Regulation of excitatory synapses and fearful memories by stress hormones

Krugers, H.J.; Zhou, M.; Joëls, M.; Kindt, M.

DOI
10.3389/fnbeh.2011.00062

Publication date
2011

Document Version
Final published version

Published in
Frontiers in Behavioral Neuroscience

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Memories for emotionally arousing and fearful events are generally well retained. From the evolutionary point of view this is a highly adaptive behavioral response aimed to remember relevant information. However, fearful memories can also be inappropriately and vividly reexpressed, such as in posttraumatic stress disorder. The memory formation of emotionally arousing events is largely modulated by hormones, peptides, and neurotransmitters which are released during and after exposure to these conditions. One of the core reactions in response to a stressful situation is the rapid activation of the autonomic nervous system, which results in the release of norepinephrine in the brain. In addition, stressful events stimulate the hypothalamus–pituitary–adrenal axis which slowly increases the release of glucocorticoid hormones from the adrenal glands. Here we will review how glucocorticoids and norepinephrine regulate the formation of fearful memories in rodents and humans and how these hormones can facilitate the storage of information by regulating excitatory synapses.

**Keywords:** glucocorticoids, norepinephrine, fear conditioning, AMPA

**INTRODUCTION**

In our daily life we face many emotionally arousing and stressful experiences, ranging from small displeasures to major life events such as accidents or loss of relatives. The perception of these events results in behavioral and physiological responses which enable adaptation to these potentially threatening situations (Chrousos, 1998; Kim and Diamond, 2002; de Kloet et al., 2005). Enhanced memory for stressful experiences is a highly adaptive behavioral response, which helps to remember relevant information (McGaugh, 2000) and prepares individuals to cope appropriately with similar events in the future (de Kloet et al., 1999).

One of the core neuro-endocrine reactions in response to a stressful situation is the rapid activation of the autonomic nervous system (ANS), which results in the release of norepinephrine in the brain, in part by neurons located in the locus coeruleus. These noradrenergic projections regulate neuronal function via β-adrenergic receptors in areas that are critically involved in learning and memory such as the hippocampus, prefrontal cortex, and amygdala (Foote et al., 1983; Gibbs and Summers, 2002; Roozendaal et al., 2009). Stressful events also stimulate activation of the hypothalamus–pituitary–adrenal (HPA) axis, which leads to a slow increase in the release of glucocorticoid hormones from the adrenal cortex (cortisol in most rodents; cortisol in humans). These hormones enter the brain and bind to two subtypes of discretely localized receptors, i.e., the mineralocorticoid receptor (MR) and glucocorticoid receptor (GR), which (like adrenergic receptors) are expressed in regions that are critical for memory formation such as hippocampus, amygdala, and prefrontal cortex (de Kloet et al., 2005). MRs are occupied when hormone levels are low; these receptors exert their effects classically via the genome. GRs have a 10-fold lower affinity for corticosterone, become substantially activated when hormone levels rise after stress and exert slow genomic actions in cells carrying the receptor. Recent evidence has revealed that corticosteroid hormones can also regulate synaptic function via non-genomic effects, both via activation of MRs and GRs (Orchikin et al., 1991; Venero and Borrell, 1999; Di et al., 2003; Karst et al., 2005, 2010; Groc et al., 2008).

In this review we will highlight behavioral studies emphasizing how norepinephrine and glucocorticoids, via their receptors, regulate fearful memories, both in rodents and humans. Second, we will address the cellular mechanism by which norepinephrine and glucocorticoids promote learning and memory processes by focusing on regulation of excitatory synapses. Recent studies have revealed that these hormones modulate these synapses by regulating the function of AMPA type glutamate receptors (Karst et al., 2005; Hu et al., 2007; Groc et al., 2008; Martin et al., 2009; Yuen et al., 2009, 2011; Krugers et al., 2010; Liu et al., 2010; Tenorio et al., 2010), which are critically involved in synaptic transmission and activity-dependent changes in synaptic transmission – a major cellular model for learning and memory (Malino and Malenka, 2002; Malenka, 2003; Neves et al., 2008; Kessels and Malinow, 2009; Box 1).

**FEAR CONDITIONING AND INHIBITORY AVOIDANCE**

Various tasks are being used to examine hormonal regulation of emotional memories. Here we will briefly address two of the most used behavioral tasks, Pavlovian fear conditioning and
Excitatory synapses, plasticity, and memory.

Changes in synaptic connectivity are generally believed to underlie learning and memory processes (Doyere and Larocque, 1992; Bliss and Collingridge, 1993; Neves et al., 2008). Plasticity at synapses can be regulated at the presynaptic site (by changing the release of neurotransmitters) and/or the postsynaptic site (by changing the function and number of their receptors; Malinow and Malenka, 2002). The most explored forms of plasticity at excitatory synapses are N-methyl-D-aspartic acid receptor (NMDAR)-dependent long-term potentiation (LTP) and long-term depression (LTD), which have been associated with changes in postsynaptic signaling (Bliss and Collingridge, 1993; Neves et al., 2008).

