A specific role for hippocampal mossy fiber’s zinc in rapid storage of emotional memories

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We investigated the specific role of zinc present in large amounts in the synaptic vesicles of mossy fibers and coreleased with glutamate in the CA3 region. In previous studies, we have shown that blockade of zinc after release has no effect on the consolidation of spatial learning, while zinc is required for the consolidation of contextual fear conditioning. Although both are hippocampo-dependent processes, fear conditioning to the context implies a strong emotional burden. To verify the hypothesis that zinc could play a specific role in enabling sustainable memorization of a single event with a strong emotional component, we used a neuropharmacological approach combining a glutamate receptor antagonist with different zinc chelators. Results show that zinc is mandatory to allow the consolidation of one-shot memory, thus being the key element allowing the hippocampus submitted to a strong emotional charge to switch from the cognitive mode to a flashbulb memory mode. Individual differences in learning abilities have been known for a long time to be totally or partially compensated by distributed learning practice. Here we show that contextual fear conditioning impairments due to zinc blockade can be efficiently reduced by distributed learning practice.
induction of long-term potentiation (LTP) is crucial for one-shot associative storage of sensory elements into CA3, without any need of repetitive pattern presentation (Bliss and Collingridge 1993). Therefore, mossy fibers could be crucially involved in rapid learning. Although long-term MF plasticity is known to result from a presynaptic NMDAR-independent mechanism, mediated by presynaptic kainite receptors (KAR) (Schmitz et al. 2001; Bortolotto et al. 2003), bursts of granule cell firing can also induce heterosynaptic potentiation in the TA–CA3 synapses (Ikegaya et al. 2003). Moreover, the existence of NMDA-dependent plasticity between MF and CA3 pyramidal cells which rely on NMDAR activation in the MF terminal zone has been established (Kerr and Jonas 2008; Kwon and Castillo 2008). This NMDAR-LTP could contribute to the property of conditional detonator of MF–CA3 synapses (Yeckel et al. 1999), which is supported by computational theories concerning the functioning of the autoassociative matrix of the CA3 region (Rolls 2007; see also Cerasti and Treves 2010, 2013). For a review of the various mechanisms of MF plasticity, refer to Nicoll and Schmitz (2005). A core issue of this study is to understand why there are large amounts of Zn2+ that corelease with glutamate at this synapse, though it is also found elsewhere, particularly in synaptic vesicles of the Schaffer collaterals (Sindreu et al. 2003), but in smaller quantities. As stated by Takeda et al. (2006), 45% of Schaffer collateral boutons are Zn2+ positive whereas all giant MF terminals in the CA3 region contain synaptic vesicles that stain for Zn2+. These authors hypothesized that Zn2+ released from Schaffer collaterals might suppressively modulate presynaptic and postsynaptic calcium signaling in the CA1, followed by the suppression of glutamate release. Using electrophysiological studies, they showed that low micromolar concentrations of Zn2+ potentiate CA1 LTP (Takeda et al. 2008a) and, more precisely, that they can differentially act on components of LTP at this synapse according to the strength of tetanic stimulation (Takeda et al. 2010). In the CA1 region of rat hippocampal slices, Izumi et al. (2006) observed that low micromolar concentrations of Zn2+ depressed NMDAR responses by 40%–50% and inhibited LTD but not LTP. Conversely, in CA3 low micromolar concentrations of Zn2+ attenuate MF LTP (Takeda et al. 2008b). Therefore, the main point of our study focused on understanding the particular advantage or functional specificity Zn2+ would give to the MF–CA3 synapse. Although the role of a neurotransmitter such as glutamate or even that of dynorphin (Daumas et al. 2007) is well known, that of Zn2+ is much more controversial (for recent reviews, see Sensi et al. 2009, 2011). Zn2+ divalent cations are massively present in synaptic buttons of mossy fibers. Vesicular Zn2+ is coreleased with glutamate depending on the activity of the presynaptic element, then quickly recaptured by transporter systems (Cole et al. 1999; Linkous et al. 2008) in order to reintegrate the presynaptic element and refill synaptic vesicles (Sudhof 1995). Once released into the synaptic cleft, Zn2+ may act on many pre- as well as postsynaptic targets. For instance, it can act as a neuromodulator through its action on GABA and glutamate release (Takeda et al. 2004). It is commonly accepted that its action is confined mainly to the allosteric modulation of ionotropic glutamate receptors (Ueno et al. 2002; Smart et al. 2004), but Malherbe et al. (2005) showed that Zn2+ may also act on metabotropic receptors. Finally, Zn2+ would also possess a specific receptor (ZnR) at the MF–CA3 synapse (Besser et al. 2009). All of these targets represent a wide range of modulation of the MF–CA3 synapse by vesicular Zn2+, which gives it an extraordinarily complex role in the control of plasticity processes at this synapse. This cation has also been considered as an atypical neurotransmitter which could play a major role in potentiation of synaptic strength by translocating into the postsynaptic element (Li et al. 2001a; Gundelfinger, et al. 2010).
et al. 2006) through the ionotropic glutamate receptors permeable to calcium (NMDA, AMPA, and KA-PC) and VDCC activated during synaptic transmission (Li et al. 2001b). This property characterizes the joint action of glutamate and Zn$^{2+}$ to the extent that Zn$^{2+}$ can pass through the aforementioned receptors only if they are directly or indirectly (VDCC) activated by glutamate (Sensi et al. 2009). Once Zn$^{2+}$ has penetrated into the postsynaptic element, it may interact with protein kinases and phosphatases involved in signaling pathways driving gene expression. Thus Zn$^{2+}$, as a trans-synaptic factor, would be crucial to regulate the plasticity of the MF–CA3 synapse. Zn$^{2+}$ may also act on intracellular Ca$^{2+}$ concentration. The so-called “cross-talk” between Zn$^{2+}$ and calcium suggests a competition between these two signaling ions (Takeda et al. 2007). At the postsynaptic element it has been shown that Zn$^{2+}$ can affect a number of transduction pathways such as those involving PKC (Hubbard et al. 1991), CaMKII (Lengyel et al. 2000; Besser et al. 2009), MAPK (Park and Koh 1999; Besser et al. 2009), Erk1 and 2 (Park and Koh 1999; Sindreu et al. 2011), or the Src family tyrosine kinases (Manzerra et al. 2001). The activation of Src is particularly interesting because the substrates of this kinase are involved in processes of synaptic plasticity. Indeed, the Src kinase activated by Zn$^{2+}$ can phosphorylate the NMDA receptor and thus amplify its affinity for glutamate and enhance its excitability (Manzerra et al. 2001). Also, Huang et al. (2008) showed that Zn$^{2+}$ can potentiate the MF–CA3 synapse within minutes by transactivation of TrkB through increasing Src family kinase activity by an activity-regulated mechanism, independent of BDNF (see also Schildt et al. 2013). Finally, once entered in the cell, Zn$^{2+}$ could participate virtually instantly to the assembly of proteins constitutive of the postsynaptic density (PSD), especially by binding to a specific motif of the Shank3 protein (Gundelinger et al. 2006). Thus Zn$^{2+}$ may modulate the structure and function of the PSD, allowing the expression of synaptic plasticity.

