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Dendritic GluN2A Synthesis Mediates Activity-Induced NMDA Receptor Insertion

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Long-term synaptic plasticity involves changes in the expression and membrane insertion of cell-surface proteins. Interestingly, the mRNAs encoding many cell-surface proteins are localized to dendrites, but whether dendritic protein synthesis is required for activity-induced surface expression of specific proteins is unknown. Herein, we used microfluidic devices to demonstrate that dendritic protein synthesis is necessary for activity-induced insertion of GluN2A-containing NMDA receptors in rat hippocampal neurons. Furthermore, visualization of activity-induced local translation of GluN2A mRNA and membrane insertion of GluN2A protein in dendrites was directly observed and shown to depend on a 3′ untranslated region cytoplasmic polyadenylated element and its associated translation complex. These findings uncover a novel mechanism for cytoplasmic polyadenylated element-mediated posttranscriptional regulation of GluN2A mRNA to control NMDA receptor surface expression during synaptic plasticity.

Introduction

Long-term plasticity at glutamatergic synapses depends on both the regulation of glutamate receptor trafficking and dendritic protein synthesis, yet how these processes might be linked remains unclear (Sutton and Schuman, 2006; Rebola et al., 2010). The AMPA and NMDA families of ionotropic glutamate receptors are critical mediators of long-term synaptic plasticity and are dynamically regulated at synapses (Derkach et al., 2007; Santos et al., 2009). Several reports suggest that AMPA receptor expression and membrane insertion may be regulated by dendritic mRNA localization and local protein synthesis (Kacharmina et al., 2000; Ju et al., 2004; Smith et al., 2005; Grooms et al., 2006; Sutton et al., 2006; Maghsoodi et al., 2008; Soden and Chen, 2010). However, whether dendritic protein synthesis regulates NMDA receptor expression or membrane insertion is unknown.

NMDA receptors are composed of two GluN1 and two GluN2 subunits (types 2A–2D). Hippocampal pyramidal neurons express the GluN2A and GluN2B subunits, which have distinct functional properties and are differentially expressed during development (Traynelis et al., 2010). Furthermore, the relative surface level of GluN2A-containing and GluN2B-containing NMDA receptors affects neuronal function (Lau and Zukin, 2007). Therefore, it is important to understand the mechanisms regulating GluN2 subunit expression and membrane insertion. Similar to AMPA receptors, synaptic activity regulates the expression and trafficking of NMDA receptors (Lau and Zukin, 2007; Yashiro and Philpot, 2008; Smith et al., 2009). Activity-dependent plasticity in the hippocampus involves increased NMDA receptor-surface expression (Grosshans et al., 2002; Kwon and Castillo, 2008; Rebola et al., 2008). The NMDA receptor component of EPSPs is increased during long-term potentiation (LTP) in the dentate gyrus, and this effect is mediated by GluN2A-containing receptors (Peng et al., 2010). Interestingly, LTP in the hippocampus and sensory activation of the visual cortex lead to increased GluN2A protein expression (Williams et al., 1998, 2003; Quinlan et al., 1999; Zhong et al., 2006; Philpot et al., 2007). However, the posttranscriptional mechanisms underlying activity-induced expression of NMDA receptor subunits are unclear.

Recently, we reported that GluN2A mRNA contains a cytoplasmic polyadenylated element (CPE) in its 3′ untranslated region (UTR), and GluN2A protein expression is bidirectionally regulated by two translation factors associated with the CPE-binding (CPEB) protein, namely Gld2, a poly(A) polymerase, and neuroguidin (Ngd), an eIF4E-binding protein (Udagawa et al., 2012). Gld2 and Ngd also bidirectionally regulate theta-burst LTP in the dentate gyrus (Udagawa et al., 2012). Notably, GluN2A mRNA is localized to hippocampal neuron dendrites, suggesting that it could be locally translated (Cajigas et al., 2012; Udagawa et al., 2012). CPEB and associated factors are also localized to dendrites (Udagawa et al., 2012), but whether they regulate GluN2A mRNA localization or dendritic translation has not been studied. Moreover, whether the CPEB-associated translation complex regulates NMDA receptor-surface expression is unknown. Here, we tested the hypothesis that CPEB-mediated...
dendritic synthesis of GluN2A regulates activity-induced NMDA receptor insertion. Our findings demonstrate a requirement for dendritic protein synthesis and the CPEB-associated translation complex in the activity-dependent synthesis and membrane insertion of GluN2A in dendrites.