**Box 1 | Excitatory synapses, plasticity, and memory.**

Changes in synaptic connectivity are generally believed to underlie learning and memory processes. Plasticity at synapses can be regulated at the presynaptic site (by changing the release of neurotransmitters) and/or the postsynaptic site (by changing the function and number of their receptors). The most explored forms of plasticity at excitatory synapses are N-methyl-D-aspartic acid receptor (NMDAR)-dependent long-term potentiation (LTP) and long-term depression (LTD), which have been associated with changes in postsynaptic signaling.

Long-term potentiation (LTP) reflects a long-lasting increase in synaptic connectivity (Neves et al., 2008) that can be experimentally elicited by high-frequency stimulation or by afferent stimulation in combination with postsynaptic depolarization (Bliss and Lomo, 1973; Bliss and Collingridge, 1993). NMDA receptors play a critical role in the induction of LTP. This receptor is a unique ligand-gated ion channel since activation requires binding of glutamate as well as membrane depolarization which is needed to release the magnesium block of the channel and to open the channel with high probability (Novak et al., 1984). Therefore, the NMDA receptor functions as a coincidence detector that determines specificity and associativity of synaptic potentiation. Activation of NMDA receptors allows Ca^{2+} influx into dendritic spines of postsynaptic neurons which activates calcium-dependent enzymes, such as calcium/calmodulin-dependent calcium kinase II (CaMKII; Barria et al., 1997), protein kinase A (PKA; Man et al., 2007), and protein kinase C (Boehm et al., 2006). These kinases impact synaptic transmission, including regulation of the function of AMPA receptors (Lledo et al., 1996; Barria et al., 1997; Mammen et al., 1997; Lee et al., 2000; Boehm et al., 2006; Derkach et al., 2007). Moreover, these enzymes may help to organize structural processes that lead to the incorporation of AMPA receptor-binding proteins into the postsynaptic density (PSD), followed by subsequent anchoring or additional AMPA receptors (Lisman and Zhivotitsky, 2001).

AMPA receptors are highly mobile and the link between AMPA receptor surface diffusion and cycling is evident in synaptic plasticity paradigms. Recent studies have shown that AMPA receptor trafficking is regulated by both exocytotic and endocytotic processes and by their surface lateral diffusion in the plasma membrane (Kennedy and Ehlers, 2006; Shepherd and Huganir, 2007; Newpher and Ehlers, 2008). Endocytosis of AMPA receptors is important for the number of AMPA receptors at the membrane surface and recycling endosomes supply AMPA receptors for LTP (Park et al., 2004). Receptor recycling from postsynaptic endocytic zones appears to be crucial for maintaining a mobile population of surface AMPA receptors that can be synaptically inserted to increase synaptic strength (Blanpied et al., 2002; Petrin et al., 2007; Petrin et al., 2009). Together, the regulation of synaptic AMPA receptor number relies on a dynamic equilibrium between intracellular, extrasynaptic, and synaptic pools, and is regulated by the activity status of the neuronal network (Malinow and Malenka, 2009; Petrin et al., 2009).

The trafficking of AMPA receptors governs rules that appear to be dependent on the subunit composition: the GluA1 carboxyl terminus mediates regulated delivery of AMPARs onto synapses upon synaptic activation while the GluA2 carboxyl terminus determines the continuous delivery of AMPARs onto synapses independent from synaptic stimulation (Shi et al., 2001). Upon LTP induction, GluA1-containing calcium-permeable AMPA receptors are incorporated into synaptic membrane, rapidly, and transiently from intracellular reserve pool (Shi et al., 2001), and are replaced by GluA1-lacking calcium-impermeable AMPA receptors shortly after LTP induction (Plant et al., 2006). Functionally, these GluA1-lacking AMPA receptors (such as GluR2/3) are calcium-impermeable (Burridge et al., 1992; Kauer and Malenka, 2006; Plant et al., 2006) and may play a role in maintaining synaptic strength (Malinow and Malenka, 2002; Malenka, 2003; Kauer and Malenka, 2006; Plant et al., 2006).