In previous studies from our group we analyzed the effects of CA3 mossy-fiber blockade on distributed spatial learning in the Morris water maze (MWM) by using Zn$^{2+}$ chelators. We have shown that the injection, in the CA3 region, of diethylthiocarbamate (DDC or DEDTC), a transmembrane chelator that chelates Zn$^{2+}$ within synaptic vesicles, disrupted the acquisition of spatial learning with no effect on consolidation and recall. In contrast, the chelator calcium ethylenediamine tetraacetic acid (CaEDTA), which does not cross synaptic membranes and chelates selectively Zn$^{2+}$ only after its release into the synaptic cleft, had no effect (Lassalle et al. 2000). However, Florian and Roulet (2004), using a massed procedure, showed that DEDTC also induced a disruption of consolidation in spatial learning whereas CaEDTA was still ineffective. It is therefore relevant to conclude that the disruptive effect of mossy-fiber blockade on spatial learning by DEDTC resulted actually from preventing glutamate release that normally occurs simultaneously with that of Zn$^{2+}$, while Zn$^{2+}$ itself had no specific role in this kind of learning, as demonstrated by the lack of effect of CaEDTA (Ceccom et al. 2013). Therefore glutamate, which is in all cases necessary to the acquisition of spatial learning, is also mandatory for its consolidation when acquisition is performed under a massed procedure. Unexpectedly, we demonstrated that both DEDTC and CaEDTA impaired the acquisition and consolidation of contextual fear conditioning (CFC), suggesting that in addition to glutamate, Zn$^{2+}$ could also have a specific role in this kind of hippocampo-dependent task (Daumas et al. 2004). In a more recent study, we confirmed that, whereas Zn$^{2+}$ blockade by CaEDTA still does not impair memory consolidation of the platform location in the spatial navigation task when acquired under massed learning practice, CaEDTA prevents memory consolidation of one-session contextual fear conditioning (Ceccom et al. 2013). The key difference between these two types of hippocampo-dependent memories likely relates to the burden of emotional charge involved in CFC. According to Diamond et al. (2007), following a strong emotional learning experience, hippocampus and amygdala are both activated, the hippocampus rapidly shifting from a “configural/cognitive map” mode to a “flashbulb memory” mode. As a consequence, both structures afterward undergo a state in which the induction of new plasticity is suppressed, which facilitates the process of memory consolidation. It has been shown that the basolateral nucleus of the amygdala (BLA) and the basomedial nucleus of the amygdala (BMA) can modulate LTP at the perforant path–dentate granule cell synapses in association with perforant-path stimulation (Ace 2001; Abe et al. 2003; Nakao et al. 2004). Many studies showed that emotion enhances both hippocampal LTP and learning via norepinephrine regulation (Huang and Kandel 1996; Ikegaya et al. 1997; Nakazawa et al. 2003; Hu et al. 2007; Tully and Bolshakov 2010), confirming the obvious link between emotional feeling and integration degree of a unique spatio-temporal event.

We therefore analyzed the role of Zn$^{2+}$ and that of glutamate receptors in a form of learning involving the memorization of an event with a strong emotional component and so likely to be acquired at once and to remain permanently associated with the context in which it occurred (Kuriyama et al. 2010), thus constituting episodic-like memory, a form of autobiographical declarative memory which is referred to as flashbulb memory. As in our previous studies, we chose fear conditioning, a form of Pavlovian conditioning that can be achieved in a single session (Phillips and Le Doux 1992; Daumas et al. 2007). The main feature of the CFC paradigm is to simultaneously implement two forms of Pavlovian conditioning: an association between a simple conditioned stimulus (CS), the tone and the US, which can be achieved only by involving the basolateral nucleus of the amygdala (BLA) (Siggurdsson et al. 2007) and a more complex form of conditioning, linking the US to the context in which it is issued. CFC can be achieved independently of the association sound–US provided that the mouse is allowed to explore the conditioning chamber for a sufficient time (at least 2 min) before shock delivery (Fanselow et al. 1990). The hippocampus is then involved, in addition to the BLA, to assemble in memory a representation of the context that will be later associated with US (Anagnostaras et al. 2001; Wiltgen et al. 2010) in one-shot memory.