Materials and Methods

Cell culture and drug treatments. Hippocampal neuron cultures were prepared from Sprague Dawley rat embryos of either sex at day E18, as described previously (Goolin and Banker, 1998). Neurons were cultured for 21–24 d in vitro (DIV) on poly-L-lysine-coated tissue culture plastic for biochemical experiments and glass coverslips for imaging experiments. Neuro 2A cells, a mouse neuroblastoma cell line, were cultured in DMEM (Sigma-Aldrich) with 10% FBS (Hyclone) and grown on tissue culture plastic.

For glycine stimulation experiments, hippocampal neurons were incubated in extracellular solution lacking magnesium (in mM: 150 NaCl, 2 CaCl2, 5 KCl, 10 HEPES, 30 glucose, 0.0005 TTX, 0.001 strychnine, 0.02 CaCl2, 5 KCl, 10 HEPES, 30 glucose, 0.0005 TTX, 0.001 strychnine, 0.02 for 21–24 d prepared from Sprague Dawley rat embryos of either sex at day E18, as described previously (Goolin and Banker, 1998). Neurons were cultured for 21–24 d in vitro (DIV) on poly-L-lysine-coated tissue culture plastic for biochemical experiments and glass coverslips for imaging experiments. Neuro 2A cells, a mouse neuroblastoma cell line, were cultured in DMEM (Sigma-Aldrich) with 10% FBS (Hyclone) and grown on tissue culture plastic.

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natants were added to neutravidin beads and rotated at 4°C for 2 h, then washed 4 times with lysis buffer; 2% of the supernatant volume was kept for SDS-PAGE analysis. Laemmli buffer was added to the samples, and they were boiled for 5 min, followed by SDS-PAGE and Western blotting.

**Synaptoneurosome preparation.** Synaptoneurosomes were prepared from male C57BL/6 mice at postnatal day 18–21 as described previously (Hollingsworth et al., 1985; Scheetz et al., 2000). Briefly, the dissected hippocampus was homogenized on ice in 10 volumes of homogenization buffer containing the following (in mM): 118 NaCl, 4.7 KCl, 1.2 MgSO₄, 2.5 CaCl₂, 1.53 KH₂PO₄, 212.7 glucose, and 1 DTT, pH 7.4, and supplemented with complete protease inhibitors (Roche). A sample of the total homogenate was removed and kept on ice. The homogenate was passed through three 100 μm nylon mesh filters, followed by one 11 μm filter (Millipore) and centrifuged at 1000g at 10000 × g for 10 min. The synaptoneurosome pellets were resuspended in the same buffer. Protein concentrations were estimated using the Bradford protein assay (Bio-Rad). Samples were incubated at 37°C for 15 min with vehicle or anisomycin, and then treated for 15 min with 100 μM glutamate and 50 μM glycine. Laemmli buffer was added to the samples, which were then boiled for 5 min and processed by SDS-PAGE.

**Fixed image acquisition and analysis.** Cultured neurons were imaged with a Nikon Ti inverted microscope using a 60 × 1.4 NA Plan Apo objective and an HQ2 cooled CCD camera (Photometrics). Within each experiment, all treatment groups were imaged with the same acquisition settings and within the same imaging session. Z-series were obtained at 0.15 μm steps. Image stacks were deconvolved using a 3-D blind constrained iterative algorithm (AutoQuant, CyberMetrics). Quantification of immunofluorescence and FISH signals was performed using ImageJ (version 1.46). Mean fluorescence intensities were quantified within a cellular region, and mean background fluorescence intensities were quantified from an adjacent, noncellular region. Dendrites were straightened using the Straighten plugin in ImageJ. For dendritic granule counts, a dendritic region was chosen in ImageJ and a threshold level was determined that included all granules above background. The threshold was applied and the Particle Analysis function was used to compute the number of granules within the area. The same threshold was used across all images and groups. The representative images shown within a single figure panel are presented with identical lookup table settings. The experimenter was blind to the treatment conditions during image acquisition and analysis.