Inhibitory avoidance (IA) learning. Pavlovian fear conditioning is a behavioral paradigm that can be used to study the memory formation of emotionally arousing events, both in rodent animals and humans (e.g., Nader et al., 2000; Kindt et al., 2009). In fear conditioning, an emotionally neutral conditioned stimulus (CS) such as a tone or light is paired with an aversive CS such as a foot shock unconditioned stimulus (US). After pairing, the CS elicits defensive behavior of which freezing behavior is most frequently studied (Rodrigues et al., 2009). The amygdala is critically involved in fear conditioning (LeDoux, 2000): the lateral amygdala (LA) receives auditory, visual, olfactory, and somatosensory information from the thalamus and cortex, and plasticity in the LA is believed to underlie the association between the CS (cue) and US (Rogan et al., 1997). The hippocampus also plays a role in fear conditioning in that it provides information about the context of a fearful event (LeDoux, 2000). Finally, the medial prefrontal cortex regulates the expression and control of fear responses (LeDoux, 2000). A second task that is widely used to examine the memory formation of emotionally arousing events is IA training. In IA training, rodents are placed in a light chamber and can subsequently enter a dark chamber. Upon entry of this chamber, animals receive a footshock, which is well remembered. Inhibitory avoidance memory formation is believed to be hippocampal dependent (e.g., Whitlock et al., 2006) with the amygdala playing a modulatory role (McGaugh, 2000). In addition, regulating prefrontal cortex function by the amygdala regulates memory consolidation in this task (e.g., Barsegyan et al., 2009).

**NOREPINEPHRINE, GLUCOCORTICOIDS, AND FEARFUL MEMORIES IN RODENTS**

Norepinephrine and corticosteroid hormones, via their receptors, mediate (at least in part) the memory enhancing effects of stress...
and emotion (Joëls et al., 2006, 2011; Roozendaal et al., 2009). Nor-
epinephrine enhances memory formation of emotional events via
brain β-adrenergic receptors: application of norepinephrine or β-
adrenergic receptor agonists promotes memory consolidation in
various aversive memory tasks such as IA task, fear conditioning,
and in Morris water-maze learning (Hu et al., 2007; Roozen-
daal et al., 2009; but see also Hatfield and McGaugh, 1999; Lee
et al., 2001; Bush et al., 2010), and blocking β-adrenergic receptors
reduces contextual fear memories (Ji et al., 2003). Activation of α-
adrenergic receptors also enhances memory, but presumably act
by enhancing β-adrenergic actions (Ferry et al., 1999a,b). Finally,
noradrenaline has been reported to enhance reconsolidation of
information (e.g., Debiec and LeDoux, 2006).

Corticosteroid hormones, via MRs have been implicated in the
appraisal, and response selection during the learning process
(Oitzl and de Kloet, 1992; Sandi and Rose, 1994). Recent studies
provide evidence that MRs are also involved in encoding of infor-
mation, possibly linked to effects on appraisal, and/or response
selection: application of the MR antagonist spironolactone prior
to training lastingly suppress the expression of fear (Zhou et al.,
2010). Moreover, genetic deletion of MRs in the forebrain led
to various cognitive impairments, including impaired learning in
a Morris water-maze task (Berger et al., 2006) and reduced fear
learning (Zhou et al., 2010). Via GRs, corticosteroid hormones
have been reported to promote long-term consolidation of infor-
mation (de Kloet et al., 1999; Joëls et al., 2006; Roozendaal et al.,
2009). For instance, a point mutation in the mouse GR was found
to impair spatial memory formation (Oitzl et al., 2001), and block-
ing GRs impairs fear conditioning (Pugh et al., 1997a; Donley et al.,
2005). In agreement, in several fearful learning paradigms, includ-
ing fear conditioning and IA learning, post-training application of
corticosterone, or GR agonists promoted the consolidation of
information (Corodimas et al., 1994; Sandi and Rose, 1994; Pugh
et al., 1997b; Hui et al., 2004; Roozendaal et al., 2009). These studies
imply that GRs are involved in consolidation of fearful information
and that genomic actions are involved. This does not exclude the
possibility that other GR-dependent pathways are also involved.
For instance, a recent study suggested that membrane-associated
GRs also promote long-term memory in an object recognition
task via chromatin modification (Roozendaal et al., 2010). Thus,
it is possible that both non-genomic as well as genomic actions of
corticosteroid hormones, via GRs, promote the storage of relevant
information.

In addition to these well-documented effects of stress and
glucocorticoids on consolidation processes, these hormones also
affect memory retrieval mechanisms (de Quervain et al., 1998)
and extinction processes (Brinks et al., 2009). Exposure to stress
and elevated corticosteroid levels hampers the retrieval of already
stored information (de Quervain et al., 1998) and glucocorticoids
promote the extinction of information (de Kloet et al., 1999).
Finally, blocking GRs has been reported to hamper reconsolid-
ation of cue-conditioned fear (Pitman et al., 2011). Taken together,
there is ample evidence that corticosteroid hormones, via activa-
tion of MRs and GRs, exert a repertoire of behavioral effects that
promote the consolidation of relevant (fearful) information, facil-
itate the extinction of information that is no longer relevant, and
ultimately favor behavioral adaptation (de Kloet et al., 1999).

Corticosteroids act in concert with other hormones such as nor-
epinephrine (Roozendaal et al., 2009), endocannabinoids (Cam-
polongo et al., 2009), corticotropin releasing hormone (CRH;
Roozendaal et al., 2008) for optimal memory performance both
in humans and rodents (de Quervain et al., 2009; Roozendaal
et al., 2009). It is generally thought that noradrenergic activation
is essential for the memory enhancing effects and that glucocor-
ticoids play a permissive role in noradrenergic actions, thereby
promoting memory formation (Hui et al., 2006; Roozendaal et al.,
2006, 2009). These studies emphasize that concerted action of
various stress-related mediators is required for optimal memory
performance in rodents (Joëls and Baram, 2009).

