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Dopaminergic modulation of the persistence of one-trial hippocampus-dependent memory

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The persistence of new memory traces in the hippocampus, encoded following appropriate activation of glutamatergic receptors and the induction of synaptic plasticity, can be influenced by heterosynaptic activation of neuromodulatory brain systems. We therefore investigated the effects of a hippocampus-specific blockade of dopamine D1/D5 receptors on the persistence of spatial memory encoded in one trial using a delayed matching-to-place (DMP) task in a water maze in which rats learn a new escape location each day. A within-subjects design was used such that both short (20 min) and long (6 h) retention intervals, and both drug (SCH23390, a D1/D5 receptor antagonist) and vehicle (aCSF) infusions were tested on different days in the same animals. Bilateral intrahippocampal infusion of SCH23390 (5 µg in 1 µL per side) prior to trial 1 (encoding) caused a differential impairment as a function of memory delay—with no effect during trial 2 (memory retrieval) after a 20-min interval, but a block of memory at 6 h. Further experiments revealed that infusion of SCH23390 immediately after trial 1 (encoding) caused no effect on retention 6 h later, and the poor memory seen at long retention intervals when the drug was present at encoding was not due to a state-dependent failure of retrieval. These results suggest that activation of D1/D5 receptors during memory encoding is necessary for the formation of a persistent memory trace in the hippocampus. The complementary effects of D1/D5 receptor blockade on the persistence of LTP and the duration of memory are consistent with the idea that changes in synaptic strength underlie memory.
Results

A series of three experiments was conducted, consisting of “pre-training” on the DMP task (over 8 d), during which the win-stay strategy was learned, followed by different drug-infusion and memory-delay conditions during a further series of eight “testing” days. As noted previously, the DMP task involves moving the hidden platform between separate locations across days, with varying intervals between trials 1 and 2 of each day (Fig. 1A). On a given day, the platform is placed in a novel location and then stays there for all four trials. In Experiment 1, addressing the primary issue of memory strength vs. persistence, drug or vehicle was infused 15 min prior to trial 1 of the day (Fig. 1B), with the memory delay between trials 1 and 2 varying between 20 min and 6 h. The interval between trials 2, 3, and 4 was always 30 sec (spent on the escape platform). Experiment 2 was concerned with the impact of drug treatment after encoding, and so involved drug or vehicle being infused 15 min after trial 1 and a single 6-h memory delay. In Experiment 3, to test for state-dependent effects, drug or vehicle was infused 15 min before trial 1, and a second infusion—always of SCH23390—was made 15 min before trial 2. Performance was compared with that on interleaved “no infusion” days during the testing sequence; a 6-h ITI between trials 1 and 2 was again used throughout. Whereas most watermaze studies plot performance across days (reference memory experiments), the DMP procedure focuses on changes within a day averaged across days.

Pretraining: Acquisition of the DMP task

During pretraining, all animals swam effectively using the usual posture of forepaw inhibition and learned to search for the hidden platform in trial 1. They then found this location more quickly on subsequent trials. Overall performance improved during the first few days, typically reaching a stable asymptote by day 4. Trial 1 was characterized by high escape latencies indicating the lack of knowledge of each day’s novel platform position, but when placed back in the pool in trial 2, escape latencies were substantially reduced—reflecting the repeated acquisition of one-trial memory. Figure 2 shows the development of this matching-to-place performance over the course of pretraining in Experi-
Experiment 1: A delay-dependent memory deficit following intrahippocampal infusions of SCH23390

In Experiment 1, the testing phase was procedurally identical to pretraining, except that rats received a 5-min bilateral intrahippocampal infusion of either aCSF or SCH23390, finishing 15 min before trial 1 of each day (Fig. 1B). Figure 3A shows normalized path length across trials for the two memory delays after trial 1 (20 min on the left, 6 h on the right). For each animal, every combination of drug and ITI was repeated twice (see Materials and Methods). These two values were averaged for each of the four trials. Data were then averaged across all 23 rats, and a between-subjects standard error calculated, to produce each of the four acquisition curves shown in Figure 3A. Both SCH23390- and aCSF-treated rats exhibited good memory for the platform location in trial 2 after 20 min, but the drug-treated group was impaired after a 6-h memory delay. An analysis of variance of path lengths in trials 1 and 2 revealed a significant triple interaction of trial, drug treatment, and memory delay ($F_{(1,22)} = 4.90; P < 0.05$).