**Live-cell imaging.** A Nikon A1R microscope, NIS-Elements software, and a 60 × objective (Apo TIRF, NA 1.49) were used for live-cell imaging. The neurons were maintained at 37°C and 5% CO₂ throughout the experiment. Thirty minutes before imaging, the growth media was removed and exchanged with extracellular solution (without glycine). For some experiments, neurons were pretreated with anisomycin (40 μM) and GluN2B surface expression in dendrites and that these effects were blocked by anisomycin (Fig. 1A). GluN1 and GluN2A surface expression was significantly increased 30 min after glycine application, and these effects were blocked by the protein synthesis inhibitor anisomycin (Fig. 1A, B). GluN1 and GluN2A protein levels in a protein synthesis-dependent manner (Fig. 1A). In contrast, total and surface levels of GluN2B were unaffected by glycine treatment (Fig. 1A–C). These results indicate that the ratio of GluN2A to GluN2B surface levels increased by 30%. Similarly, surface immunolabeling and quantitative imaging demonstrated that glycine increased GluN1 and GluN2A surface expression in dendrites and that these effects were blocked by anisomycin (Fig. 1D,E). In contrast, dendritic surface expression of GluN2B was not affected by glycine or anisomycin (Fig. 1F). Together, these data indicate that glycine treatment increases the dendritic surface expression of GluN2A-containing NMDA receptors in a protein synthesis-dependent manner.

**Dendritic protein synthesis is required for glycine-induced GluN2A surface expression**

Dendritic protein synthesis is necessary for certain types of LTP (Kang and Schuman, 1996; Cracco et al., 2005; Huang and Kandel, 2005; Vickers et al., 2005) and regulates AMPA receptor surface expression (Kacharmina et al., 2000; Ju et al., 2004; Maghsoudi et al., 2008; Soden and Chen, 2010). Given that NMDA receptor surface expression is also activity-regulated and GluN2A mRNA is localized to dendrites (Cajigas et al., 2012; Udagawa et al., 2012), we hypothesized that dendritic protein synthesis could mediate the insertion of GluN2A-containing NMDA receptors during glycine-induced LTP. To test whether dendritic protein synthesis is necessary for glycine-induced NMDA receptor expression and membrane insertion, neurons were cultured in microfluidic devices that allow for separate
pharmacological treatment of cell bodies and distal dendrites (Fig. 2A, B) (Taylor et al., 2005). Fluorescent dyes and time-lapse imaging were used to ensure that fluidic isolation was maintained throughout the glycine treatment paradigm (Fig. 2C). Glycine application to the dendritic compartment significantly increased dendritic GluN2A surface expression 30 min after the glycine treatment. Anisomycin blocked this effect when locally applied to dendrites, but not when applied to cell bodies (Fig. 2D). These data suggest that dendritic protein synthesis is necessary for the insertion of GluN2A-containing NMDA receptors during glycine-induced LTP. In microfluidic devices, glycine application to dendrites also increased total dendritic GluN2A levels (Fig. 2E). Importantly, anisomycin application to the cell body compartment did not abolish the glycine-induced increase in total dendritic GluN2A expression, although overall GluN2A levels were decreased (Fig. 2E). Anisomycin treatment to dendrites did not affect basal GluN2A levels, but led to a glycine-induced decrease in total dendritic GluN2A levels (Fig. 2E). This observation suggests that glycine treatment to dendrites may lead to the turnover of GluN2A, which would be replaced by newly synthesized subunits; although, the mechanisms underlying this are unknown. Importantly, these data indicate that dendritic protein synthesis is required for glycine-induced GluN2A expression, whereas somatic protein synthesis regulates constitutive GluN2A protein levels in dendrites.