NOREPINEPHRINE, GLUCOCORTICOIDS, AND FEARFUL
MEMORIES IN HUMANS

The involvement of noradrenergic receptor activation in human
emotional memory has been investigated by either stimulating
or decreasing the release of norepinephrine (Table 1). Blocking
the β-adrenergic receptors with propranolol selectively impairs
memory performance for emotional arousing information (Cahill
et al., 1994; Van Stegeren et al., 1998; Hurlemann et al., 2005;
Van Stegeren, 2008). Conversely, adrenergic receptor agonist epi-
nephrine (Cahill and Alkire, 2003) or the α2-adrenergic receptor-
agonist yohimbine – which stimulates central noradrenergic
activity by blocking the α2-adrenergic autoreceptor (Charney
et al., 1987; Peskind et al., 1993) – enhances memory consol-
dation of emotionally arousing information (Southwick et al.,
2002). These findings support that noradrenergic receptors are
critically involved in the formation of human emotional memory
(McGaugh, 2004).

The effect of glucocorticoids on memory formation, is typically
studied by either a stress manipulation such as the Trier Social
Stress Test (TSST; Kirschbaum et al., 1993), the cold pressor test
(CPT), or by administering cortisol directly. Although stress or
cortisol treatment generally impairs memory retrieval (de Quer-
vain et al., 2000), the same hormone has been reported to enhance
memory consolidation (Het et al., 2005; Wolf, 2009). These mem-
ory effects of the corticosteroids are often stronger for emotional
arousing material (Wolf, 2009).

Even though the memory enhancing effects of emotional
arousal are extremely functional from an evolutionary perspec-
tive, the impact of emotion on memory can also have long-term
detrimental consequences. Research into the effects of stress on
emotional memory is highly relevant for a better understand-

<table>
<thead>
<tr>
<th>Role noradrenergic hormones in emotional memories.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enhanced noradrenergic tone</strong></td>
</tr>
<tr>
<td>Emotional memory formation ↑</td>
</tr>
<tr>
<td>Extinction fear conditioning ↓</td>
</tr>
<tr>
<td>Reconsolidation fear ↑</td>
</tr>
<tr>
<td>Fear generalization ↑</td>
</tr>
</tbody>
</table>
of the etiology and maintenance of emotional disorders, such as anxiety disorders. In humans the effects of stress on memory are traditionally investigated for non-associative and distinct emotional stimuli such as emotional stories and pictures (McGaugh, 2004; Wolf, 2009). Given that patients with anxiety disorders either fear for stimuli that are intrinsically non-threatening or they persist in fear responding whilst the acute threat already disappeared (e.g., after traumatic experiences), the emotional memory literature seems to be inconclusive for the understanding of these disorders. Indeed, an important aspect of the pathogenesis of anxiety disorders is that they originate from a learned association between a previously neutral event (CS; such as a stranger) and an anticipated disaster (US; such as physical assault). This can be experimentally modeled in a differential human fear conditioning paradigm. In contrast to animal research, the effect of stress hormones such as noradrenaline on associative fear memory is not extensively studied in humans.

Another notable aspect of research into human emotional memory is that most studies did not assess the emotional response but the declarative memory for the emotional stimuli. However, not the factual recollection but the concomitant excessive emotional expression is the main problem in emotional disorders (Ehlers et al., 2004). In particular, hyper-noradrenergic activity in the wake of a life-threatening event may contribute to the “overconsolidation” of memory for trauma, generating disturbing intrusive memories that are characteristic of posttraumatic stress disorder (PTSD; Pitman and Delahanty, 2005; Glannon, 2006; Henry et al., 2007). In patients with PTSD, these involuntary traumatic memories may be experienced as reenactments of the original trauma (“flashbacks”) and are associated with significant emotion and distress (DSM-IV-R; American Psychiatric Association, 2000).

In two human fear conditioning studies, we recently demonstrated that the systemic administration of the α₂-adrenergic receptor-antagonist yohimbine (20 mg) during memory formation strengthened the later expression of human associative fear memory (fear potentiated startle reflex; Soeter and Kindt, 2011a,c). More specifically, stimulation of the noradrenergic system by the administration of yohimbine during memory formation did not directly augment the differential startle fear response. Yet, the retention tests presented 48 h later uncovered that the earlier administration of yohimbine extensively delayed the process of extinction learning and generated a superior recovery of fear (reinstatement and reacquisition). The competition between the original excitatory fear association and the newly formed inhibitory memory trace determines the behavioral outcome of extinction learning (Bouton, 1993). Given that yohimbine was administered during fear conditioning (48 h prior to fear extinction), the noradrenergic manipulation apparently delayed the process of extinction by strengthening the original excitatory fear association. In addition, the yohimbine administration promoted fear generalization, a core feature of anxiety disorders (Soeter and Kindt, 2011c). In rodents, the generalization of fear seems to be dependent on the strength of the memory as operationalized by training intensity (both US intensity and the number of CS+ and US applied; Laxmi et al., 2003). Allegedly, the strengthening of a specific fear memory trace by α₂-adrenergic receptor-manipulation may produce fear generalization similar to training intensity.