Our main hypothesis is that MF Zn$^{2+}$ and Glut could play complementary roles, especially during memory consolidation of CFC. To verify this assumption, we performed an in vivo pharmacological study in order to specify the role of Zn$^{2+}$, along with that of ionotropic NMDA glutamate receptors of the three synapses likely to be involved in the consolidation of CFC acquired during a single session. As in our previous studies, we used the DEDTC and CaEDTA chelators along with ZnEDTA (zinc ethylenediamine tetraacetic acid) as a control chelator. Our results match those of Martel et al. (2010) and Sindreu et al. (2011) showing that mice lacking the ZnT3 transporter were actually impaired in contextual fear memory. In a second step we investigated the possible compensatory effects that could be generated by distributed learning practice on memory deficits induced by pharmacological blockade of Glut or/and Zn$^{2+}$. In this case, varying the time period between two sessions of conditioning by observing a 2-h or a 24-h delay restored CFC memory abilities in treated mice. Altogether, this resulted in three companion experiments.

Results

Overall view
In order to investigate the involvement of Zn$^{2+}$ and glutamate in contextual fear memory consolidation and the potential of
remediation of spaced learning when this process is impaired, we compared mice performances following a 2-min, 2-h, or 24-h interval condition (IC) as presented in Figure 2A. Inactivation of zinc was enabled by the use of DEDTC (200 mM) and CaEDTA (200 mM) using as a control ZnEDTA (200 mM). The concentrations of chelators were based on previous studies (Lassalle et al. 2000; Daumas et al. 2004). D-2-Amino-5-phosphonopentanoate (APS) (0.6 μg/μL) was used to block glutamatergic transmission, following Fellini et al. (2009).

The expected actions of the various drugs used in this study and of their combinations result from the analysis of the literature presented in the introduction. They are developed below in the drugs section of the Materials and Methods.

In a first step, results of the three experiments were pooled for a global analysis (Fig. 2B). Afterward, analyses were performed by training interval condition. The homogeneity of freezing levels, around 80% in the three control groups across the three learning procedures, allowed direct comparisons between the three experiments. One-way analysis of variance (ANOVA) shows that the treatment factor had a significant contribution to the variation \( F(7,176) = 36.78, P < 0.001 \) as well as the condition factor \( F(2,176) = 105.95, P < 0.001 \) and that both factors interacted significantly \( F(14,176) = 8.96, P < 0.001 \). The ANOVA model explained 77.6% of the overall variance.

Three control groups were constituted to check for possible side effects linked to surgery and drug infusion: Sham mice underwent classical surgery for the implantation of guide cannulae but did not receive intracerebral injections of drug immediately after the fear-conditioning session. This first group of mice displayed a great percentage of freezing during the contextual fear memory assay (81.48 ± 2.00%), showing that the implantation of guide cannulae by surgery did not disturb either learning or memory of CFC. A second group of mice received bilateral infusions of NaCl in the CA3 hippocampal area immediately after the CFC session. Mice injected with NaCl displayed a great amount of freezing when submitted to the contextual fear memory assay (82.11 ± 1.50%) that did not differ from that of the sham group \( (P = 0.451) \). These results show that infusion of a harmless solution like NaCl does not disturb learning and memory. This group can be considered as the best control for the APS-injected group because this drug was dissolved in NaCl. Finally, a third group of mice received ZnEDTA, which is the most appropriate control for \( \text{Zn}^{2+} \) chelators because it shows the highest similarity with chelator-treated groups. Indeed, ZnEDTA is a divalent ion chelator like NaCl and DEDTC but it is saturated with \( \text{Zn}^{2+} \). Mice injected with ZnEDTA displayed somewhat lower freezing scores (74.5 ± 2.8%) than sham and NaCl mice during the contextual fear recall test, although there was no significant variation \( F(2,22) = 1.414, P = 0.264 \) among these three groups. In order to improve the power and efficiency of ANOVAs, we finally selected ZnEDTA-injected animals as a unique control group because it provides the most conservative control reference.

**Figure 3.** Contextual fear memory assay: 2-min interval condition. Effects on freezing levels of five pharmacological treatments administered immediately after the second conditioning trial of the massed learning session and measured 24 h later, compared to the ZnEDTA control. Results are presented as mean ± SEM. (***) \( P < 0.001 \).

**Treatments effects under massed learning conditions**

**Experiment 1: 2-min interval condition**

A total of 55 mice received only one injection at the end of the CFC learning session in the 2-min interval condition (2-min IC). Freezing values for cue learning (not shown) ranged from 60.4% to 64.8%, displaying no significant variance \( F(5,38) = 0.107, P = 0.990 \). In contrast, as shown by Figure 3, injections of \( \text{Zn}^{2+} \) chelators and/or the NMDAR antagonist AP5 in the CA3 area of the dorsal hippocampus resulted in a significant overall variation of freezing to the context \( F(5,49) = 22.739, P < 0.001 \). The proportion of the total variance explained by this model accounted for 69.88%.