CPEB and the CPE sequence regulate dendritic GluN2A mRNA localization

We previously reported that the GluN2A 3' UTR contains a CPE sequence (Udagawa et al., 2012), yet the role of CPEB and the 3' UTR CPE sequence in regulating GluN2A translation has not been studied. The CPEB-associated translation complex is localized to dendrites and dendritic spines, and CPEB as well as CPE sequences have been shown to regulate dendritic mRNA localization and local translation (Wells et al., 2001; Huang et al., 2003; Udagawa et al., 2012). Therefore, we hypothesized that the CPE sequence and associated factors modulate NMDA receptor-surface expression in dendrites by controlling the dendritic localization and local translation of GluN2A mRNA. To test this hypothesis, we first investigated the interaction between CPEB and GluN2A mRNA. In cultured hippocampal neurons, FLAG-tagged CPEB immunoprecipitated endogenous GluN2A mRNA as well as αCaMKII mRNA, a known CPEB target mRNA, whereas GluN1 and γ-actin mRNAs were not immunoprecipitated (Fig. 3A). In a neuroblastoma cell line, FLAG-CPEB immunoprecipitated a portion of the GluN2A 3' UTR containing the CPE sequence, but not the 3' UTR with a mutated CPE sequence (ACPE-GluN2A) (Fig. 3B, C). These data suggest that CPEB associates with GluN2A mRNA via the 3' UTR CPE sequence.

Given that CPEB has been shown to interact with kinesin and to regulate mRNA transport (Huang et al., 2003), we assessed...
whether CPEB and the CPE sequence control dendritic localization of GluN2A mRNA. CPEB expression was reduced in cultured hippocampal neurons using lentiviral shRNA, and knockdown (KD) was confirmed by Western blotting (Fig. 3E). Fluorescence in situ hybridization for endogenous GluN2A mRNA demonstrated that CPEB knockdown reduced the dendritic localization of endogenous GluN2A mRNA by \(~50\%\) (control: 44 \(\pm\) 3 dendritic granules/50 \(\mu\)m\(^2\); CPEB KD: 21 \(\pm\) 3 dendritic granules/50 \(\mu\)m\(^2\); \(n=25\)–30 cells, Student’s \(t\) test, \(p<0.001\)) (Fig. 3D). CPEB knockdown increased total GluN2A mRNA levels as assessed by quantitative real-time PCR (CPEB KD: 128 \(\pm\) 6.6% of control, \(n=5\), paired \(t\) test, \(p=0.024\)), indicating that the decrease in dendritic GluN2A mRNA levels was due to impaired localization rather than reduced transcription or mRNA stability. To investigate whether the CPE sequence regulates GluN2A mRNA localization, GFP fused to the GluN2A 3’ UTR or ΔCPE-GluN2A 3’ UTR was expressed in cultured hippocampal neurons for 12 h, and then dendritic GFP mRNA levels were examined by FISH. Dendritic GFP mRNA levels were significantly reduced in neurons expressing the ΔCPE-GluN2A 3’ UTR compared with the wild-type GluN2A 3’ UTR (Fig. 3F). The 3’ UTR sequence did not significantly affect total GFP mRNA levels, as assessed by quantitative real-time PCR (ΔCPE-3’ UTR: 102 \(\pm\) 6.0% of WT-3’ UTR, \(n=6\), paired \(t\) test, \(p=0.929\)). Together, these data indicate that CPEB and the CPE sequence regulate GluN2A mRNA localization to dendrites.

