-hoc test) (Fig. 2E). In fact, *Bmal1*<sup><small>−/−</small></sup> mice even spent more time interacting with a novel object 24 h after exploring the original object (\( P < 0.001 \), Tukey post-hoc test) (Fig. 2E).

**Figure 1.** *Bmal1*<sup><small>−/−</small></sup> mice locomotor activity. Mice were monitored in 12-h LD conditions for 1 wk before exposed to DD conditions for 2 wk. Analysis of DD conditions is restricted to the second week of monitoring. (A) Representative *Bmal1*<sup><small>−/−</small></sup> and *Bmal1*<sup><small>+/+</small></sup> double-plotted actograms in 12-h LD conditions. Each line represents 48 h. (B) *Bmal1*<sup><small>−/−</small></sup> and *Bmal1*<sup><small>+/+</small></sup> \( \chi^2 \)-square periodograms. *Bmal1*<sup><small>+/+</small></sup> periodogram reveals \( \tau = 1445 \) min, or 24.1 h. *Bmal1*<sup><small>−/−</small></sup> periodogram does not reveal a period of 24 h. For the one peak that does cross the line of significance, \( \tau = 1083 \) min, or 18.1 h. (C) Representative *Bmal1*<sup><small>−/−</small></sup> and *Bmal1*<sup><small>+/+</small></sup> double-plotted actograms in DD conditions. (D) *Bmal1*<sup><small>−/−</small></sup> periodogram reveals \( \tau = 1410 \) min, or 23.5 h. *Bmal1*<sup><small>−/−</small></sup> periodogram does not reveal a period of 24 h. For the one peak that does cross the line of significance, \( \tau = 1130 \) min, or 18.8 h.

**Figure 2.** *Bmal1*<sup><small>−/−</small></sup> mice have impaired LTP

The Schaffer collateral efferent fibers in the stratum radiatum of hippocampal CA1 were stimulated in the acute brain slice and the resulting fEPSPs recorded. Before inducing LTP, the input/output (I/O) curve and paired-pulse facilitation were characterized. There was no significant difference between the *Bmal1*<sup><small>−/−</small></sup> and *Bmal1*<sup><small>+/+</small></sup> I/O values at each stimulus (Tukey’s multiple comparison test) (Fig. 3A). There was also no significant difference between the normalized slopes of the second fEPSP at each interpulse interval for paired-pulse facilitation (Tukey’s multiple comparison test) (Fig. 3B). To induce LTP, three tetanic stimuli separated by 5 min were delivered to the acute slice and fEPSPs monitored for 2 h (Fig. 3C). For the first 30 min following LTP induction, the *Bmal1*<sup><small>+/+</small></sup> hippocampus mean fEPSP slope response was 251.50 ± 3.43% of baseline, while the *Bmal1*<sup><small>−/−</small></sup> hippocampus demonstrated significantly reduced LTP with a mean fEPSP slope response of 152.20 ± 2.51% of baseline (\( U = 0.0, P < 0.0001, r = 1.21 \), Mann–Whitney).

The *Bmal1*<sup><small>−/−</small></sup> hippocampus continued to demonstrate a significantly reduced response (228.7 ± 1.2% of baseline vs. 251.50 ± 3.43% baseline).
phospho-MAPK at ZT4 compared to ZT16 (P < 0.05, Bonferroni post-hoc test) (Fig. 4B). Bmal1+/− hippocampi showed no diurnal change in phospho-MAPK at ZT4 and exhibited lower levels of phospho-MAPK at ZT4 compared to Bmal1+/− hippocampi (P < 0.05, Bonferroni post-hoc test) (Fig. 4B). Similarly, two-way ANOVA revealed a significant effect of genotype (F(1,54) = 21.56, P < 0.0001) and time of day (F(2,54) = 9.101, P = 0.0039) on diurnal cAMP levels. Bmal1+/− hippocampi demonstrated increased levels of cAMP at ZT4 compared to ZT16 (P < 0.05, Bonferroni post-hoc test) (Fig. 4C). Bmal1+/− hippocampi showed no diurnal change in cAMP at ZT4 and exhibited lower levels of cAMP at ZT4 compared to Bmal1+/− hippocampi (P < 0.001, Bonferroni post-hoc test) (Fig. 4C).