Post-hoc analyses showed that freezing levels in the different groups could vary significantly according to the drug they received. Mice injected with \( \text{Zn}^{2+} \) chelators and/or the NMDAR antagonist AP5 expressed significantly lower freezing than ZnEDTA.
mice \( (P < 0.001) \). The NMDAR antagonist AP5 caused significantly lower freezing than in the ZnEDTA control group \( (P < 0.001) \) during the contextual fear memory assay, suggesting that blockade of NMDARs by the antagonist AP5 induced a disruption of the consolidation process. The extracellular \( Zn^{2+} \) chelator CaEDTA induced reduced levels of freezing compared to the control group \( (ZnEDTA) \) \( (P < 0.001) \) but not to the AP5 group \( (P = 0.209) \). In the same way, mice injected with the intracellular \( Zn^{2+} \) chelator DEDTC displayed significantly lower freezing than the ZnEDTA control group \( (P < 0.001) \), the AP5 group \( (P = 0.002) \), and the CaEDTA group, although the difference was only marginally significant in this case \( (P = 0.081) \). Coinjection of CaEDTA and AP5 induced significantly lower freezing compared with that in the ZnEDTA control group \( (P < 0.001) \). Moreover, their freezing level was even lower than that of AP5 \( (P = 0.001) \) and CaEDTA-injected mice \( (P = 0.040) \). These results suggest cumulative effects of CaEDTA and AP5 when they are coinjected. DEDTC and AP5 were also coinjected in the same way. This group showed significantly lower freezing than the ZnEDTA control group \( (P < 0.001) \) and the AP5-injected group \( (P = 0.011) \), but did not differ significantly from CaEDTA \( (P = 0.178) \), DEDTC \( (P = 0.745) \), or CaEDTA + AP5 -injected groups \( (P = 0.502) \).

To summarize, simultaneous blockade of postsynaptic NMDARs of MF–CA3, TA–CA3 and ARCs by AP5 dramatically disrupts the consolidation of fear conditioning to the context in 2-min IC. In addition, blockade of \( Zn^{2+} \) after being released into the MF–CA3 synaptic cleft by CaEDTA induces a disruption that is comparable to that of blocking NMDARs. When we combine the blocking of NMDARs at the three synapses and blocking of \( Zn^{2+} \) in the MF–CA3 synapse (CaEDTA + AP5) we obtain an even greater effect. In contrast, this effect does not differ from that resulting from the injection of DEDTC, that blocks the release of \( Zn^{2+} \) and Glut at MF–CA3 without affecting NMDARs at TA–CA3 and ARCs, which suggests that the latter are not sufficient to allow consolidation of CFC. Besides blocking the simultaneous release of \( Zn^{2+} \) and Glut at MF–CA3 with that of NMDARs at the three synapses by DEDTC + AP5, coinjection does not have a greater effect in the 2-min IC. We can therefore conclude that (1) the activation of the MF–CA3 synapse plays a crucial role in the consolidation of CFC in the 2-min IC and (2) the actions of \( Zn^{2+} \) and Glut at this synapse are essential and that these two mediators have complementary effects. We can consequently suggest that \( Zn^{2+} \) could act as a “booster” on memory consolidation of emotional learning achieved in one session, thus allowing the formation of a flashbulb memory. Total or partial experimental blockage of the release of these neurotransmitters or blockage of their receptors would allow simulating NMDARs or zincergic dysfunctions in the CA3 region, potentially resulting in disruption of the acquisition and/or memorization. Hence, when CA3 is prevented from operating as a detonator (by blocking \( Zn^{2+} \), once released, by CaEDTA) it will rather operate in cognitive mode and therefore a one-shot memory is no longer possible.

This raises the question whether hippocampal impairments obviously resulting from \( Zn^{2+} \) deficits definitely prevent emotional memories or can be, nonetheless, compensated in any way. Thus, it could be hypothesized that when CA3 can operate only in cognitive mode, splitting learning into different sessions could, nevertheless, allow learning achievement. Indeed, it has long been known that distributed practice, i.e., reviewing learning (Commins et al. 2003; Lehmann and McNamara 2011) or practicing a skill at spaced intervals (Overduin et al. 2006) is far more effective than massed practice in one heavy session. Thus, experimental data show that variations in learning abilities and memory between different strains of mice (Bovet et al. 1969), or in KO mice (Bourtchuladze et al. 1994) that fail to learn or memorize with massed learning trials, can be partially or totally overcome when trials are spaced in time. If that happens, the roles of Glut and NMDA receptors need to be clarified, assuming that in cognitive mode FM–CA3 LTP would be only presynaptic, whereas in detonator mode, \( Zn^{2+} \) would also activate the postsynaptic element through its action on NMDARs and/or through its translocation into the postsynaptic element as detailed above.

Therefore we wanted, in addition, to study whether the effects induced by these treatments on hippocampal deficits could be alleviated by a distributed learning procedure. We wondered if \( Zn^{2+} \) and Glut would be implicated in the same way if mice were submitted to spaced (distributed) trial learning. We tried to assess this hypothesis by using a modified protocol of fear conditioning. We designed two new experiments. In experiment 2, conditioning sessions were spaced by a 2-h interval (2-h IC), whereas in experiment 3, the second trial was delayed by 24 h (24-h IC). In both cases, mice received the infusion of drugs immediately after each trial (see Fig. 2A).

### Treatments effects under distributed learning conditions

#### Experiment 2: 2-h interval condition

A total of 48 mice were injected immediately after conditioning (Fig. 4). Injections of \( Zn^{2+} \) chelators and/or the NMDAR antagonist in the CA3 area of the dorsal hippocampus resulted in a significant overall variation of freezing \( (F_{(5,42)} = 11.384, P < 0.001) \). The proportion of total variance explained by this model accounted for 57.54%. As expected, freezing values for cue learning ranging from 60.4% to 71.6% (not shown) displayed no significant variance \( (F_{(5,41)} = 0.839, P = 0.530) \). Post-hoc analyses showed that mice infused with the NMDAR antagonist AP5 showed again significantly lower freezing levels than the ZnEDTA control group \( (P < 0.002) \) during the contextual fear memory assay. On the other hand, this time the extracellular \( Zn^{2+} \) chelator CaEDTA had no significant effect on freezing levels (CaEDTA vs. ZnEDTA, \( P < 0.286) \), whereas mice injected with the intracellular \( Zn^{2+} \) chelator DEDTC displayed significantly lower freezing than the ZnEDTA control group \( (P < 0.001) \) and the CaEDTA group \( (P = 0.001) \), while the DEDTC group did not differ significantly from the AP5 group \( (P = 0.397) \). Mice coinjected with CaEDTA + AP5 displayed significantly lower freezing than mice of the ZnEDTA control group \( (P = 0.016) \). Moreover, this coinjected group also showed