The effect of β-adrenergic interference has not yet been demonstrated for the consolidation of associative fear memory. For reconsolidation, however, a series of studies showed a robust memory impairing effect of the β-adrenergic receptor blocker propranolol (Kindt et al., 2009; Soeter and Kindt, 2010, 2011b,c). Disrupting reconsolidation by propranolol (40 mg) – administered before or after memory retrieval – “deleted” the emotional expression of a fear memory in humans (Kindt et al., 2009; Soeter and Kindt, 2010, 2011b,c). The anxiolytic properties of propranolol could not explain the fear erasure, as omission of memory reactivation after propranolol intake yielded intact fear responding. Together, these recent studies illustrate the involvement of noradrenergic modulation in the (re)consolidation and generalization of human associative fear memory. Given that fear generalization is a main characteristic of anxiety disorders, these findings suggest that norepinephrine may play an important role in the etiology and maintenance of anxiety disorders.

In contrast to the noradrenergic modulation of associative fear memory, the modulatory role of cortisol seems to be more complex. A mixture of fear conditioning paradigms reveals ambiguous findings regarding the effect of cortisol on the emotional expression of associative fear memory in humans. Cue or context fear conditioning and eyelink conditioning studies – using either a trace or delay reinforcement schedule – have shown impairing as well as enhancing effects of cortisol on associative fear memory. First, a relatively low dose of hydrocortisone (30 mg) affected cue fear conditioning, decreasing it in men and increasing it in women (Stark et al., 2006; Merz et al., 2010; Tabbert et al., 2010). In contrast to this gender effect, exposure to a stress manipulation (elevating both the sympathetic and the glucocorticoid stress response) facilitated cue fear conditioning in men but not in women (Zorawski et al., 2005, 2006; Jackson et al., 2006). Furthermore, a high dose of hydrocortisone (60 mg) exclusively enhanced context fear conditioning in both sexes, while leaving cue fear conditioning unaffected (Grillon et al., 2011). Finally, delay eyelink conditioning is impaired in men and women after a stress manipulation (TSST; Wolf et al., 2009), whereas trace eyelink conditioning is improved by a stress manipulation (CPT; Duncko et al., 2007) as well as by cortisol (2 mg, administered intravenously; Kuehl et al., 2010), but also by a cortisol inhibitor (1500 mg metyrapone; Nees et al., 2008). In summary, future research is required to clarify the modulatory role of cortisol on associative fear memory in humans and the possible interaction with the noradrenergic system.

**EXCITATORY SYNAPSES AND LEARNING AND MEMORY**

An import question that remains to be addressed is which mechanisms are involved in the effects of norepinephrine and glucocorticoids on fear learning. The current view of how memories are formed is that neurons are activated during the learning process thereby changing synaptic communication (Neves et al., 2008). AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazole propionate) type glutamate receptors mediate most of the fast excitatory synaptic transmission in the brain and controlling the number of synaptic AMPA receptors on the postsynaptic membrane is an
AMPA receptor subunits (Whitlock et al., 2006). Studies using a working memory task and elevated Y-maze (Shimshek et al., 2006) found that Morris water-maze spatial navigation was unaffected (Zamanillo et al., 2009), critical for fear learning (Rumpel et al., 2005).

These studies indicate that GluA1 and GluA2 subunits are at least partially responsible for the rapid recruitment of AMPA receptors to the postsynaptic membrane and for the concurrent increase in AMPA-mediated transmission whereas LTD reflects a decrease in synaptic AMPA receptor function.

AMPA receptors are heteromeric tetramer complexes formed of different combinations of GluA1, GluA2, GluA3, and GluA4 subunits (Keinanen et al., 1998; Tanabe et al., 1992; Wisden and Seeburg, 1993; Hollmann and Heinemann, 1994; Wentholt et al., 1996). In adult hippocampal pyramidal neurons, two main populations of AMPA receptor complexes are found: GluA1/GluA2 and GluA2/GluA3 containing AMPA receptors. The trafficking of AMPA receptors to and from the synapse is regulated by (1) exocytotic/endocytotic recycling between intracellular and membrane receptor pools (Passafaro et al., 2001; Gerges et al., 2002); and (2) surface diffusion between extrasynaptic and synaptic receptor pools (Adesnik et al., 2005; Ashby et al., 2006; Ehlers et al., 2007; Makino and Malinow, 2009; Petrini et al., 2009; Box 1). The leading model for constitutive and activity-dependent AMPA receptor trafficking is that activity-dependent processes (such as induction of LTD) promote synaptic delivery of GluA1-containing AMPA receptors which are believed to be gradually replaced by the cycling GluA2/GluA3 heteromers after LTD induction (Shi et al., 2001; Plant et al., 2006).

