Learning-Induced Reversal of the Effect of Noradrenalin on the Postburst AHP

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Brosh, Inbar, Kobi Rosenblum, and Edi Barkai. Learning-induced reversal of the effect of noradrenalin on the postburst AHP. J Neurophysiol 96: 1728–1733, 2006. First published July 5, 2006; doi:10.1152/jn.00376.2006. Pyramidal neurons in the piriform cortex from olfactory-discrimination-trained rats have reduced postburst afterhyperpolarization (AHP), for 3 days after learning, and are thus more excitable during this period. Such AHP reduction is caused by decreased conductance of one or more of the calcium-dependent potassium currents, $I_{AHP}$ and $sI_{AHP}$, that mediate the medium and slow AHPs. In this study, we examined which potassium current is reduced by learning and how the effect of noradrenalin (NE) on neuronal excitability is modified by such reduction. The small conductance (SK) channels, which selectively block $I_{AHP}$, reduced the AHP in neurons from trained, naïve, and pseudo-trained rats to a similar extent, thus maintaining the difference in AHP amplitude between neurons from trained rats and controls. In addition, the protein expression level of the SK1, SK2, and SK3 channels genes (SK1, SK2, and SK3) was also similar in all groups. NE, which was shown to enhance the protein expression level of the SK1, SK2, and SK3 channels (Sailer et al. 2002; Sah and Faber 2002; Stocker et al. 1999), whereas SK1 channels have a significantly lower sensitivity to apamin. The identity of the channel that mediates $sI_{AHP}$ is yet unknown (Sah and Faber 2002).

Noradrenalin (NE) has several actions in target structures that would suggest a role in learning and memory processes, particularly in odor-discrimination tasks (Gervais andPager 1983; Linster andHasselmo 2001; Przybyslawski et al. 1999; Sullivan andWilson 1991, 1993, 1994).

NE was shown to enhance neuronal excitability (Foehring et al. 1989; Madison and Nicoll 1984; Stocker et al. 1999). This action is mediated by reducing the $sI_{AHP}$ conductance, whereas $I_{AHP}$ is enhanced (Stocker et al. 1999).

Learning-induced modifications in the ratio between $I_{AHP}$ and $sI_{AHP}$ conductances may alter also the responses of these neurons to NE. Consequently, NE may play different roles before and after learning.

Here we show that the effect of NE on intrinsic neuronal excitability is indeed reversed after learning. We suggest that, after learning, NE increases the threshold for activity-induced synaptic enhancement, thereby stabilizing the cortical network and preventing runaway synaptic strengthening.

METHODS

Animal training

SUBJECTS AND APPARATUS. Age-matched young adult Sprague-Dawley male rats were used. Before training, they were maintained on a 23.5-h water-deprivation schedule, with food available ad libitum.

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OD training protocol was performed daily on each trained and pseudotrained rat in a four-arm radial maze, as previously described (Saar et al. 1999, 2001), with commercial odors that are regularly used in the cosmetics and food industry.

TRAINING. Olfactory training consisted of 20 trials/day for each rat as previously described (Saar et al. 2001). In short, in each trial, the rat had to choose between two odors (positive and negative cue) presented simultaneously. Rats designated to the trained group were rewarded on choosing the positive cue. Rats in the pseudotrained group were rewarded in a random fashion, on choosing any odor. The criterion for learning was ≥80% positive-cue choices in the last 10 trials of a training day, as was previously used (Saar et al. 1999, 2001; Staubli et al. 1987). Rats in the naive group were water deprived but not exposed to the maze. Typically, two to three trained rats and two to three pseudotrained rats were trained at the same training period, and all the rats in the trained group had to meet the criteria for the first pair of odors before all trained and pseudotrained rats were exposed to a second pair of odors. Training for a third pair began (if necessary) only after training for the second pair was completed for all rats. Rats were trained to discriminate between two to three pairs of odors to confirm that rule learning was achieved and to ensure that rats were always killed 3 days after the last training session. Pairs of odors used were as follows: orange-pineapple, lemon-peach, and coconut-apple. As previously described (Saar et al. 1999, 2001), rats indeed learned the second and third pairs of odors much faster than the first pair (7–8 days of training for the first pair and 1–2 days for the second and third pairs).