The Bmal1−/− hippocampus shows no training-induced activation of MAPK

When wild-type mice are trained for contextual fear memory, there is a measurable increase in MAPK activity in area CA1 of the hippocampus (Sindreu et al. 2007). Therefore, Bmal1+/+ and Bmal1−/− mice were exposed to a novel context (ZT4 to ZT16) and either immediately received a 0.7-mA foot shock or were first allowed to explore for 2 min. Bmal1+/− mice that experienced the paired association between the novel context and foot shock showed an increase in phospho-MAPK in the hippocampus 30 min after training compared to unpaired controls which were shocked immediately (Bmal1+/− hippocampi t(10) = 2, P = 0.0121, two-tailed unpaired t-test) (Fig. 5). There was no difference between Bmal1−/− paired and unpaired hippocampi (t(15) = 1.585, P = 0.1339, two-tailed unpaired t-test) (Fig. 5), indicating that MAPK activity did not increase when Bmal1−/− mice were trained for contextual fear memory.

Discussion

Bmal1−/− mice offer the opportunity to investigate the relationship between a functional molecular clock and memory. We discovered that Bmal1−/− mice are impaired in hippocampus-dependent memory tasks. At 24 h after training for contextual fear conditioning, Bmal1−/− mice freeze less than wild-type littermates when trained and tested during the day. While Bmal1−/− mice do learn and exhibit fear memory for the foot shock, their memory for contextual fear is similar to that of wild-type littermates during the night. Bmal1−/− mice are also impaired in spatial learning and memory, as measured by the Morris water maze. Consistent with these memory deficits, LTP at the Schaffer-collateral pathway is reduced in the Bmal1−/− hippocampus. The Bmal1−/− hippocampus also does not demonstrate
diurnal changes in cAMP or MAPK activity in the hippocampus, which Eckel-Mahan et al. (2008) demonstrated are necessary for the maintenance of contextual fear learning. Furthermore, the Bmal1\(^{-/-}\) hippocampus exhibits impaired training-induced activation of MAPK, which is normally seen when wild-type mice are trained for contextual fear conditioning (Sindreu et al. 2007). The hippocampal memory deficits exhibited by Bmal1\(^{-/-}\) mice are most likely due to deficiencies in key signaling events required for formation and maintenance of hippocampus-dependent memory, including activation of MAPK and diurnal oscillation of cAMP and MAPK activity. The dampened level of MAPK activity in the Bmal1\(^{-/-}\) hippocampus may still be sufficient to permit learning and memory of contextual fear conditioning. Alternatively, other signaling pathways leading to the phosphorylation of CREB and CRE-mediated transcription could compensate for the reduction of MAPK activity (Johannesen et al. 2004).

We were surprised to find that Bmal1\(^{-/-}\) mice demonstrate no deficits in novel object recognition, and even enhancement 24 h later compared to wild-type littersmates. Though it is clear that the hippocampus is required for spatial memory, there exists debate as to the extent of the hippocampus’ involvement for recognition memory (Clark et al. 2000; Broadbent et al. 2004; Winters et al. 2004; Good et al. 2007). Phan et al. (2011) similarly find that SCN lesioned mice demonstrate no deficit in novel object recognition, despite the impairment to both contextual and fear and Morris water maze memory. Kondratova et al. (2010) report that Bmal1\(^{-/-}\) mice exhibit altered exploratory activity, which may explain their behavior in the novel object recognition task. Specifically, Bmal1\(^{-/-}\) mice are hyperactive when exposed to novelty, as assessed by open field activity.