AMPA receptors have been shown to underlie memory formation. Inhibitory avoidance training rapidly (and reversibly) increases hippocampal synaptic insertion of GluA1 and GluA2 AMPA receptor subunits (Whitlock et al., 2006). Studies using mutant mice revealed that GluA1 mutant mice are hampered in short-term memory processes (Reisel et al., 2002; Schmitt et al., 2005; Sanderson et al., 2007, 2009, 2011), while the mutation leaves Morris water-maze spatial navigation unaffected (Zamanillo et al., 1999). Moreover, GluA2 mutant mice are impaired in a spatial working memory task and elevated Y-maze (Shimshek et al., 2006). These studies indicate that GluA1 and GluA2 subunits are at least relevant for short-term memory processes. Finally, the observation that preventing synaptic insertion of GluA1-containing AMPA receptors in the amygdala hampers tone-cue fear conditioning implies that trafficking of GluA1-containing AMPA receptors is critical for fear learning (Rumpel et al., 2005).

**STRESS HORMONES AND HIPPOCAMPAL EXCITATORY SYNAPSES**

The cellular mechanisms via which norepinephrine and corticosterone facilitate learning and memory processes are starting to be unraveled. Here we summarize studies – mainly in the rodent hippocampus – that have examined how these hormones regulate synaptic transmission and synaptic plasticity. Recent studies have revealed that AMPA receptors are regulated by norepinephrine and glucocorticoid hormones. Via activation of β-adrenergic receptors, norepinephrine can rapidly – but reversibly – activate PKA and CaMKII (Wang et al., 2004; Hu et al., 2007) and increase the phosphorylation of GluA1 at Ser845 and Ser831. Likewise, stress, via activation of β-ARs increases phosphorylation of Ser831 and Ser845 (Hu et al., 2007). In agreement with the observations that phosphorylation of AMPA receptors at these sites is critical for LTD, activation of β-adrenergic receptors facilitates the induction of hippocampal LTD (Thomas et al., 1996; Winder et al., 1999; Hu et al., 2007; Tenorio et al., 2010) and enhances activity-dependent synaptic insertion of AMPA receptors (Hu et al., 2007). Interestingly, activation of β-adrenergic receptors facilitates LTD in a time-dependent manner; these receptors only facilitate LTD when these receptors are activated during and shortly after induction of LTD, i.e., when the adrenergic receptors enhance phosphorylation of GluA1 (Hu et al., 2007).

Also corticosteroid hormones can rapidly and reversibly promote hippocampal synaptic transmission. Within minutes after application, glucocorticoids increase synaptic transmission in the hippocampus (Karst et al., 2005), via activation of low affinity MRs which are located in the cellular membrane. This rapid and reversible increase in synaptic transmission after glucocorticoid exposure most likely results from an increase in the presynaptic release of glutamate (Karst et al., 2005) in which the Erk pathway is critically involved (Olijslagers et al., 2008). At the same time scale, glucocorticoid exposure, via membrane MRs rapidly increases the lateral diffusion of GluA1 and GluA2 subunits, without altering the number of postsynaptic AMPA receptors (Groc et al., 2008; Martin et al., 2009). At this time, glucocorticoids, via MRs, promote the activity-dependent synaptic insertion of GluA2-containing AMPA receptors (Groc et al., 2008). Finally, glucocorticoids also facilitate LTD in a time-dependent manner; LTD is only facilitated when elevated corticosteroid levels are present at the moment of high-frequency stimulation (Wiegert et al., 2006). These studies show that both norepinephrine and glucocorticoids can rapidly facilitate synaptic plasticity and thereby increase the ability to encode information at the cellular level (Figure 1). While glucocorticoids and norepinephrine act in concert for optimal memory performance, they also affect synaptic function in a synergistic fashion (Joels et al., 2011). Application of a β-adrenergic receptor agonist together with corticosterone facilitates the induction of LTD in the hippocampus (Pu et al., 2007). Moreover, activation of β-adrenergic receptors together with corticosterone enhances AMPA receptor function (Zhou et al., 2011).