A separate ANOVA of performance at the 20-min delay revealed a significant overall improvement between trials 1 and 2 ($F_{(1,22)} = 14.81; P = 0.001$), but no interaction between trial and drug treatment ($F_{(1,22)} = 1.07; P > 0.3$). The trend toward a delayed memory deficit in trial 2 did not reach significance ($F_{(1,22)} = 3.13; 0.1 > P > 0.05$). In contrast, at the 6-h memory delay a highly significant interaction of trial and drug treatment was observed ($F_{(1,22)} = 20.11; P < 0.001$). Whereas aCSF-treated rats improved between trials 1 and 2 ($t = 4.04, df = 22; P = 0.002$), no change in performance between trials was evident following the administration of SCH23390 ($t = 1.56, df = 22; P > 0.2$).

A separate analysis was conducted of absolute savings in path length (in meters) between trials 1 and 2 as a function of memory delay (20 min or 6 h). This also highlights the delay-dependent effects of treatment with SCH23390 (see Fig. 3B). An overall ANOVA revealed a significant interaction between drug treatment and memory delay ($F_{(1,22)} = 4.90; P < 0.05$). Performance was insensitive to delay following aCSF infusion ($t = 0.85, df = 22; P > 0.9$) but significant delay-dependent forgetting was evident after treatment with SCH23390 ($t = 3.04, df = 22; P < 0.005$). The savings in absolute path length in the two drug conditions did not differ at the 20-min interval ($t = 1.04, df = 22; P > 0.6$), but a clear difference was evident after a 6-h delay ($t = 4.48, df = 22; P < 0.001$). In fact, at a 6-h memory delay, the performance of SCH23390-treated rats did not differ from chance ($t = 1.56, df = 22; P > 0.1$; one-sample t-test). Upon return to the short interval between trials 2 and 3, and then 3 and 4, the performance of the animals in the SCH23390 6-h delay condition reached levels equivalent to those of aCSF-treated controls ($t = 2.74; P > 0.1$). This indicates that drug-treated animals were able to remember the position of the platform onto which they escaped in trial 2 (over 6 h after drug infusion) and so perform well in trials 3 and 4.

Measurement of swim speed revealed a small but transient decline following treatment with SCH23390 (Fig. 3C). This effect appeared predominantly in trial 1, with little effect on subsequent trials, and sometimes resulted in slower swim speeds. An analysis of variance of swim speeds across all trials revealed a significant interaction between drug treatment and trial ($F_{(3,66)} = 5.54; P < 0.05$). Pairwise comparisons showed that swim speeds were significantly lower in trial 1 following SCH23390 treatment, compared with aCSF ($F_{(1,22)} = 35.80; P < 0.001$), further justifying our use of path length rather than escape latency for the main data measures. The impairment was short-lasting, with the difference in swim speed being no more than a trend in trial 2 ($F_{(1,22)} = 4.30; 0.1 > P > 0.05$).

Experiment 2: SCH23390 has no effect on memory at a long delay when given after trial 1

We then sought to establish whether the effect observed in Experiment 1 was due to a requirement for hippocampal dopamine receptor activation during the encoding of the novel platform position or during the subsequent processing of this information after acquisition. In Experiment 2, following the usual pretraining sessions (as shown in Fig. 2), the animals received a 5-min intrahippocampal infusion of either aCSF or SCH23390 between 10 and 15 min after trial 1 on each of the 8 d of further training. Only the 6-h memory delay was used.

The key finding was that when infused with SCH23390, the animals showed good memory for the platform location in trial 2 conducted 6 h later. Performance was indistinguishable from that shown by these same animals on aCSF-infusion days. Figure 4A shows normalized path lengths averaged across the 4 d on which the relevant drug was administered. An analysis of vari-
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Figure 3. Experiment 1. (A) Drug injections prior to trial 1—impact of memory delay. Normalized path length averaged across days during the drug-infusion phase, showing performance across the four trials of each day (n = 23). A delay-dependent deficit is apparent, with the condition in which the animals received SCH23390 and a long memory delay resulting in no memory in trial 2 of each day. The syringes’ symbols and dotted lines indicate the time of drug infusion. (B) Savings in path length between trials 1 and 2. The change in performance between trials 1 and 2 (i.e., savings) is plotted in terms of absolute path length. These data show exactly the same pattern as in the normalized scores. (C) Swim speed. The drug did transiently decrease swim speeds, but the effect is only apparent in trial 1 of each day, scheduled 15 min after the intrahippocampal drug infusion. Means ± 1 SEM.