![Figure 4](link-to-image)
Significantly lower freezing than the CaEDTA-injected group ($P < 0.001$), whereas no significant differences appeared with the AP5 ($P = 0.443$) and DEDTC groups ($P = 0.110$). Coinjection of DEDTC and AP5 decreased freezing compared to the ZnEDTA control group ($P < 0.001$). However, this coinjected group showed a marginally significant lower level of freezing than the AP5 treated group ($P = 0.085$) and a significantly lower level of freezing than the CaEDTA + AP5 ($P = 0.015$) group, whereas no significant difference appeared with the DEDTC group ($P = 0.371$).

To summarize, in the 2-h IC, Zn$^{2+}$ was no longer necessary to the consolidation of CFC since CaEDTA had no effect on freezing level expressed during the contextual memory assay, whereas functional NMDARs were still required. On the other hand, and contrary to what could be observed in the 2-min IC, coinjection of DEDTC + AP5 resulted in a significantly greater impairment of CFC consolidation than coinjection of CaEDTA + AP5. This difference implies that blockade of Glut release by DEDTC at MF–CA3 also prevents any action of Glut on presynaptic KARs while not blocking NMDARs at the other two synapses, as explained in the drugs section of Materials and Methods. If such an effect could be detected in the 2-h IC while it was not in 2-min IC, it is because the spacing between the two trials increased the memory strength of CFC in treated animals, whereas this phenomenon was masked by a floor effect in the 2-min IC.

**Experiment 3: 24-h interval condition**

As can be seen from Figure 5, the injection of Zn$^{2+}$ chelators and/or the NMDAR antagonist AP5 in the CA3 area after each learning session to a total of 50 mice resulted in a low, albeit significant, overall variation of freezing ($F_{5,43} = 3.657$, $P = 0.007$). The proportion of total variance explained by this model thus accounted for 29.36%. Post-hoc analyses confirmed that only the DEDTC + AP5 group showed significantly impaired freezing when compared to the other groups ($P$ values ranged from $<0.008$ to $0.001$). Then again, freezing values for cue learning (not shown) displayed no significant variance ($F_{5,43} = 1.917$, $P = 0.111$). They ranged from 62.5% to 81.2%, showing slightly higher values than in the 2-min IC and 2-h IC experimental conditions.

Therefore, a widely distributed training procedure allows impairments of CFC memory induced by various treatments to be fully restored, except for mice coinjected with DEDTC + AP5.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Contextual fear memory assay: 24-h interval condition. Effects on freezing levels of five pharmacological treatments administered immediately after each conditioning trial of the distributed learning session and measured 24 h later, compared to the ZnEDTA control. Results are presented as mean ± SEM. (**$P < 0.01$.

The result from this outcome is that functional impairments induced by Zn$^{2+}$ chelators and NMDAR blockade can be rescued by the 24-h IC training procedure, except when the action of Glut on presynaptic KARs at the MF–CA3 synapse is also prevented, as explained in the Materials and Methods section.

**Discussion**

Selective blockades of the various CA3 synapses have overall detrimental effects on consolidation of HPC-dependent CFC. Conversely, as expected, they have no impact on consolidation of HPC-independent fear conditioning to the sound (data not shown).

An important outcome of this study is that the effects of treatment interact extensively with training procedures. The treatment × training condition interaction is both quantitative, since the effects of treatments are more pronounced in the 2-min IC than the 2-h IC and, a fortiori, the 24-h IC (the minimum rate of freezing induced by the most effective treatment [DEDTC + AP5] increases, respectively, from 26.8% to 38.5% and 62% when the IC delay shifts from 2 min to 2 h then 24 h), and qualitative since treatment effects differ according to the training procedure (while all treatments have a significant effect in the 2-min IC, the effect of CaEDTA disappears in the 2-h IC and only the DEDTC + AP5 treatment still exerts a residual effect in the 24-h IC).

It is of paramount importance to point out that training conditions do not affect memory performances of control mice since sham, NaCl, and ZnEDTA control groups display optimal capacities for acquiring and storing CFC whatever the training conditions. On the other hand, distributed training conditions allow fairly good levels of CFC achievement when CA3 functioning is disturbed by the treatments. Duration of the consolidation phase that separates the two acquisition trials is the main factor differentiating training conditions implemented in this study. Although the drug infusion regimen differed between experiment 1 and experiments 2 and 3, control mice receiving a second injection of saline did not show impaired freezing scores. Therefore, it is likely that different drug infusion regimens did not bias the results and that between groups variations are specific to drug effects.

The basic rationale for this study was that the 2-min IC procedure matches the conditions for one-shot memory with a very strong emotional component leading to the establishment of a flashbulb memory. In such a kind of rather extreme experience, all synapses in the CA3 autoassociative network are required since blockade of the action of Glut on postsynaptic NMDARs at MF–CA3, CA3–PP, and ARCs by AP5 as well as blockade of Zn$^{2+}$ at MF–CA3 synapses by CaEDTA impair CFC memory consolidation. Therefore Zn$^{2+}$ and Glut must both be considered as necessary to flashbulb memory formation. Our conclusion is strengthened by the results of CaEDTA + AP5 coinjections that exert cumulative effects while each one is sufficient to partially disrupt CFC consolidation in the 2-min IC.