The 3’ UTR CPE sequence regulates translation of GluN2A mRNA in dendrites

Next, we evaluated whether GluN2A could be translated at synapses and within dendrites. In synaptoneurosome fractions isolated from mouse hippocampus, the application of glutamate (100 \(\mu\)M) and glycine (50 \(\mu\)M) for 15 min induced a protein synthesis-dependent increase in endogenous GluN2A protein levels, suggesting that GluN2A is synthesized at synapses (Fig. 4A). To study local protein synthesis directly, dendritic mRNA translation was imaged in live neurons using a diffusion-restricted translation reporter Dendra2 fused to the GluN2A 3’ UTR, similar to the reporter we previously used to study local translation of β-actin mRNA (Welschmans and Bassell, 2011). Glycine induced the dendritic synthesis of Dendra2 fused to the GluN2A 3’ UTR, but not when the UTR was removed or anisomycin was applied (Fig. 4B). Dendra2 fluorescence levels were significantly increased at 25 min after glycine application and reached a plateau by 40 min. These data suggest that glycine treatment induces the local translation of GluN2A mRNA in dendrites. In addition, the CPE sequence was required for the GluN2A 3’ UTR to mediate glycine-induced dendritic synthesis of Dendra2 (Fig. 4C). In these experiments, the Dendra2 constructs were expressed for 48 h before imaging; this expression time resulted in similar dendritic localization of the wild-type and ΔCPE 3’ UTRs under both control and glycine-treated conditions (as assessed by GFP FISH) (Fig. 4D). In Figure 3, we showed that mutation of the CPE sequence significantly reduced...
dendritic localization when the GFP constructs were expressed for only 12 h. These data are consistent with that of all other constructs we have tested including GFP with only the vector 3′/H11032 UTR, which also show robust dendritic localization after 48 h of expression (data not shown). These data indicate that Dendra2-3′/H9004 CPE-GluN2A 3′/H11032 UTR is localized to dendrites during the translation assay (48 h expression), but it does not undergo glycine-induced local translation, suggesting that the CPE sequence is necessary for glycine-induced GluN2A mRNA translation in dendrites.

The CPE sequence and CPEB-associated factors regulate GluN2A surface expression in dendrites

Finally, we tested whether the CPE sequence and associated translation factors, Gld2 and Ngd, regulate activity-induced GluN2A surface expression. In biotinylation assays, lentiviral shRNA-mediated knockdown of Gld2 reduced the surface and total levels of GluN2A protein at basal state, and blocked the glycine-induced increase in surface and total GluN2A expression (Fig. 5A, B). Ngd knockdown increased the basal level of GluN2A surface expression and potentiated the glycine-induced increase in GluN2A surface expression (Fig. 5C). Ngd knockdown increased basal and glycine-induced total GluN2A levels similarly, as there were significant main effects with Ngd knockdown and glycine treatment, but no significant interaction effect in the ANOVA analysis (Fig. 5C). These data indicate that Gld2 facilitates and Ngd inhibits the activity-induced expression and membrane insertion of GluN2A.

To determine whether these factors regulate dendritic protein synthesis, neurons were cultured in microfluidic devices and treated with Gld2- or Ngd-specific shRNA for 3–4 d. Glycine was added to the dendritic compartment of these microfluidic cultures, and anisomycin was applied to the cell bodies to block somatic protein synthesis (Fig. 5D shows a schematic of the experimental design). Gld2 was required for the glycine-induced increases in GluN2A expression and membrane insertion in den-
drites; whereas, Ngd knockdown enhanced glycine-induced GluN2A surface expression in dendrites (Fig. 5E, F). In this immunofluorescence assay, Gld2 and Ngd knockdown did not have a significant impact on basal levels of GluN2A, whereas basal levels were altered in the biotinylation assay (Fig. 5B, C). This may be due to Western blotting being a more sensitive technique than immunofluorescence, or perhaps this result suggests that basal GluN2A levels in distal dendrites (200 µm from the cell body) are regulated differently than the somatic pool, which likely contributes a majority of the protein detected by biotinylation. Given that glycine-induced insertion of GluN2A in the dendritic compartment is dependent specifically on dendritic protein synthesis, these data suggest that Gld2 and Ngd bidirectionally regulate GluN2A synthesis and surface expression via dendritic mRNA regulation.