Normalization of path lengths in trials 1 and 2 revealed no significant effect of drug treatment (F < 1), and no interaction between drug treatment and trial (F < 1). This finding is supported by an analysis of savings in path length between trials 1 and 2 for both groups. As shown in Figure 4B, there was no difference in savings between the SCH23390 and aCSF groups (t = 0.33, df = 7; P > 0.7).

Normalization of path lengths offered the opportunity to compare across experiments. Path length in trial 2 of Experiment 2, after a 6-h ITI, was ±60% of that in trial 1 for both the aCSF and SCH23390 conditions. In Experiment 1, the same value was obtained following aCSF infusions given prior to trial 1, whereas the SCH23390 condition was characterized by a much longer mean path length in trial 2 (112%). Thus, there is a dramatically different effect of giving SCH23390 at a point 15 min before or 15 min after the memory-encoding trial on memory measured 6 h later.

Experiment 3: Absence of state-dependent effects of SCH23390 on retention after a long delay

State-dependent memory is a phenomenon in which the retrieval of information is possible only if the subject experiences the same sensory context and physiological state as that present during the encoding phase. One possible explanation for the drug-induced retrieval deficit observed in Experiment 1 at the 6-h interval is that the drug was no longer present when the rats were placed back into the pool in trial 2. In contrast, at the 20-min interval, the drug would almost certainly have been present in both trial 1 and trial 2, maintaining the same physiological state during both the encoding and retrieval phases of the experiment.

Experiment 3 was conducted in order to address this alternative possibility; 15 min before trial 1 of each day, animals received an intrahippocampal infusion of either aCSF or SCH23390; a second infusion, always of SCH23390, was made 15 min prior to trial 2 (see Fig. 1B). The interval between trials 1 and 2 was always 6 h. Days when animals had no infusions were interleaved between days with infusions to provide an internal within-subjects control for baseline performance on the task. A counterbalanced sequence of the two conditions continued for 8 d.

The key finding was that when animals received intrahippocampal infusions of SCH23390 both 15 min before trial 1 and 15 min before trial 2, they showed poor memory (at 6 h) for the platform location in trial 2 (Fig. 5A). However, when the animals were injected with aCSF 15 min before trial 1, and then given SCH23390 before trial 2, retention was normal; performance was equivalent to that observed on the “no infusion” days. An ANOVA of performance in trials 1 and 2 revealed a significant interaction between treatment and trial (F2,14 = 5.14; P < 0.05), with no significant improvement between trials in the SCH23390/SCH23390 condition (t = 0.58, df = 7; P > 0.9), but a significant reduction in path length on aCSF/SCH23390 (t = 3.64, df = 7; P < 0.05). An ANOVA of savings data revealed a main effect of drug treatment (F2,14 = 6.37; P < 0.02), with significantly higher savings in the aCSF/SCH23390 condition relative to the SCH23390/SCH23390 condition (t = 5.94, df = 7; P < 0.001), in which no significant savings were observed (t = 0.58, df = 7; P > 0.5; one-sample t-test).

Normalization again allowed interexperiment comparisons. In Experiment 3, performance in trial 2 (ca 45% of trial 1 path length) was slightly better than in Experiments 1 and 2, but the overall pattern shown across groups was comparable. Path length in trial 2 in the SCH23390/SCH23390 condition of Experiment 3
was \(\cong 91\%\) of that in trial 1 (compared with \(\cong 39\%\) for the aCSF/SCH23390 condition), a deficit of similar magnitude to that found in Experiment 1.

**Histology**

Cannulae were correctly placed within the dorsal hippocampal formation in all cases; a representative example of Nissl-stained brain sections is shown in Figure 6A. Infusion sites for all 39 rats tested in Experiments 1–3 are illustrated in Figure 6B, mapped onto successive coronal sections of the Paxinos and Watson (1998) atlas. The tips of all infusion cannulae were correctly located in the hippocampal formation.