In contrast, previous work (Lassalle et al. 2000) showed that Zn$^{2+}$ is not essential to the acquisition of spatial localization in the Morris water maze since CaEDTA did not impair learning, whereas the action of Glut at the MF presynaptic NMDARs and KARs would be still required, as shown by DEDTC injections. Such discrepancy between the involvement of Zn$^{2+}$ in MWM and CFC arises because in the Morris water maze, the spatial component of learning (to be compared to the representation of context in the CFC) is acquired gradually over multiple trial sessions spaced 24 h apart. It requires an extended stay on the platform during which the gradual integration of bits of spatial information acquired during each trial and their progressive association with the positive reinforcement takes place. These are less stressful...
conditions than an unconditional negative reinforcement supplied by a violent shock. This argument still holds when spatial navigation learning is acquired under massed training practice (Ceccon et al. 2013).

On the other hand, during one-shot learning (2-min IC), as Zn$^{2+}$ acts merely at mossy fibers synapses, it can be hypothesized that it allows them to shift from the “cognitive” to the “detonator” mode, which is critical for efficient consolidation of one-shot memory (Diamond et al. 2007). This would require both presynaptic and postsynaptic action of Zn$^{2+}$ and glutamate since DEDTC and CaEDTA + AP5 induce similar disturbances. In CFC, such an operating mode could result from the activation of BLA (Ikegaya et al. 1997; Nakao et al. 2004; Diamond et al. 2007) which is able to drive hippocampal activity (Abe et al. 2003; Calandreau et al. 2006).

Moreover, in one-shot learning, the action of Glut on MF presynaptic KARs, likely responsible for the NMDAR independent presynaptic LTP, may not play a major role because the lack of stimulation of KARs resulting from the action of DEDTC + AP5, in addition to blocking of Zn$^{2+}$ and Glut postsynaptic effects, exerts no additional disruptive effect on consolidation. However, such a presynaptic effect of Glut might be masked by a floor effect of the freezing level in the 2-min IC condition. In all experiments performed with massed learning condition, none of the treatments has lowered the freezing below $\approx$ 25%. On the other hand, when the delay between trials or sessions is increased, the consolidation level is higher, even more so in the 24-h IC than in the 2-h IC. CaEDTA injections clearly show that Zn$^{2+}$ is no longer necessary in either 2-h IC or 24-h IC. However, the postsynaptic action of Glut mainly at MF–CA3 synapses remains necessary to memory consolidation in the 24-h IC which is no longer the case in the 2-h IC, as shown by AP5 and DEDTC injections.

Finally, even in distributed learning conditions (2-h IC and, a fortiori, 24-h IC), the presynaptic action of Glut at MF–CA3 remains necessary to the consolidation of pieces of learning acquired by mice whose NMDA receptors are blocked at the three synapses, since the additional blocking of the action of Glut receptors on the presynaptic MF–CA3 KARs induced by DEDTC + AP5 vs. CaEDTA + AP5 still induces a partial memory deficit.

Learning conditions with two trials distributed over 2 h or 24 h can therefore restore a normal level of acquisition and consolidation in mice whose activity of NMDARs at the MF–CA3, TA–CA3, and ARCs and the action of Zn$^{2+}$ at MF–CA3 and ARC synapses are blocked, as long as the presynaptic action of Glut at MF–CA3 is preserved. On the other hand, when all actors of the CA3 autoassociative matrix are blocked simultaneously by DEDTC + AP5, there still remains a possibility for a “meaningful” level of consolidation with distributed learning (40% of freezing in the worst case in 2-h IC and around 60% in 24-h IC).

These observations suggest that in the absence of MF–CA3 function, other synapses that would not be directly implicated in driving CA3 recurrent network could partially overcome this disruption. On the other hand, it could also be considered that other hippocampal subregions, like CA2 or CA1, might partially compensate CA3 dysfunction in case of recurrent network impairment. As this is not likely because of the lack of experimental support, we rather suggest that the spacing effects observed in our experiments rely on a particular dynamic of protein synthesis machinery in the CA3 area during spaced training, as already suggested by Scharf et al. (2002). Also, Bourouchcoulade et al. (1998) and Koh et al. (1997) showed that a spaced learning procedure could induce multiple CREB activation (even of small intensity) that could imply multiple protein synthesis waves. In our experimental conditions, these small amounts of protein might be sufficient to partially or totally compensate for the disruption of CA3 area function.

When mice are reexposed to the apparatus after a large ITI (24-h IC), reconsolidation may occur, although it can only reactivate a defective memory from the first session whose consolidation was blocked by drugs. This process may, in turn, be blocked by the drugs, although the effects of chelators on reconsolidation are not actually known. Regarding NMDAR receptors, Lee et al. (2004) have shown that, although there is a common requirement for NMDAR activity in consolidation and reconsolidation, there are divergent neurobiological pathways of hippocampal contextual fear memory consolidation and reconsolidation at the level of intracellular cascades. Indeed, whereas BDNF expression is required for memory consolidation, Zif268 expression is necessary for reconsolidation. More recently, Lee and Hynds (2013) revealed that there are functional NMDAR–ERK–BDNF and NMDAR–IKKa–Zif268 pathways for consolidation and reconsolidation, respectively.

In summary, the present pattern of results reveals that Zn$^{2+}$ released in the MF–CA3 pathway is the key element, in addition to Glut, to allow one-shot learning of contextual fear memory, although a Zn$^{2+}$ deficiency might be compensated by distributed learning sessions based on various possible mechanisms according to ITI duration.

### Materials and Methods

All experiments were performed in strict accordance with the policies of the European Union (86/609/EEC), the French National Committee of Ethics (87/848), and the local committee’s recommendations (C.31-S55-11, Direction départementale de la protection des populations) for the care and use of laboratory animals. Animal surgery and experimentation are authorized by the French Direction of Veterinary Services to J.M.L. (#31-122, 2007) and S.D. (#75-1651).