After exposure to a stressful event, plasma corticosteroid levels slowly return to their pre-stress level in about 2 hours (de Kloet et al., 2005). Nevertheless, these hormones exert – via a slow, genomic mode of action – long-lasting effects on excitatory synapses (Figure 1). Elevated glucocorticoid levels increase the membrane expression and synaptic insertion of GluA2-containing AMPA receptors in the hippocampal neurons (Groc et al., 2008; Martin et al., 2009). These effects are mediated via GRs, require time as well as the synthesis of new proteins, and most likely result from increased lateral diffusion and/or altered ratio of endocytosis/exocytosis of GluA2-containing AMPA receptors (Groc et al., 2008; Martin et al., 2009). Functionally, glucocorticoids also slowly increase the amplitude of evoked as well as spontaneous AMPA receptor-mediated synaptic currents in hippocampal primary cultures and hippocampal slices (Karst and Joels, 2005; Martin et al., 2009), thereby enhancing AMPA receptor-mediated...
synaptic transmission. Furthermore, glucocorticoids – via a slow mode of action – suppress the induction of LTP (Alfárez et al., 2002; Wiegert et al., 2005), facilitate LTD (CousSENS et al., 1997; Xu et al., 1997) and increase endocytosis of synaptic AMPARs upon stimuli that weaken synaptic transmission (Martin et al., 2009).

**STRESS HORMONES: FROM EXCITATORY SYNAPSES TO FEARFUL MEMORIES**

The release of norepinephrine and glucocorticoids promotes the consolidation of fearful memories in rodents and humans (Roozendaal et al., 2009). Recent findings indicate that stress hormones like norepinephrine and corticosterone both rapidly and slowly increase AMPA receptor mediated synaptic transmission. These differential effects on AMPA receptor trafficking may provide a cellular mechanism that underlies the memory enhancing effects of these hormones. Initially glucocorticoids and norepinephrine promote the AMPA receptor mediated synaptic transmission and synaptic insertion of AMPA receptors (Karst et al., 2005; Hu et al., 2007; Groc et al., 2008; Olijslagers et al., 2008). These effects are accompanied by an increased ability to elicit LTP (Thomas et al., 1996; Winder et al., 1999; Wiegert et al., 2006; Hu et al., 2007) and may therefore contribute to an enhanced capacity to acquire and store information (Figure 1).

Next, glucocorticoids via a slow genomic action enhance synaptic insertion of AMPA receptors. At the same time, glucocorticoids suppress activity-dependent increase in synaptic AMPA receptors (Groc et al., 2008), activity-dependent increase in AMPA receptor-mediated synaptic transmission (Hui Xiong, unpublished observations), and synaptic plasticity (e.g., Wiegert et al., 2005). Thus, these hormones slowly reduce the ability to encode novel information. The consequence could be that these hormones also prevent the ability to overwrite information that is present in the network, in a meta-plastic manner (Joels et al., 2006; Krugers et al., 2010), thereby preserving the original memory trace. Furthermore, glucocorticoids promote the loss of synaptic AMPA receptors which is enhanced upon stimuli that reduce synaptic transmission (Martin et al., 2009), thereby accentuating synaptic efficacy. This provides a picture where glucocorticoids, via MRs, and β-adrenergic receptor activation rapidly enhance the ability to store information, which is consolidated and accentuated via activation of GRs (Krugers et al., 2010; Figure 1).

**FUTURE PERSPECTIVES**

There are a number of relevant issues which need to be addressed:

1. First, it is unknown how activation of MRs and GRs enhance (activity-dependent) synaptic insertion of AMPA receptors. Potential candidates are enzymes that regulate the phosphorylation of AMPA receptors, regulators of endocytosis/exocytosis (Liu et al., 2010), and/or proteins that promote transport and synaptic retention of AMPA receptors (Nicoll et al., 2006).

2. A behaviorally very relevant question is whether AMPA receptors mediate the memory enhancing effects of stress hormones. Studies using mice carrying mutations in the GluR1 phosphorylation sites indicate that norepinephrine-regulated phosphorylation of GluR1 facilitates emotional memory (Hu et al., 2007). Moreover, application of pep2m, which blocks trafficking of GluA2-containing AMPA receptors also prevents the memory enhancing effects of stress (Conboy and Sandi, 2010), and fearful memories (Migues et al., 2010). Also, stress-induced regulation of Rab4/SGK may underlie stress-effects on AMPA receptor function and stress-effects on working memory (Yuen et al., 2011). Studies using temporal erasure of functional AMPA receptors will be required to reveal whether regulation of AMPA receptor function is critical for stress-induced facilitation of the different learning phases (such as acquisition and/or consolidation of information).

3. The studies carried out so far mainly focused on the hippocampal formation. However, region-specific effects of stress hormones on excitatory synapses – even in the hippocampus – need to be considered. For example, in an elegant series of studies it was shown that corticosteroid hormones may have different effects on synaptic plasticity within the hippocampal formation; corticosteroid hormones suppress synaptic plasticity in de dorsal hippocampus but enhance synaptic plasticity in the ventral hippocampus (Maggio and Segal, 2007, 2009; Segal et al., 2010).