**Discussion**

The main finding of these experiments is that bilateral intrahippocampal infusion of the D1/D5 receptor antagonist SCH23390 produced a delay-dependent impairment of spatial memory. There was a modest trend, but no significant impairment of memory after a short delay (20 min), arguing against a substantial contribution of dopaminergic activation to memory strength under the present circumstances, but a clear loss of spatial memory after 6 h, implying an effect on persistence (Experiment 1). Moreover, the effect of SCH23390 on performance after the 6-h interval was specific to it being present during the encoding of the platform location during trial 1, as no effects on performance after the 6-h interval were observed when the drug was infused after trial 1 (Experiment 2). The impairment seen at 6 h was not due to state dependency (Experiment 3) as a deficit was also seen if drug infusions occurred prior to both the encoding trial (trial 1) and the first memory retrieval trial (trial 2). The findings of Experiment 3 also replicate the delay-dependent effects of dopamine receptor blockade observed in Experiment 1: Long-term memory in trial 2 (6-h ITI) was impaired following an infusion of SCH23390 before trial 1, but short-term memory between trials 2 and 3 (30-sec ITI) was unimpaired following a second drug infusion before trial 2.

**Infusion of SCH23390: Dose, timing, and side effects**

The concentration of SCH23390 used in the present study (5 µg in 1 µL) was based on the highest dose infused into the prefrontal cortex in the study by Seamans et al. (1998), but is higher than concentrations typically infused intrahippocampally (e.g., Bernabeu et al. 1997) (maximum dose = 5 µg per hippocampus). In the absence of microdialysis data (see Davis et al. 1992), it is difficult or impossible to estimate the effective hippocampal concentration of a drug following an acute intrahippocampal infusion. Accordingly, we cannot exclude the possibility that SCH23390 has agonist actions at 5-HT2a and c receptors at the concentration used (see Porter et al. 1999). However, the activation of these receptors has been implicated in the facilitation of hippocampus-dependent memory (Buhot et al. 2000; Harvey 2003), in contrast to the findings reported here.

In the present study, drug infusion was associated with a very mild hypokinesia and a reduction in swim speed in trial 1, but these effects were transient, dissipated rapidly, and were largely absent by trial 2. A sensorimotor account of the effects of SCH23390 on retention performance is therefore unlikely. More tellingly, such an account would be inconsistent with our finding of better memory at a short delay after infusion before trial 1 (Experiment 1; 20-min memory delay), when the drug was most likely still present, compared with the impairment seen at the long delay (Experiment 1; 6-h memory delay). This argument is
further supported by the absence of an impairment following drug infusion prior to retention testing in Experiment 3 when aCSF was given prior to trial 1. Nonetheless, the differential effect of SCH23390 infused before or after trial 1 raises the possibility that the drug affects perceptual or attentional processes during encoding, rather than memory per se. However, the use of two different memory-delay intervals and the finding that the drug affects long-term but not short-term memory makes this unlikely; a disruption of such processes should cause a delay-independent impairment; this was not observed.

State-dependent learning is a phenomenon in which the retrieval of newly acquired information is facilitated if the subject is in the same sensory context and physiological state as that during the encoding phase (Overton 1964). By infusing animals just prior to both trial 1 and trial 2 in Experiment 3, we were also able to address the possibility that the animals trained with the 20-min ITI in Experiment 1 were still influenced by the drug in trial 2 and thus able, on state-dependent grounds, to perform well. The drug would have washed out in the 6-h condition, leaving the animals in a different physiological “state” during trial 2. The findings of Experiment 3 revealed that the only group of animals displaying poor retention was that infused twice with SCH23390. This is inconsistent with the effects being due to state-dependency.

It is interesting that the 6-h drug treatment condition exhibits such a marked improvement in performance between trials 2 and 3, with asymptotic performance reached after a single re-exposure to the platform location. Although a failure of retrieval in trial 2 cannot be ruled out, this may not be the most likely explanation. First, a state-dependent failure of retrieval in trial 2 is ruled out by the results of Experiment 3. Second, it is possible that some time-limited effect of the drug infusion procedure, perhaps caused by stress or the change in context, might have impaired subsequent learning during trial 2 at the 20-min ITI. This might explain the poorer savings between trials 2 and 3 in both drug and aCSF conditions following the 20-min ITI, compared with the 6-h ITI. And in Experiment 3, when infusions were always given before trial 2 as well as trial 1, performance in trial 3 in the 6-h drug/drug-treated condition was no better than would be expected based on the one-trial improvement observed in the other conditions, and slightly worse than that observed in Experiment 1.