It is possible that the shRNA-mediated knockdown of Gld2 and Ngd regulated GluN2A expression through a mechanism independent of CPEB or the CPE sequence, as the depletion of these proteins is known to alter synaptic plasticity (Udagawa et al., 2012). Thus, we sought to determine whether GluN2A surface expression in dendrites is dependent on posttranscriptional regulation of GluN2A mRNA. To do so, we used the pH-sensitive fluorescent protein SEP fused to the GluN2A coding region and either the wild-type or ΔCPE GluN2A 3’ UTR. Because SEP is only fluorescent when expressed on the cell surface (Royle et al., 2008), we could assay whether mutating the 3’ UTR CPE sequence directly affected GluN2A surface expression. Time-lapse imaging of surface SEP-GluN2A fluorescence revealed a significant increase in dendritic GluN2A surface expression 10 min after glycine treatment, and the CPE sequence was required for this glycine-induced insertion of GluN2A (Fig. 6). These data indicate that the CPE sequence, and likely the associated translation factors, can control glycine-induced GluN2A membrane insertion in dendrites via direct regulation of GluN2A mRNA.

**Discussion**

This study establishes a novel role for dendritic protein synthesis in regulating activity-dependent NMDA receptor expression. Using microfluidic devices, we discovered that dendritic protein synthesis was necessary and sufficient for glycine-induced expression and membrane insertion of endogenous GluN2A. Furthermore, a CPE-dependent mechanism mediated dendritic localization and local translation of GluN2A mRNA. This posttranscriptional mechanism also regulated activity-induced surface expression of GluN2A protein in dendrites. Thus, we propose that activity-induced membrane insertion of GluN2A-containing NMDA receptors is one means by which dendritic protein synthesis regulates glutamatergic synapses.

Several studies have focused on the dendritic synthesis of AMPA receptors as changes in AMPA receptor expression and...
membrane insertion contribute to long-term synaptic plasticity (Kacharmina et al., 2000; Ju et al., 2004; Smith et al., 2005; Grooms et al., 2006; Sutton et al., 2006; Maghsoodi et al., 2008; Kessels and Malinow, 2009; Soden and Chen, 2010). However, synaptic activity also regulates NMDA receptor expression and membrane insertion (Lau and Zukin, 2007; Yashiro and Philpot, 2008). We focused on the translational regulation of the GluN2A subunit because GluN2A mRNA is localized to dendrites (Cajigas et al., 2012; Udagawa et al., 2012), and the expression and membrane insertion of GluN2A have been shown to increase during LTP (Williams et al., 1998; Grosshans et al., 2002). Herein, we show that glycine treatment leads to GluN2A membrane insertion in hippocampal neurons. Moreover, we discovered that dendritic protein synthesis is required for the glycine-induced expression and membrane insertion of endogenous GluN2A. Notably, somatic protein synthesis was not sufficient for activity-induced GluN2A membrane insertion in dendrites, although somatic protein synthesis did regulate basal levels of dendritic GluN2A protein. These data suggest a model whereby local protein synthesis is necessary and sufficient for at least some forms of activity-induced GluN2A expression and membrane insertion in dendrites, whereas constitutive expression of dendritic GluN2A requires somatic protein synthesis (Fig. 7). A previous study found no change in NMDA receptor-mediated currents following glycine treatment (Lu et al., 2001). In that study, the neurons were cultured for 12–17 d, whereas neurons were cultured for 21–28 d in our study. The different culture times could have caused this discrepancy as activity-induced NMDA receptor in-