Moreover, other brain areas such as prefrontal cortex and amygdala are also critically involved in the regulation of fearful memories. It will therefore also be necessary to carefully investigate the effects of stress hormones on excitatory synapses in
these brain areas. Indeed corticosteroid hormones have been reported to affect AMPA receptor mediated synaptic transmission in the amygdala (Karst et al., 2010) differently from the hippocampus (see Karst et al., 2005), and stress and corticosteroid hormones regulate AMPA receptors (Yuen et al., 2011) and function of the prefrontal cortex (Arnsten, 2009).

(4) Behaviorally, several neurotransmitters (e.g., norepinephrine, endocannabinoids, dopamine), neuropeptides, and steroid hormones (e.g., corticosteroid hormones; Joëls and Baram, 2009) may act together for optimal memory performance (de Quervain et al., 2009; Roozendaal et al., 2009) and cellular plasticity (Pu et al., 2007). It will therefore be relevant to examine whether and how these stress-mediators interact to regulate AMPA receptor function as well as learning and memory.

(5) In susceptible individuals, memories for aversive events may remain inappropriately present and lead to anxiety disorders such as in (PTSD; de Kloet et al., 2005). This underscores the importance of understanding how individual differences in cognitive development, and the ability to cope with threatening events later in life, are determined. These differences are largely regulated by environmental factors, in particular during the early postnatal period – in conjunction with genetic factors – (Hackman et al., 2010). When comparing rodent offspring of mothers that exhibited low levels of maternal care with the adult offspring of mothers that exhibited high levels of maternal care, enhanced memories for fearful events and increased anxiety was observed (Weaver et al., 2006; Champagne et al., 2008). Also, material deprivation results in enhanced fear learning (Oomen et al., 2010). It will therefore be important to examine how stress hormones promote the retention of stressful memories and regulate molecular mechanisms that are fundamental for learning and memory (such as AMPA receptors) in individuals who suffered from negative early life experiences.

(6) Finally, studies over the past decade have shown that stored memories are rendered labile after being retrieved, and require de novo protein synthesis for reconsolidation (Nader et al., 2000). Reconsolidation has been demonstrated in various tasks and species (Nader et al., 2000; Eisenberg et al., 2003; Sangha et al., 2003), including humans (Kindt et al., 2009; Schiller et al., 2010). The notion that stored memories can be turned into a labile state has opened new avenues to reduce the expression of fear more permanently than the traditional extinction procedure (Pitman et al., 2005), e.g., by targeting noradrenergic receptors (Pitman et al., 2002; Orr et al., 2006; Brunet et al., 2008; Kindt et al., 2009; Soeter and Kindt, 2010, 2011b,c) and corticosteroid receptors (Barrett and Gonzalez-Lima, 2004; Cai et al., 2006; Abrari et al., 2008). Future studies will be needed to test whether targeting stress hormones and their receptors can be used to effectively reduce fear and whether these fear-reducing effects are mediated via AMPA receptors (Clem and Huganir, 2010).

ACKNOWLEDGMENTS

The authors are supported by a special grant from the Cognitive Science Center Amsterdam (CSCA).

REFERENCES


Alfárez, D. N., Wiegert, O., Joëls, M., and Krugers et al., Stress, fear, and synapses


Krugers et al. Stress, fear, and synapses


ture excitatory postsynaptic cur-
rent amplitude in mice CA1 hip-


Kim, J. I., and Diamond, D. M. (2002). The stressed hippocampus, synap-


Kindt, M., Soeter, H., and Vervliet, B. (2009). Beyond extinction: erasing human fear responses and prevent-


cholminergic drugs do not mod-

Lee, H. K., Barbarosie, M., Kameyama, K., Bear, M. E., and Huganir, R. L. (2000). Regulation of distinct AMPA receptor phosphorylation sites dur-


Liu, W., Yuen, E. Y., and Yan, Z. (2010). The stress hormone corticosterone increases synaptic alpha-amino-3-hydroxy-5-methyl-4-isoxazolepro-
ponic acid (AMPA) receptors via 
serum- and glucocorticoid-

costerone alters AMPAR mobility and facilitates bidirectional synaptic plasticity. *PLoS ONE* 4, e4714. doi: 10.1371/journal.pone.0004714

McGaughey, J. L. (2000). Memory—a cen-

McGaughey, J. L. (2004). The amygd-

ing the impact of sex and cortisol on implicit fear conditioning with DMR. *Psychoneuroendocrinology* 35, 33–46.

Migues, P. V., Hardt, O., Wu, D. C., Gamache, K., Sacktor, T. C., Wang, Y. T., and Nader, K. (2010). PKMζ maintains memories by regulat-
ing GluR2-dependent AMPA recep-


Neves, G., Cooke, S. F., and Bliss, T. V. (2008). Synaptic plasticity, memory and the hippocampus: a neural net-


ral and spatial patterns of AMPA 


Petrinin, E. M., Lu, J., Cognet, L., Lou-

Krugers et al. Stress, fear, and synapses

Frontiers in Behavioral Neuroscience www.frontiersin.org October 2011 | Volume 5 | Article 62 | 10


Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.