Relationship of these findings to the synaptic tagging and capture hypothesis

Long-term potentiation (LTP), an activity-dependent persistent increase in synaptic strength (Bliss and Lømo 1973), is the prevailing model of hippocampal learning-related synaptic plasticity, and the cornerstone of the generic “synaptic plasticity and memory” hypothesis. (Goelet et al. 1986; Bliss and Collingridge 1993; Martin et al. 2000; Martin and Morris 2002). However, an efficient memory system must retain relevant information selectively, while permitting the decay of irrelevant memory traces (McGaugh 2000). As discussed in the introduction, novelty has been implicated in the selection of hippocampal memory traces to be stored for long or short periods of time, but other factors such as stress and reward are also known to modulate hippocampal memory (McGaugh 2004; Wittmann et al. 2005; Kors and Frey 2005; Ahmed et al. 2006; Kavushansky et al. 2006). In one variant of this idea, the “synaptic tagging and capture” (STC) hypothesis (Frey and Morris 1997, 1998; Kelleher III et al. 2004), mechanisms underlying the persistence of LTP in the hippocampus involve the intersection of two dissociable events: the local set-

![Figure 6. Histology. (A) Photomicrographs showing representative cannula tracks into the dorsal hippocampus on each side of the brain. (B) Plots of the locations of the tips of the cannulae (n = 39 per hippocampus) as revealed in Nissl-stained brain sections. Infusion sites are marked on the appropriate section of a stereotaxic brain atlas (reprinted with permission from Elsevier © 1998, Paxinos and Watson 1998 [Figs. 35–39]).](learning_memory.png)
ting of tags at activated glutamatergic synapses, followed by the sequestration of plasticity proteins newly synthesized in response to the activation of neuromodulatory inputs—and the subsequent activation of metabotropic cAMP-coupled receptors. Neuromodulatory inputs that regulate hippocampal synaptic plasticity include dopaminergic afferents to CA1 (see Introduction), noradrenergic inputs to the dentate gyrus (Straube et al. 2003; Harley 2004; Almaguer-Melian et al. 2005), and direct or indirect projections from other brain areas, such as the basolateral amygdala (Abe 2001; Frey et al. 2001; Almaguer-Melian et al. 2003; Richter-Levin and Akirav 2003; McGaugh 2004; Roozendaal et al. 2006). Once information is computed as novel or motivationally significant, feedback from neuromodulatory inputs such as those emanating from the VTA may rapidly influence the subsequent storage of such information. For example, Lisman and Otmakhova (2001) and Lisman and Grace (2005) suggest that synaptic plasticity following the exposure to and computation of novelty is critical to the formation of hippocampus-dependent memory.

Although there is some evidence that activation of hippocampal dopamine receptors with D1/D5 receptor agonists can alone be sufficient to induce late-LTP in hippocampal slices (Huang and Kandel 1995), more recent evidence points to the neuromodulatory effect that dopamine exerts on glutamate-induced events (Sajikumar and Frey 2004). Specifically, there is growing evidence for multilevel functional interactions between D1 and ionotropic glutamate receptors (e.g., Yang 2000; for review, see Cepeda and Levine 2006). It seems that the conditions necessary for “synaptic tagging” to occur require simultaneous coactivation of both D1/D5 and NMDA receptors to trigger the up-regulation of protein synthesis (O’Carroll and Morris 2004) or sufficient increases in intracellular CAMP concentrations through synergistic interaction between the two classes of receptor (Mockett et al. 2004). According to this view, the primary physiological impact of dopaminergic activity is not on the strength of potentiation directly, but in contributing to the triggering of cellular consolidation processes immediately after encoding (although effects on LTP magnitude should not be discounted) (see Li et al. 2003). These ideas are compatible with the Lisman and Grace (2005) model of VTA-hippocampal interactions, and are consistent with our observation that SCH23390 was only effective in blocking memory when given at the time of trial 1. If SCH23390 blocked a chronic or constitutive effect of D1/D5 receptor activity on downstream signal-transduction pathways that enable memory persistence, its infusion 15 min after trial 1 might still have limited the persistence of memory. This was not observed. Such findings are also consistent with Kentros et al.’s (2004) data revealing opposite effects of a dopamine agonist (SKF38392) and antagonist (SCH23390) on place field stability, although interpreted by these investigators more in attentional terms. It may seem surprising that D1/D5 blockade as little as 15 min after trial 1 has no effect on memory, but this lack of effect is consistent with the need for dopamine/NMDA receptor interactions at the time of encoding, whether to affect spatial memory or place field stability. More direct evidence in support of the STC framework would include studies showing the induction of long-term memory during blockade of D1/D5 receptors if they had earlier been coactivated with glutamatergic afferent stimulation in the same neurons. Separate studies are underway to investigate this paradoxical prediction.