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**Figure 5.** Gld2 and Ngd regulate glycine-induced GluN2A synthesis and surface expression in dendrites. A, Hippocampal neurons were treated with control, Gld2 shRNA, or Ngd shRNA for 3–4 d, and stimulated with glycine or vehicle. Surface proteins were biotinylated, and total and surface proteins were immunoblotted for GluN2A and α-tubulin (loading control). Protein levels were quantified by densitometry (two-way ANOVA, post hoc Bonferroni tests; n = 6; B, Gld2 KD effects on basal and glycine-induced labeling of surface: *p = 0.001, #p = 0.007; total: *p = 0.015, #p = 0.005; C, surface: main: p = 0.001, Ngd KD main: p = 0.001, interaction: p = 0.006, *p = 0.001, #p = 0.012, †p = 0.001, ‡p = 0.002; total: cLTP main: *p = 0.005, Ngd KD main: p = 0.001, interaction: 0.940). D, A schematic showing neuron culture and treatment in microfluidic devices. Lentiviral shRNA was applied to the CB compartment at 24 DIV, and the cultures were used 3–4 d later. For glycine treatment, anisomycin was applied to the CB compartment 30 min before glycine treatment (applied to dendrites only). Glycine was applied for 3 min then removed; anisomycin was present in the CB compartment throughout the experiment. E, F, Hippocampal neurons were fixed in the microfluidic devices, and then immunostained for MAP2 and either (E) surface or (F) total GluN2A (two-way ANOVA, Bonferroni t tests; E, n = 40–45, *p = 0.015, †p = 0.012; F, n = 40–45, *p = 0.012, ‡p = 0.006). Scale bars, 3 μm. Data are mean ± SEM.
insertion has been shown to be more robust later in development (Grosshans et al., 2002). Alternatively, the newly inserted NMDA receptors observed herein may be extrasynaptic, and therefore would not have been detected in the previous study (Thomas et al., 2006). In future studies, it would be interesting to measure the synaptic versus extrasynaptic localization of newly inserted NMDA receptors as well as extrasynaptic NMDA receptor currents after glycine treatment.

Although several locally synthesized proteins could regulate NMDA receptor insertion, our data suggest that locally synthesized GluN2A likely contributes to the glycine-induced surface expression of GluN2A-containing NMDA receptors. In this regard, we show that: (1) dendritic protein synthesis is necessary for glycine-induced dendritic GluN2A protein expression, (2) GluN2A protein is synthesized in synaptoneurosomes, (3) the GluN2A 3’ UTR regulates dendritic translation of a reporter protein, and (4) the GluN2A 3’ UTR regulates surface expression of a GluN2A fusion protein. Together, these findings support the assertion that GluN2A is synthesized within dendrites in an activity-dependent manner. Our findings are consistent with previous reports showing Golgi outposts and a satellite secretory pathways in spines (Pierce et al., 2001; Horton and Ehlers, 2003), which could mediate the membrane insertion of locally synthesized proteins. More work is needed to understand the cellular components that couple local translation of receptors to their insertion in the plasma membrane.

Previous reports have shown that synaptic receptors can be locally synthesized and inserted into the plasma membrane, but the posttranscriptional mechanisms regulating these processes have not been reported. Our data support a role for a 3’ UTR CPE sequence and the CPEB-associated translation complex in regulating the local synthesis and insertion of GluN2A. To our knowledge, these data are the first to describe a localized posttranscriptional mechanism that controls the activity-induced expression and membrane insertion of synaptic receptors. We propose that CPEB has a dual role in regulating the dendritic synthesis of GluN2A: CPEB regulates the dendritic localization of GluN2A mRNA and the activity-dependent translation of GluN2A mRNA in dendrites. Our live-imaging experiments using SEP-GluN2A fused to the GluN2A 3’ UTR indicate that CPEB also regulates glycine-induced membrane insertion of GluN2A. Because we found that dendritic protein synthesis was necessary for glycine-induced insertion of endogenous GluN2A (Fig. 2), we propose that some of the inserted SEP-GluN2A molecules (Fig. 6) were synthesized within dendrites during the time course analyzed (0–30 min). However, given the time necessary for synthesis, assembly, and trafficking of NMDA receptors, it is likely that receptors inserted within 5 min after glycine treatment had
been previously synthesized. The CPE sequence was required for glycine-induced SEP-GluN2A insertion, therefore we postulate that the CPE mutation likely blocked glycine-induced local synthesis of SEP-GluN2A. In addition, the CPE mutation likely reduced the preexisting pool of dendritic SEP-GluN2A protein available to traffic in response to glycine. This effect could be due to reduced basal mRNA localization or local translation of SEP-GluN2A, or reduced somatic synthesis and trafficking of SEP-GluN2A. Currently, we cannot distinguish between dendritic and somatic effects of the CPE. Future studies combining microfluidic devices with translation reporters and/or SEP-GluN2A could be used to delineate these mechanisms. Nonetheless, our data show that activity-regulated surface expression of GluN2A requires a cis-acting mRNA sequence, which has established roles in mRNA localization and local translation.