Slice preparation, stimulation, and recording

Coronal brain slices (400 μm) were cut as previously described (Saar et al. 1998) and kept in oxygenated (95% O₂-5% CO₂) normal saline Ringer (NSR) solution (in mM: 124 NaCl, 3 KCl, 2 MgSO₄, 1.25 NaH₂PO₄, 26 NaHCO₃, 2 CaCl₂, and 10 glucose). Intracellular recordings were obtained from pyramidal cells in layer II of the piriform cortex, with 4 M K-acetate–filled sharp glass microelectrodes. As previously described (Saar et al. 1999, 2001), neurons were held at membrane potential of 1729 mV and action potential amplitude of 80 mV or more). To standardize AHP recordings, neurons were depolarized to holding potential of −60 mV by DC application through the recording electrode. Postburst AHP amplitude was measured after a 100-ms depolarizing current step with intensity that generates six action potentials. The AHP amplitude was determined from an average of eight consecutive measurements of AHP evoked in response to stimuli applied once every 10 s.

The postburst AHP amplitude was measured from baseline to the peak(s) of the hyperpolarizing voltage deflection that follows an evoked train of six action potentials (Fig. 1A).

The identity of the rat from which neurons were recorded (naïve, trained, or pseudotrained) was not known to the person conducting the experiments and measurements.

DRUG APPLICATION. All drugs were applied into the perfusing Ringer solution at the following concentrations: 50 nM apamin and 10 μM NE. Slices were exposed to drugs for ≥45 min before the recordings. In each recording condition, several cells were recorded before and after drug application, whereas others were recorded under one condition only (e.g., in NSR or in the presence of drugs).

Immunoblot analysis

The olfactory cortex was rapidly dissected in the same saline Ringer solution as used for brain slices and immediately homogenized in ice-cold homogenization buffer [in mM: 10 HEPES, 2 EDTA, 0.5 DTT, phosphatase inhibitor cocktail (Sigma p5726), and protease inhibitor cocktail (Sigma p834)]. Tissue was homogenized in a teflon-glass tissue homogenizer (Kontes, Vineland, NJ), the homogenate was centrifuged at 5,000 g for 1 min at 4°C, and the supernatant was centrifuged at 14,000 g for 60 min at 4°C. The resulting pellets were resuspended in SDS sample buffer (10% glycerol, 0.5% SDS, 60 mM Tris-HCl, pH 5.0, and 7% β-mercaptoethanol), boiled for 5 min, and stored at −80°C. Protein concentration for each sample was assessed using the Lowry method (Lowry et al. 1951). Similar amounts of membranal proteins were separated on 10% polyacrylamide gels, transferred to nitrocellulose, and probed with anti-SK1 (Santa Cruz), anti-SK2 (Alomone), anti-SK3 (Santa Cruz), or anti-β-actin (Santa Cruz) polyclonal antibodies, followed by the appropriate secondary antibody coupled to horseradish peroxidase (HRP). For scaling purposes, we first identify the linear scale of the different antibody–protein interaction, as defined by an increased protein concentration. We have thus used loading of 10, 30, and 15 μg for SK1, 2, and 3 accordingly. Visualization of immunoreactive bands was produced by enhanced chemiluminescence (ECL plus, Amersham) captured on medical ECL-sensitive film (Fuji). Scanned images were quantified using National Institutes of Health Image 1.60 software. The ratio between SK 1/2/3 and β-actin for each rat was calculated and normalized to a naïve run on the same gel.