Given that sleep is also strongly associated with hippocampus-dependent memory (Diekelmann and Born 2010) and Bmal1\(^{-/-}\) mice have an impaired sleep architecture and diurnal distribution, even in LD conditions (Laposky et al. 2005), sleep disruption could contribute to impaired hippocampus-dependent function in Bmal1\(^{-/-}\) mice. Bmal1\(^{-/-}\) mice spend more time in REM and NREM sleep, but this increase in sleep is not concentrated during the day as it is with wildtype mice. Eckel-Mahan et al. (2008) find that the peak in MAPK signaling activity in the hippocampus occurs during the day in wild-type mice, when mice spend the most time sleeping. Luo et al. (2013) further demonstrate that the cAMP/MAPK/CREB transcriptional pathway is higher specifically during REM sleep compared to NREM and wake stages when evaluated at ZT14–ZT18 under 12-h LD conditions. Perturbing sleep can disrupt hippocampus-dependent memory, synaptic plasticity, and molecular signaling. In rats, sleep deprivation negatively affects consolidation of contextual fear conditioning, but not cued fear conditioning (Graves et al. 2003), and decreases LTP, synaptic transmission, and MAPK activation in the hippocampus (Ravassard et al. 2009). Thus, alterations in sleep may contribute to the reduction of diurnal, hippocampal cAMP/MAPK signaling activity and impairments in hippocampus-dependent memory in Bmal1\(^{-/-}\) mice.

Our data are consistent with the observation that lesioning the SCN impairs memory persistence and inhibits the diurnal oscillation of MAPK activity and CAMP in the hippocampus (Phan et al. 2011). There is no direct synaptic link between the SCN and the hippocampus (Watts et al. 1987; Morin et al. 1994) thereby implicating indirect synaptic input and/or diffusible factors in entraining hippocampal rhythms. The SCN indirectly projects to the limbic system (including the amygdala and hippocampus) through the paraventricular nucleus, the lateral septum, and the bed nucleus of the stria terminalis (Morin et al. 1994). Potential diffusible candidates include glucocorticoids (Girotti et al. 2009; Dickmeis et al. 2013) and melatonin (Stehle et al. 2013) as they are susceptible to circadian influence from the SCN and also act on the hippocampus (Reul and de Kloet 1985; Musshoff et al. 2002). For example, melatonin is a night cue for mammals which inhibits the activity of type 1 adenyl cyclase and compromises LTP (Wang et al. 2005). However, C57BL/6 mice, the most background in transgenic mouse strains, including the global Bmal1\(^{-/-}\) mouse, have a natural melatonin knockdown due to Known aceytyltransferase (AANAT) (Roseboom et al. 1998). As C57BL/6j mice maintain circadian oscillations outside of the SCN (Stehle et al. 2002) despite dramatically

Figure 3. LTP at the Schaffer-collateral synapse is impaired in the Bmal1\(^{-/-}\) hippocampus. (A) Input/output (I/O) relationship between stimulus (μA) and the slope of the postsynaptic evoked fEPSP (mV/ms). Stimulus ranged from 20 to 150 μA. There is no difference between the Bmal1\(^{+/+}\) and Bmal1\(^{-/-}\) I/O values at each stimulus. Tukey's multiple comparison test. n = 10–12. (B) Paired-pulse facilitation with interpulse interval ranging from 20 to 290 msec. There was no difference between the normalized slopes of the second iEPSP at each interpulse interval. Tukey's multiple comparison test. n = 7–9. (C) Averaged LTP response of the Schaffer-collateral fibers, represented by fEPSP slope and normalized to pretetanic baseline. To induce LTP, three tetanic stimuli (1-sec, 100-Hz train with 0.1-msec pulse length) separated by 5 min were delivered. Bmal1\(^{-/-}\) hippocampus demonstrated significantly reduced LTP with a mean fEPSP slope response within first 30 min following induction (U = 0.0, P < 0.0001, r = 1.21, Mann–Whitney). The Bmal1\(^{-/-}\) hippocampus continued to demonstrate a significantly reduced response 60–90 min following induction (U = 0.0, P < 0.0001, r = 1.22, Mann–Whitney). (D) Representative LTP traces from individual slices. Black is 5 min after tetanic stimulations. Red is 60 min after tetanic stimulations. All values represent mean ± SEM.
reduced melatonin signaling, melatonin is not essential. Similar to melatonin, glucocorticoids are not essential in entraining periphery circadian rhythms. In adrenalectomized Per1::luciferase rats, only some peripheral tissues exhibited a phase shift of activity (Pezuk et al. 2012). The SCN likely contributes to the molecular oscillations of signaling activity in the hippocampus through redundant inputs rather than relying on a single mechanism. The connection between the SCN and signaling oscillations in the hippocampus warrants further investigation.

We find that genetically abolishing the molecular clock compromises hippocampus-dependent learning and memory tasks. This report extends our understanding of the relationship between diurnal rhythms and the hippocampus and is consistent with substantial literature implicating the circadian system in memory (Gerstner and Yin 2010).