### Animals

Subjects were 9- to 12-wk old C57BL/6j male mice obtained from Charles River and reared in the CRCa breeding facility. They were housed in groups of 3–5 per cage and maintained at a constant temperature (21 ± 1°C) with a 12-h light/12-h dark cycle (lights on at 8:00 a.m.) Water and food were available ad libitum.

### Drugs

All drugs were provided by Sigma Chemical Co. Various heavy metal chelators were used for their particular affinity with Zn$^{2+}$ ions and their functional properties.

To assess the role of NMDARs in CFC, we used the D-2-amino-5-phosphonopentanoate (AP5) competitive antagonist of NMDA receptors. AP5 was applied alone or jointly with a Zn$^{2+}$ chelator, immediately after learning. It acts at the three synapses of the hippocampal CA3 region (MF–CA3, TA–CA3, and ARCs). In contrast, AP5 does not prevent the binding of Glut on other receptors such as AMPA/kainate or mGlur. Thus NMDA-independent plasticity of MF–CA3 synapses, dependent on presynaptic kainic receptors (KRs), should not be affected by this treatment. It is therefore expected that postsynaptic LTP at TA–CA3 and ARC synapses is mostly disturbed. However, this does not exclude a deleterious effect of AP5 on MF postsynaptic LTP leading to a disruption of the metaplasticity of the MF–CA3 synapse. This treatment should allow evaluating the involvement of TA–CA3 and ARC synaptic plasticity in the consolidation of CFC acquired in a single session.

Sodium chloride (NaCl) was used as a control for this antagonist.

CaEDTA (calcium ethylenediamine tetraacetic acid) is a Ca$^{2+}$-saturated chelator of divalent ions widely used as an extracellular zinc chelator (Koh et al. 1996; Li et al. 2001a,b). It has a particular affinity for Zn$^{2+}$ ($K_d = 10^{-16.4}$ M) but its affinity for Ca$^{2+}$ and Mg$^{2+}$ is low enough not to alter the concentrations of...
these two cations. Its action kinetics is proportional to its concentration. Furthermore, this molecule cannot pass through membranes, making it an exclusively extracellular Zn\textsuperscript{2+} chelator that does not affect its intracellular homeostasis. This molecule was chosen to trap specifically free Zn\textsuperscript{2+} and Zn\textsuperscript{2+} resulting from the exocytosis of glutamate vesicles at the MF–CA3 synapse following the volley of glutamatergic cells of the dentate gyrus. The action of CaEDTA will thus be limited mainly to this synapse by preventing Zn\textsuperscript{2+} acting on its multiple targets. Specifically, CaEDTA will block the action of Zn\textsuperscript{2+} on glutamate receptors (NMDA, AMPA, KA) on VDCC, on TrkB, KATP, ZnR, and prevent its translocation into the postsynaptic element. The decrease of Zn\textsuperscript{2+}ergic activity should result mainly in a disruption of MF plasticity and possibly of ARCs that experience the spillover of Zn\textsuperscript{2+} from MF. In contrast, fast glutamatergic transmission and glutamate-related plasticity should be preserved which allows us to suggest that plasticity of TA–CA3 synapses and ARCs would not be disrupted by this treatment. Moreover, presynaptic and postsynaptic LTP of NMDA receptors in the MF–CA3 synapse should not be altered if the Zn\textsuperscript{2+} is not a critical modulator of both forms of plasticity. This treatment would allow evaluating the involvement of Zn\textsuperscript{2+} released into the CA3 region and especially in the MF–CA3 synapse during CFC consolidation.

DEDTC (diethyldithiocarbamate) is another chelator of divalent ions with high affinity for Zn\textsuperscript{2+} that has the particularity to cross membranes. Thus, this molecule has been successfully used in both in vitro and in vivo studies to trap intracellular Zn\textsuperscript{2+} (Frederickson et al. 1990; Takeda et al. 1999; Lassalle et al. 2000; Lu et al. 2000; Daumas et al. 2004). Moreover, its specific action at MFs suggests that it inhibits exocytosis of synaptic vesicles containing co-located Zn\textsuperscript{2+} and Glut, like DCGIV that inhibits the machinery of MF synaptic transmission (Daumas et al. 2009). The use of this drug would therefore hinder the action of Zn\textsuperscript{2+} and Glut on all their targets, whether pre- or postsynaptic, and specifically at the FM–CA3 synapse. DEDTC could theoretically disrupt presynaptic MF LTP by preventing the release of glutamate and thus its binding on KARs, but also the postsynaptic LTP of NMDA receptors, and thus suppress any excitatory influence on the FM–CA3 synapse. However, DEDTC would not affect LTP of TA–CA3 synapses or that of the ARCs. However, the chelation of Zn\textsuperscript{2+} at the MF–CA3 synapse preserves ARCs from modulatory influences resulting from the spillover of Zn\textsuperscript{2+} released by MF and could therefore modify the properties of LTP at this synapse. Were transmission and LTP at the MF–CA3 synapse to play a role in the consolidation of contextual learning achieved in a single session, the effect of DEDTC on Glut and Glut from vesicles of the MF–CA3 synapse and Glut from vesicles of the MF–CA3 synapse and Glut from vesicles of the MF–CA3 synapse and Glut from vesicles of the MF–CA3 synapse, respectively, would be (100 mg/kg, i.p.) (Vibrac) and xylazine (15 mg/kg, i.p.). Stainless-steel guide cannulae (24G, 7 mm) were implanted bilaterally in the cortex above the dorsal hippocampus using standard stereotaxic procedures. Cannula coordinates for the CA3 infusion site were as follows: (AP) – 1.7 mm posterior to bregma, (ML) ± 2.5 mm, (DV) – 1.5 mm from the skull, according to the brain atlas of Paxinos and Franklin (2001). Dental cement (poly-carboxylate, Sigma) was used to fasten guide cannulae to the skull. Stainless-steel obturators were inserted in guide cannulae to prevent occlusion and left in place until the infusions were made. A total of 280 male mice underwent surgery and behavioral testing. After surgery, mice were allowed at least 1 wk to recover. All experiments were carried out in the afternoon during the diurnal phase.