Statistical analysis

For each treatment, between-group comparison of postburst AHPs amplitudes was done using one-way ANOVA for the three groups (naïve, trained, and pseudotrained), and post hoc multiple t-tests were applied to compare between each two groups. The effect of each treatment on each of the three groups was evaluated by comparing the AHP amplitude in neurons from the same group, with and without the treatment, using an independent t-test. Values throughout the text are presented as mean ± SD. Data are graphs is presented as mean ± SE.
RESULTS

Recordings in neurons from trained and pseudotrained rats were performed 3 days after the last training session, when learning-related reduction in AHP amplitude is most prominent (Saar and Barkai 2003). In NSR, the averaged postburst AHP in neurons from trained rats was significantly smaller compared with the averaged AHPs in neurons from pseudotrained and naive rats (Fig. 2A), confirming our earlier reports (Saar et al. 1998, 2001). As previously reported (Saar et al. 1998, 2001), resting membrane potential (79.2 ± 7.0 mV, n = 34 in naïve, 79.0 ± 6.9 mV, n = 50 in trained, and 81.8 ± 7.4 mV, n = 34 in pseudotrained) and input resistance (32.4 ± 13.2 MOhm, n = 25 in naïve, 29.5 ± 8.8 MOhm, n = 31 in trained, and 35.9 ± 13.8 MOhm, n = 20 in pseudotrained) did not differ between neurons from the three groups.

Learning-related reduction in AHP is mediated by a decrease in $I_{AHP}$

To examine whether the reduction in postburst AHP amplitude is mediated by reduction in $I_{AHP}$, we applied its specific blocker apamin (50 nM). In piriform cortex neurons, the postburst AHP has a considerably shorter duration than in hippocampal neurons, and the two types of AHP may overlap (Saar et al. 2001). Whenever the medium and slow AHPs were clearly distinguishable, apamin affected only the first postburst negative peak (Fig. 1B). More frequently, the medium and slow AHPs did not have separate peaks. In these occasions, apamin reduced the amplitude of the single peak (Fig. 1C). Apamin significantly reduced the AHP in neurons from all groups; in neurons from trained rats, the averaged AHP value decreased from 4.98 ± 1.70 mV ($n = 32$) in NSR to 2.76 ± 1.81 mV ($n = 20$) in apamin ($P < 0.01$). In neurons from naïve rats, the averaged AHP value decreased from 6.76 ± 1.82 mV ($n = 24$) in NSR to 4.73 ± 0.92 mV ($n = 9$) in apamin ($P < 0.01$), and in neurons from pseudotrained rats, the averaged AHP value decreased from 6.78 ± 1.80 mV ($n = 23$) in NSR to 4.76 ± 2.34 mV ($n = 16$) in apamin ($P < 0.01$). Thus in the presence of apamin, the difference in AHP amplitude between neurons from trained rats and controls was maintained (Fig. 2A), and the proportion of the AHP amplitude reduced by apamin was greater in neurons from trained rats (Fig. 2B). The contribution of the apamin-sensitive portion of the AHP to the AHP amplitude was calculated by subtracting for each cell the amplitude of the AHP in the presence of apamin from the averaged amplitude of AHP in its group, in NSR. The averaged value of the apamin-sensitive part of the AHP was similar in all groups (2.03 ± 1.81 in naïve, 2.22 ± 1.69 in trained, and 2.12 ± 1.80 in pseudotrained), indicating that this part remains intact after OD learning. Resting membrane potential in neurons from the three groups (79.7 ± 5.5 mV, n = 30 in naïve, 80.3 ± 6.7 mV, n = 38 in trained, and 80.1 ± 5.4 mV, n = 25 in pseudotrained) and input resistance (38.7 ± 10.8 MOhm, n = 14 in naïve, 38.0 ± 8.9 MOhm, n = 19 in trained, and 30.8 ± 14.4 MOhm, n = 22 in pseudotrained) were not affected by apamin application.