These findings have important implications for studies of activity-induced trafficking of recombinant receptor proteins. In most cases, these plasmid-based experiments use only the protein coding sequence and not the untranslated regions. Our data show that activity-dependent GluN2A insertion is regulated by the 3′ UTR. Although untranslated sequences do not directly regulate interactions between the coded protein and trafficking partners, these sequences are necessary for proper subcellular protein expression and, therefore might be critical for localized regulation, as described herein, or to expose the nascent protein to the appropriate binding partners or regulatory proteins.

Dendritic protein synthesis has been proposed to be a means for input-specific protein delivery during synaptic plasticity. We recently reported that the CPEB-associated translation complex is present within dendritic spines (Udagawa et al., 2012). Thus, it is possible that these translation factors could regulate GluN2A synthesis at specific synapses. This CPEB-dependent regulation also provides a reversible mechanism, which allows for translational repression during mRNA transport and local translational activation beneath the synapse. We previously showed that glycine induces CPEB phosphorylation and mRNA polyadenylation in dendrites (Udagawa et al., 2012). We also showed that the CPEB-associated translation factors Gld2 and Ngd bidirectionally regulate LTP and GluN2A protein expression, but whether these effects were mediated by dendritic and/or somatic protein synthesis was not examined. Importantly, in the current study, we demonstrated that Gld2 and Ngd bidirectionally regulate activity-induced synthesis and surface levels of GluN2A in dendrites. Altogether, these findings suggest that the CPEB-associated complex can repress translation in dendrites until synaptic activity induces GluN2A-dependent GluN2A synthesis. The observation that glycine treatment increases GluN2A expression even when Ngd is depleted suggests that additional factors control activity-induced GluN2A translation, one such factor might be the CPEB-associated deadenylase PARN (Udagawa et al., 2012). PARN is likely present complexes containing GluN2A mRNA as it is known to interact with CPEB and Gld2. Future studies are needed to discern the roles of these two translational repressors in regulating GluN2A synthesis.

In addition, the differential expression of GluN2A and GluN2B subunits critically regulate neuronal function (MacDonald et al., 2006; Yashiro and Philpot, 2008; Smith et al., 2009). Herein, glycine treatment increased GluN2A synthesis and surface expression, but GluN2B levels were unaffected. Therefore, this CPEB-mediated mechanism is also a means for modulating NMDA receptor expression in a subunit-specific manner. Interestingly, glycine treatment increased the total levels of GluN1 protein, but no CPE-like sequences were found in the GluN1 3′ UTR, and GluN1 mRNA did not associate with CPEB in our pull-down assays. Thus, GluN1 synthesis is likely mediated by a CPEB-independent mechanism. GluN1 mRNA is localized to dendrites, and dendritic GluN1 mRNA levels are increased during injury-induced synaptogenesis in the dentate gyrus (Miyashiro et al., 1994; Benson, 1997; Gazzaley et al., 1997; Cajigas et al., 2012). Posttranscriptional mechanisms regulating GluN1 mRNA stability and translation have been identified (Kumari, 2001; Anji and Kumari, 2006, 2011), but a mechanism for GluN1 mRNA transport and local translation has not been reported.

Increasing evidence indicates that NMDA receptors are not unlike AMPA receptors in that they are dynamically regulated at synapses (Lau and Zukin, 2007; Rebola et al., 2010). Herein, we show that local protein synthesis is necessary for one form of activity-dependent NMDA receptor insertion in dendrites, whereas somatic protein synthesis did not contribute to activity-induced NMDA receptor insertion in dendrites. These data indicate that dendritic protein synthesis might be a key regulator of activity-dependent NMDA receptor expression. Given the crucial role of NMDA receptors in brain development, plasticity, and disease, this study motivates further work to investigate how dendritic protein synthesis and specific posttranscriptional mechanisms control NMDA receptor function.

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