**Apparatus for behavioral testing**

 Conditioning took place in a conditioning chamber that consisted of a cubic metal box (27 cm × 26.5 cm × 27 cm) with three black sides and a Plexiglas front wall, through which experimental subjects were videotaped. The floor was made of a grid with 22 stainless-steel rods (diameter 4 mm) spaced 1 cm apart and connected to a generator (Panlab) delivering shocks of defined duration (2 sec) and intensity (0.7 mA) through a shock-scrambler unit. The grid was placed on a high-precision scale to measure the variations of weight induced by the movements of the animal. This device allows an automatic detection of movements and consequently a detection of freezing behavior. The loudspeaker producing the tone (1500 Hz, 85 db, 30 sec) was fixed on the lid of the conditioning chamber. The experimental device, lit by a 60-W red bulb, was surrounded by a white curtain. Two black and white patterns faced the conditioning chamber, providing distal cues, and two proximal patterns were attached to the internal walls of the chamber. Experiments were videotaped on line with a camera placed in front of the conditioning chamber and recorded on the computer acquisition system. Monitors were placed in the adjacent room where all the electronic system was settled. The conditioning chamber was cleaned with 70% aqueous ethanol before each conditioning session and before each contextual fear memory assay. Contextual memory level was measured in the same experimental conditions as conditioning, whereas tone learning was assessed in a modified context. For that purpose, the curtain and external patterns were removed. The modified chamber was made triangular by the adjunction of two walls and a floor partition made of uniform light-brown polycarbonate. This apparatus was washed with 1% acetic acid and lit by a 40-W red bulb.

**Contextual fear conditioning procedure**

Behavioral testing started 1 wk after surgery. In this study we used three types of conditioning procedures. The first, called “2-min interval condition” (2-min IC), is a classic version of contextual fear conditioning which consisted of a single conditioning session with two trials. During conditioning, each mouse was introduced into the conditioning chamber for a total of 5 min 30 sec. After a 2-min exploration period, a sound (CS) was emitted for 30 sec, and a foot-shock (US) was superposed to the tone during the last 2 sec. After an inter-trial interval of 2 min, the control for other chelators since its affinity for Zn\textsuperscript{2+} is such (K\textsubscript{d} = 10\textsuperscript{−15} M) that it is unable to sequester other ions (Koh et al. 1996). Therefore, Zn\textsuperscript{2+} fastened on this drug will not be released to allow the capture of other cations, such as calcium or magnesium, that have much lower affinity (K\textsubscript{d} = 10\textsuperscript{−7.3} M and K\textsubscript{d} = 10\textsuperscript{−5.4} M, respectively). All these drugs were stabilized in NaCl (0.9%) and stored at –20°C. The time window for DEDTC and CaEDTA had been estimated as 2 h (Stupien et al. 2003). The concentration of chelators was 200 mM and 3.04 mM for APS.
CS–US pairing was repeated, then, 30 sec after the second foot-
shock, the mouse was gently removed from the chamber and
underwent the injection process. After the infusion, the mouse
was returned to its home cage. The second conditioning proce-
dure consisted of two sessions with one learning trial each, spaced
by a 2-h interval (2-h IC). During each session the mouse stayed
in the conditioning chamber for a total of 3 min. After a 2-min
exploration period, a sound was emitted for 30 sec and coter-
nated with a 2-sec foot-shock. Thirty seconds later the mouse
was removed from the conditioning chamber and underwent
the injection process, and then was returned to its home cage.
The same conditioning protocol was applied to the mouse 2 h
after the first session, followed by a second injection. The last con-
ditioning procedure consisted of two one-trial sessions spaced
by a 24-h interval (24-h IC). This 24-h IC procedure used the
same conditions as those of the 2-h IC. Only the inter-session de-
lay differed.

Whatever the training procedure, 24 h after the last condi-
tioning session, freezing to the context was assessed by again plac-
ing each mouse in the conditioning chamber. The level of freezing
was measured during 4 min, no tone or foot-shock being present-
ed to the animal. Two hours later, mice were tested for freezing to
the tone in the modified context. Two minutes after introduction
in the modified chamber, freezing was recorded during a 2-min
tone presentation. Freezing is defined as the lack of movement be-
side breathing according to Blanchard and Blanchard (1969).

In the modified chamber, freezing was recorded during a 2-min
freezing test, the 2-min pre-tone, and the 2-min tone tests.

Mean freezing percentages for each group (± SEM) are presented
in the figures. Group sizes ranged from seven to 10 mice. To satisfy
the requirements for the use of ANOVA, the mean percentages
of freezing scores (P) were transformed in $Q = \arcsin(\sqrt{P}/100)$.
Statistical analyses were performed on the Q variable, using one-
way analysis of variance (ANOVA), or repeated measures ANOVA
design for related samples (SYSTAT 11 for Windows). Prior to
ANOVA, normality (Shapiro–Wilks test) and homoscedasticity
(Bartlett test) were checked for every group. Post hoc compar-
sions were conducted using Fisher’s LSD test. α levels were set at
$P < 0.05$.

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References


A specific role for hippocampal mossy fiber's zinc in rapid storage of emotional memories

Johnatan Ceccom, Hélène Halley, Stéphanie Daumas, et al.

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