Expression of SK channels is not modified by learning

Although apamin is thought to specifically reduce $I_{AHP}$, it does not affect the three types of SK channels to the same extent. The SK2 channel type is considered to be the most sensitive, whereas the SK1 channel type is the less sensitive one (Bond et al. 2004; Sah and Faber 2002). After the pharmacological experiments described above with apamin, we further examined the effect of learning on the expression level of the different SK channels. Using type specific antibodies and Western blot analysis (see METHODS), we measured the expression level of the SK channels in the piriform cortex of the different groups. We did not detect any changes in the expression level of SK1-3 after learning (Fig. 3) or in the levels of β-actin (data not shown). These results indicate that the expression level of the three types of channels that mediate $I_{AHP}$ is not modified after learning.

NE enhances the postburst AHP in neurons from trained rats

NE has a complex effect on the postburst AHP; it reduces $I_{AHP}$ and enhances $I_{AHP}$ (Stocker et al. 1999). Therefore it enhances the medium AHP and reduces the slow AHP. We hypothesized that if indeed the slow AHP is reduced by learning, whereas the medium AHP remains intact, NE application should have different effects on neurons from trained rats and controls. NE (10 μM) application to neurons from control rats reduced significantly the amplitude of the postburst AHP ($P < 0.05$). The average AHP amplitude with NE was 5.64 ± 1.96 ($n = 24$) in neurons from naïve rats and 5.20 ± 1.89 ($n = 12$) in neurons from pseudotrained rats. The same
treatment increased significantly \( (P < 0.01) \) the averaged AHP in neurons from trained rats to \( 6.32 \pm 2.65 \) \( (n = 14) \). As a result of these opposing effects, NE abolished the difference in the AHP amplitudes between neurons from trained and control rats (Fig. 4, A–C).

To examine whether the enhancing effect of NE on the postburst AHP after learning results from increasing \( I_{AHP} \) conductance, we tested its effect on neurons from trained rats in the presence of apamin. In these conditions, NE did not enhance the AHP in any of the four tested neurons (Fig. 4D). The averaged value of the AHP in apamin was \( 2.7 \pm 1.6 \) mV and in apamin + NE was \( 3.3 \pm 1.7 \) mV.

**Learning-induced modifications in the effects of NE are not the result of changes in basic neuronal properties**

Such learning-induced modification in the effect of NE on the postburst AHP may be the result of a direct effect on the AHP underlying currents or a nonspecific effect on basic membrane properties. For example, a learning-induced increase in the averaged neurons’ input resistance, or in the averaged width of single action potentials, would result in enhanced postburst AHP without modifying directly \( I_{AHP} \) or \( sI_{AHP} \). Our data show that such a nonspecific effect was not induced by NE application. Resting membrane potential in neurons from the three groups (79.8 \( \pm 6.2 \) mV, \( n = 54 \) in naïve, 76.5 \( \pm 6.2 \) mV, \( n = 39 \) in trained, and 79.2 \( \pm 7.8 \) mV, \( n = 21 \) in pseudotrained) and input resistance (38.0 \( \pm 12.6 \) MOhm, \( n = 18 \) in naïve, 32.3 \( \pm 13.8 \) MOhm, \( n = 13 \) in trained, and 33.0 \( \pm 12.4 \) MOhm, \( n = 6 \) in pseudotrained) were not affected by NE application.

As previously reported (Saar et al. 1998), the averaged action potential duration in NSR was similar in all groups (1.67 \( \pm 0.31 \) ms, \( n = 27 \) in naïve, 1.49 \( \pm 0.32 \) ms, \( n = 29 \) in trained, and 1.57 \( \pm 0.36 \) ms, \( n = 23 \) in pseudotrained). These values were not modified by NE application (1.57 \( \pm 0.27 \) ms, \( n = 28 \) in naïve, 1.41 \( \pm 0.29 \) ms, \( n = 23 \) in trained, and 1.68 \( \pm 0.32 \) ms, \( n = 13 \) in pseudotrained; Fig. 5).