Figure 4. There is no diurnal oscillation of ERK activity or cAMP in Bmal1−/− hippocampi. (A) Western blot image depicts representative phosphorylated ERK and ERK intensities from isolated hippocampi of individual mice at ZT4 or ZT16. (B) Ratio of pERK to ERK volume intensities normalized to control Bmal1+/+ ZT4 levels. There is a significant effect of genotype (F(1,26) = 6.085, P < 0.05) and time of day (F(1,26) = 6.875) on diurnal phospho-MAPK levels. For Bmal1+/+ hippocampi, phospho-MAPK is higher at ZT4 compared to ZT16 (P < 0.05). Bmal1−/− hippocampi showed no change in phospho-MAPK activity between ZT4 and ZT16 and exhibited lower levels of phospho-MAPK at ZT4 compared to Bmal1+/− hippocampi (P < 0.05). Two-way ANOVA with Bonferroni post-hoc test. All values represent mean ± SEM, n = 6–9. (C) Ratio of cAMP concentration (pmol) to protein (mg) normalized to Bmal1+/+ ZT4 group. There are significant effects of genotype (F(1,54) = 21.56, P < 0.0001) and time of day (F(1,54) = 9.101, P = 0.0039) on diurnal cAMP levels. Bmal1+/− hippocampi demonstrated increased levels of cAMP at ZT4 compared to ZT16 (P < 0.05). Bmal1−/− hippocampi showed no diurnal change in cAMP at ZT4 and exhibited lower levels of cAMP at ZT4 compared to Bmal1+/− hippocampi (P < 0.001). Two-way ANOVAs with Bonferroni post-hoc test. All values represent mean ± SEM, n = 12–16.

Materials and Methods

Mice

Bmal1+/− breeders in the C57/Bl6 background were generously provided by Dr. Christopher Bradfield from the University of Wisconsin Medical School, Madison, WI. Mice were genotyped with PCR as previously described (Bunger et al. 2000). Bmal1+/− littermates were used as controls. All experiments were performed on adult, male mice aged 3–5 mo. Food and water were provided ad libitum and animals were maintained on a 12-h light-dark (LD) cycle, with light onset ZTO at 8 a.m., unless otherwise specified. Experiments were in accordance with the Institutional Animal Care and Use Committee’s recommendations at the University of Washington.

Activity monitoring

Mice were individually housed and their voluntary activity data were acquired using QA-4 activity input modules coupled to infrared motion detectors and the VitalView Data Acquisition System (Mini Mitter, version 4.1). Actograms and periodograms were generated with the ImageJ plug-in ActogramJ (University of Wuerzburg). Mice were monitored for 7 d in 12-h LD conditions and 14 d in DD conditions. Only the last 7 d in DD conditions were included in depicted actograms and periodogram analysis.

Contextual fear conditioning

Mice were handled for at least 5 d before all behavioral testing. For contextual fear training, mice were exposed to a 10 (W) × 10 (D) × 6 (H) cm, transparent Perspex glass chamber with a metal shock grid (Colbourn Instruments). Between each subject, the chamber was wiped with diluted acetic acid. Mice were allowed to explore the novel context for 2 min before receiving a 0.7-mA foot shock. They were returned to their home cage after a 1-min recovery. Behavior during testing was video recorded and the percentage of freezing activity was scored by a blinded investigator. Freezing was scored as all four paws on the ground and no movement other than respiration. Mice were trained and tested from ZT3 to ZT5, during the light phase, or under red light from ZT15 to ZT17, during the night phase.

Morris water maze

Mice were placed in a 122-cm-diameter pool filled with room temperature water (22°C) made opaque with nontoxic, white, tempera paint. They were trained for 8 d, four times a day, to locate the hidden and fixed platform (circular, 5-cm diameter) using visual cues to navigate. Mice were placed in randomized locations of the pool for each trial. During training, the mice were given 90 sec to find the platform and guided to the platform when they did not find it. They sat on the platform for 30 sec before removal. Their memory was tested using a probe trial, where the platform is removed, lasting 90 sec. The probe trial was video recorded and their swim behavior was analyzed using Ethovision (Noldus). Mice were trained and tested from ZT3 to ZT8, during the light phase.