“Novelty” may have multiple physiological consequences

It is not yet clear what aspect of the rats’ experience during trial 1 triggers the activation of dopamine receptors necessary for long-term memory formation. Relevant factors might include unexpected reward upon encountering the escape platform, an increase in arousal induced by immersion in water, or the experience of escape in a novel spatial location. Although its relevance to the present data remains uncertain, there is growing interest in the role of novelty in synaptic plasticity and memory. For example, exposure to novelty can facilitate the persistence of LTP as well as LTD—even in strains of rat in which LTD is normally difficult to observe (Manahan-Vaughan and Braunewell 1999; Kemp and Manahan-Vaughan 2004), an effect that is prevented by the administration of SCH23390 (Lemon and Manahan-Vaughan 2006). These findings are consistent with the effects of dopamine receptor activation on late-LTP and LTD (Sajikumar and Frey 2004), and support the notion that memory formation requires both down- and up-regulation of synaptic strength (Willshaw and Dayan 1990). Exploration of a novel environment can also reverse LTP that has been recently induced in freely moving animals (Xu et al. 1998a), perhaps owing to the novelty-associated increase in 6 activity (6–8 Hz) in the hippocampus; an EEG pattern may supply the low-frequency stimulation necessary for depotentiation. However, the pharmacological activation of dopamine receptors has been reported to block depotentiation, a phenomenon that has been suggested to protect important memory traces from interference (Otmakhova and Lisman 1998; Kulla and Manahan-Vaughan 2000). In thinking about this apparent contradiction, it may be significant that different forms of novelty can influence synaptic plasticity in distinct ways (Kemp and Manahan-Vaughan 2004). To better understand the relationship between the present findings and the existing literature concerning novelty and the modulation of synaptic plasticity, further studies exploring the interactions between exposure to a novel platform location and the induction and persistence of synaptic changes will be required.

Summary

The present data suggest that the activation of hippocampal dopamine receptors is necessary for the formation of long-term spatial memory. We hypothesize that the firing of midbrain dopaminergic neurons—in response either to the unexpected reward or the spatial novelty of finding an escape platform in a new location—leads to hippocampal dopamine release and the activation of D1/D5 receptors in conjunction with the glutamatergic activation of NMDA receptors. The downstream consequences of this activity might include the up-regulation of protein synthesis, and the subsequent stabilization of synaptic changes at synapses “tagged” by glutamatergic stimulation. In the presence of a D1/D5 receptor antagonist, this selective stabilization mechanism would fail, resulting in the observed loss of long-term memory.

Materials and Methods

Animals

Adult male Lister hooded rats (250–500 g) were used as subjects. They were given ad libitum access to food and water and were maintained on a 12-h light/12-h dark cycle. The animals’ care and maintenance and all experimental procedures were carried out in accordance with UK Home Office regulations under Project License no. 603241.

Surgery

Prior to the implantation of cannulae, the rats were anesthetized with Avertin (tribromoethanol) and placed in a stereotaxic frame (Kopf) using a flat skull position. Guide cannulae (Plastics One; outer diameter = 0.46 mm) were implanted bilaterally into the dorsal hippocampus (coordinates from bregma: AP = −4.5;
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Yang, S.N. 2000. Sustained enhancement of AMPA receptor- and NMDA receptor-mediated currents induced by dopamine D1/D5 receptor activation in the hippocampus. An essential role of postsynaptic Ca2+. Hippocampus 10: 57–63.

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