**DISCUSSION**

Previous studies have shown that neuronal excitability is enhanced and the postburst AHP is reduced in hippocampal and cortical pyramidal neurons after learning (Moyer et al. 1996; Saar and Barkai 2003; Thompson et al. 1996). In piriform cortex neurons, these long-term modifications result from reduction in an acetylcholine-sensitive calcium-dependent potassium current (Saar et al. 2001) and is maintained by protein kinase C (PKC) activation (Seroussi et al. 2002). Here we show that enhanced neuronal excitability results from reduction in an apamin-insensitive current. Consequently, the effect of NE on the postburst AHP is reversed after learning.
Learning-induced enhancement of neuronal excitability is mediated by reduction in $s_{\text{AHP}}$

In most piriform cortex neurons, the medium and slow AHP overlap to the extent that only a single negative peak is observed (Saar and Barkai 2003; Saar et al. 2001). Because their underlying currents, $I_{\text{AHP}}$ and $s_{\text{AHP}}$, overlap, a pharmacological treatment affects only one of them is the preferable way to examine their relative contribution to the complex postburst AHP. Apamin, which affects only $I_{\text{AHP}}$ (Sah and Faber 2002; Stocker et al. 1999), reduced the amplitude of the AHP to a similar extent in neurons from naïve, trained, and pseudotrained rats. Accordingly, the difference in AHP amplitude between neurons from trained and control rats remained and even became more prominent. Moreover, the protein expression levels of the three SK channel types that mediate $I_{\text{AHP}}$ (Sah and Faber 2002; Stocker et al. 1999) are not modified after OD learning. Taken together, these data suggest that learning induced enhancement in neuronal excitability is mediated by long-term reduction of $s_{\text{AHP}}$.

Possible mechanism for the learning-induced reverse of the effect of NE on the postburst AHP

Because $I_{\text{AHP}}$ and $s_{\text{AHP}}$ overlap in piriform cortex neurons, a neuromodulator that has opposite effects on these two currents may change its net effect on the postburst AHP, pending on the relative contribution of the two currents to its composition.

Because NE was shown to increase $I_{\text{AHP}}$ while reducing $s_{\text{AHP}}$, its differential effect on neurons from trained rats and controls indicate that the conductance ratio $I_{\text{AHP}}/s_{\text{AHP}}$ is increased in neurons from trained rats, as would be expected if only $s_{\text{AHP}}$ conductance is reduced. Such notion is supported by the following findings: NE enhances the AHP in neurons from trained rats only, the enhancing effect of NE on the AHP after learning is abolished in the presence of apamin, and basic membrane properties are not modified by NE before or after learning.

This conclusion is in agreement with recent evidence that suggests that learning-related enhancement of neuronal excitability in hippocampal neurons results from reduction in $s_{\text{AHP}}$ (Oh et al. 2003).

Functional significance of NE action on the AHP

The postburst AHP in pyramidal neurons is modulated by several neuromodulators, such as acetylcholine (ACh) and NE (Saar et al. 2001; Schwindt et al. 1988; Stocker et al. 1999).

Interestingly, the effects of these two neuromodulators on piriform cortex pyramidal neurons are changed after learning. ACh loses its ability to enhance neuronal excitability (Saar et al. 2001), whereas NE gains an ability to reduce neuronal excitability. NE was previously shown to enhance learning processes (Przybylski et al. 1999), an action attributed to its ability to modulate synaptic transmission directly (Hasselmo et al. 1997) or to affect gene expression (Sara et al. 1999). NE-induced suppression of synaptic transmission was suggested to enhance the signal-to-noise ratio in the piriform cortex network, thus enhancing the encoding of olfactory input (Hasselmo et al. 1997).