Novel object recognition

Mice were habituated to a 17 (W) × 8.5 (D) × 6 (H) cm cage overnight. After habituation, they explored two identical plastic objects (A) for 5 min, three times, in the habituated cage. Thirty minutes after training, they were presented with object A and a new object B for 5 min. Twenty-four hours after training, they were presented with object A and a new object C for 5 min. Objects were sprayed with ethanol in between animal subjects. Investigators video recorded each trial and later scored exploration time with each object. Exploration was defined as anytime a mouse’s head was oriented toward the object and their nose was within 1 cm of the object. Time spent climbing on objects was eliminated from exploration time. Mice were trained and tested from ZT3 to ZT6, during the light phase.

Electrophysiology

Hippocampal LTP was compared between Bmal1+/− and Bmal1−/− male mice at ages 2–3 mo. After dissection at ZT2, brains were put in ice-cold cutting aCSF (12.5 mM NaCl, 0.25 mM KCl, 0.6 mM MgCl2, 0.05 mM CaCl2, 0.125 mM Na2HPO4, 10 mM glucose, 25 mM NaHCO3) containing APV (40 μM, obtained from Tocris) and then cut into 400-μm coronal sections using a vibratome (Leica VT1000S, Leica Microsystems). Slices were recovered for 2 h in recording aCSF (12.5 mM NaCl, 0.25 mM KCl, 0.1 mM MgCl2, 0.25 mM CaCl2, 0.125 mM Na2HPO4, 10 mM glucose, 25 mM NaHCO3). Slices were continuously

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1% NP-40, 100 mM NaF, 1 mM Na3VO4, 1 mM PMSF, phosphatase inhibitors I and III diluted 1:100 (Sigma), and Complete Mini protease inhibitor tablet (Roche). Homogenates were centrifuged at 10,000 g for 10 min. The supernatant was isolated and an equal volume of Laemmli Sample Buffer (BioRad) with β-mercaptoethanol (1:20) was added. The samples were sonicated for 10 sec. Samples were boiled and run on a 12.5% Tris-HCl polyacrylamide gel (BioRad). Proteins were transferred to a PVDF membrane (Millipore) and blocked with 5% milk in a phosphate-buffered saline (PBS) solution with 0.05% Tween. Proteins were detected with rabbit polyclonal antibody to phospho-p44/42 MAPK (Th202/Tyr204, 1:1,000, Cell Signaling, RRID: AB_331775), mouse polyclonal antibody to pan-ERK (1:1,000, BD Transduction Laboratories, RRID: AB_397447), and mouse antibody to actin (1:2000, Millipore, RRID:AB_94235). Blots were probed with alkaline phosphatase-conjugated goat to rabbit IgG (Sigma) and alkaline phosphatase-conjugated goat to mouse IgG (Sigma). Immunoreactivity was developed with the CDP-star western alkaline phosphatase detection system (Tropix). Blots were imaged with ChemiDoc XR+ and analyzed with Image Lab (BioRad). pERK intensity was normalized to ERK intensity, which served as a loading control.

**CAMP ELISA**

The ELISA-based CAMP Biotrak Enzyme immunoassay System protocol (Amersham Biosciences) was used with some minor deviations. Hippocampal tissue was collected and homogenized as described in the Western methods but with the addition of 1 mM of the PDE inhibitor IBMX. Ice-cold ethanol (100%) was added to the homogenate. Homogenates were spun for 2 min at a speed of 10,000g at 4°C. Resulting supernatants were evaporated in a heat block at 55°C and precipitates were resuspended in 100 μL assay buffer. Competition binding was carried out according to the Enzyme Immunoassay System instructions. Extracts were diluted 1:30 to achieve concentrations in the linear range of the assay. CAMP levels were normalized to protein concentrations.

**Statistical analysis**

Statistical tests were performed in GraphPad Prism. α value was set at 0.05. The specific tests used are reported with results.

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**References**


show normal acquisition but impaired long-term retention of place information in the water task. Neuron 75: 51–62.
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In the aforementioned article, the second author's name has been corrected to Trongha X. Phan, as noted above. The PDF and full-text versions online have been updated to reflect this change as well.
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