What functional significance may such a modification in NE effect on neuronal excitability have? While it is commonly accepted that synaptic strengthening is involved in learning and memory processes, it was pointed out by several studies that a compensation mechanism that would prevent overstrengthening of synaptic connections that are not relevant to memory storage should also be activated (Barkai et al. 1994; Quinlan et al. 2004). Such a mechanism would prevent runaway synaptic enhancement, thus preventing a situation in which the neuronal network becomes hyperexcitable, loses its ability to store memories, and responds with an epileptic-like activity to relatively mild stimulations (Barkai et al. 1994; Hasselmo and Barkai 1995). A series of physiological and morphological modifications were detected in the piriform cortex after OD learning. These modifications, which include enhanced neuronal excitability (Saar et al. 1998), enhanced synaptic transmission (Saar et al. 1999, 2002) and increased number of spines (Knafo et al. 2001), may very well drive the piriform cortex network into such a hyperexcitable state (Barkai et al. 1994). We propose that the change in NE effect after OD learning acts to counterbalance these modifications and preserve the piriform cortex ability to subserve olfactory learning by increasing the threshold for inducing neuronal activation to the point where synaptic changes are induced.

Possible mechanisms underlying induction of learning-related AHP reduction

To date, little effort has been made to reveal the mechanisms by which learning-induced AHP reduction and enhanced neuronal excitability are induced. Such lack of research is the direct consequence of the difficulty of detecting and monitoring this cellular biophysical process in vivo while the animal is behaving and performing a complicated task.

A series of studies that were performed in hippocampal brain slice preparations suggest that activation of the kainate metabotrophic glutamate receptor can initiate the sequence of events, leading to long-lasting enhancement of neuronal excitability through the GluR6 subunit.

Long-term reduction in the slow AHP was induced in CA1 pyramidal neurons by synaptically released glutamate, evoked by stimulating the Schaffer collateral and commissural fibers with trains of 100 Hz (Melyan et al. 2002). Later, the same authors went on to show that a similar effect is obtained by briefly exposing hippocampal brain slices to kainate (Melyan et al. 2004). This effect is independent of AMPA receptors, of the GluR5 subtype, of ionotropic action, and of network activity. It is blocked by inhibiting pertussis toxin–sensitive G proteins. Also, similar to the learning-induced reduction in the postburst

![Fig. 5. NE does not affect basic membrane properties. A: example of lack of effect of NE on resting membrane potential and input resistance in a neuron from a pseudotrained rat. Resting potential was $-80$ mV; input resistance was measured by voltage deflection in response to a 100-ms pulse of $-0.3$ nA, applied through the recording electrode. B: example of lack of effect of NE on duration of the action potential in a neuron from a trained rat.](http://jn.physiology.org/doi/10.1063/1.2335175)
AHP (Seroussi et al. 2002), the effect of kainate is dependent on PKC activation (Melyan et al. 2002, 2004). In accordance to its action on the AHP, kainate enhances repetitive firing frequency in these neurons (Melyan et al. 2002). Other studies present additional evidence supporting the notion that metabotropic glutamate receptors are crucial for the process of inducing long-term enhancement in neuronal excitability induced by high-frequency repetitive stimulation (Cohen et al. 1999; Ireland and Abraham 2002; Sourdret et al. 2003). The GluR5 subtype was shown to mediate long-lasting reduction of the ampa-sensitive AHP (Sourdret et al. 2003), and the Glur1 subtype was shown to mediate the long-lasting reduction of the slow AHP (Ireland and Abraham 2002).

Whether the process underlying the learning-related induction of long-term reduction of the postburst AHP shares the same mechanism as the similar reduction induced by tetanic stimulation in brain slices remains to be explored.

In conclusion, our data suggest that learning-induced long-term enhancement of neuronal excitability is maintained by reduction in sAHP and that this reduction reverses the effect of NE on neuronal excitability. Such reversal of effect may serve to prevent overstrengthening of synaptic connections during acquisition of new olfactory memory.

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