TrkB and Protein Kinase M Regulate Synaptic Localization of PSD-95 in Developing Cortex

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.
TrkB and Protein Kinase Mζ Regulate Synaptic Localization of PSD-95 in Developing Cortex

Akira Yoshii,1,3 Yasunobu Murata,1,3 Jihye Kim,2 Chao Zhang,4 Kevan M. Shokat,4,5 and Martha Constantine-Paton1,2,3

Departments of 1Brain and Cognitive Science and 2Biology, 3McGovern Institute for Brain Research, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, and 4Cellular and Molecular Pharmacology, 5Howard Hughes Medical Institute, University of California, San Francisco, San Francisco, California 94158-2280

Postsynaptic density 95 (PSD-95), the major scaffold at excitatory synapses, is critical for synapse maturation and learning. In rodents, eye opening, the onset of pattern vision, triggers a rapid movement of PSD-95 from visual neuron somata to synapses. We showed previously that the P13 kinase–Akt pathway downstream of BDNF/TrkB signaling stimulates synaptic delivery of PSD-95 via vesicular transport. However, vesicular transport requires PSD-95 palmitoylation to attach it to a lipid membrane. Also, PSD-95 insertion at synapses is known to require this lipid modification. Here, we show that BDNF/TrkB signaling is also necessary for PSD-95 palmitoylation and its transport to synapses in mouse visual cortical layer 2/3 neurons. However, palmitoylation of PSD-95 requires the activation of another pathway downstream of BDNF/TrkB, namely, signaling through phospholipase Cγ and the brain-specific PKC variant protein kinase Mζ (PKMζ). We find that PKMζ selectively regulates phosphorylation of the palmitoylation enzyme ZDHHC8. Inhibition of PKMζ results in a reduction of synaptic PSD-95 accumulation in vivo, which can be rescued by overexpressing ZDHHC8. Therefore, TrkB and PKMζ, two critical regulators of synaptic plasticity, facilitate PSD-95 targeting to synapses. These results also indicate that palmitoylation can be regulated by a trophic factor. Our findings have implications for neurodevelopmental disorders as well as aging brains

Introduction

Postsynaptic density 95 (PSD-95) is the major PSD scaffolding protein for ionotropic glutamate receptors and the signaling molecules through which these receptors function (Kim and Sheng, 2004). Overexpression of PSD-95 increases spine number, size, and synaptic efficacy (El-Husseini et al., 2000a). In the visual pathway of rodents, rapid increases in synaptic PSD-95 precede increases in synaptic strength and refinement that occur during the period encompassing eye opening (EO) (Yoshii et al., 2003; Lu and Constantine-Paton, 2004). Hippocampal slices lacking PSD-95 show prolonged NMDA receptor (NMDAR) mediated Ca2+ currents (Beique et al., 2006) and, in cultured slices, a reduced developmental increase of AMPA receptors (AMPARs) (Ehrlich et al., 2007). PSD-95 knock-out mice show disrupted spatial learning and long-term depression (LTD) but have enhanced long-term potentiation (LTP) (Migaud et al., 1998). Conversely, overexpression of PSD-95 occludes LTP while enhancing LTD (Beique and Andrade, 2003; Stein et al., 2003; Ehrlich and Malinow, 2004). These findings suggest that PSD-95 levels are critical for activity-dependent regulation of NMDARs and AMPARs by setting the range of upregulation or downregulation of these receptors.

BDNF and its receptor TrkB participate in many aspects of neural circuit formation (McAllister et al., 1999; Poo, 2001; Huang and Reichardt, 2003; Minichiello, 2009; Yoshii and Constantine-Paton, 2010). In the central visual pathway, EO and the onset of pattern vision increase BDNF/TrkB signaling (Castren et al., 1992; Vegi et al., 2002), the formation of mature dendritic spines (Chakravarthy et al., 2006), and visual cortical plasticity (Cabelli et al., 1995). BDNF also facilitates the maturation of inhibition implicated in closure of the critical period for ocular dominance plasticity (Huang et al., 1999). TrkB colocalizes with NMDA receptors (Gomes et al., 2006), and interacts with PSD-95 in an activity-dependent manner (Ji et al., 2005; Yoshii and Constantine-Paton, 2007). Furthermore, both BDNF/TrkB signaling and a brain-specific protein kinase C variant, protein kinase Mζ (PKMζ), are involved in late-LTP (Kang and Schuman, 1995; Korte et al., 1995; Figurov et al., 1996; Patterson et al., 1996; Poo, 2001; Kovalchuk et al., 2002; Pastalkova et al., 2006; Minichiello, 2009), and maintenance of long-term memory (Alonso et al., 2005; Pastalkova et al., 2006; Shema et al., 2007). BDNF increases the expression and activity of PKMζ (Adasme et al., 2011).

We showed previously that BDNF/TrkB signaling through the P13 kinase–Akt pathway facilitates PSD-95 transport to synapses via vesicular transport (Ji et al., 2005; Yoshii and Constantine-
Paton, 2007). Here, we employ a genetically modified mouse strain, TrkB F616A, to specifically block the receptor and show that TrkB activation is also necessary for trafficking PSD-95 to visual synapses after eye opening (AEO) in vivo. We also report that BDNF/TrkB signaling regulates palmitoylation of PSD-95. To our surprise, this process is mediated by PLC and PKMζ. Inhibition of PKMζ also suppresses the synaptic redistribution of PSD-95 in visual cortical layer 2/3 pyramidal neurons. Furthermore, the phosphorylation of palmitoyl acyltransferase (PAT) ZDHHC8 is regulated by PKMζ. Finally, we demonstrate that ZDHHC8 overexpression rescues the suppression of synaptic transport of PSD-95 by a PKMζ blocking peptide in vivo.

Materials and Methods

Animals. TrkB F616A mice were kindly provided by Dr. David Ginty (Johns Hopkins University, Baltimore, MD). Wild-type (WT) C57BL6 mice were from Charles River Laboratories. Animals were caged and maintained in a 12 h light/dark cycle. Both sexes were used for experiments. All manipulations were performed in accord with the guidelines of the Massachusetts Institute of Technology (MIT) Institutional Animal Care and Use Committee.

Chemicals. 1-(B-tert-butyl)-3-(naphthalen-1-ylmethyl)-1H-pyrazolo[3,4-d]pyrimidin-4-amine (1NM-PP1) and 3-[(1R,1′,2′,3′,4′)-4-yl]-1-(tert-butyl)-1H-pyrazolo[3,4-d]pyrimidin-4-amine (BPh-PP1) were prepared using procedures described previously (Bishop et al., 1999). Their chemical structures are shown in Figure 1A. These were applied chronically using the slow release plastic Elvax. U73122 (PLC inhibitor), chelerythrine, PD98059 (mitogen-activated protein kinase inhibitor), and wortmannin were purchased from Sigma-Aldrich. The PKMζ inhibitory pseudosubstrate (myr-SIVRGRARWKRKL-OH) and scrambled peptide (myr-RLYRKRWRSPAGHR) (Pastalkova et al., 2006) were made in the MIT Biopolymers Laboratory.

Elvax preparation. Elvax was made as described previously (Simon et al., 1992), 1NM-PP1 or Bph-PP1 (25 μM) was prepared in a 10% Elvax solution in methylene chloride. The solvent was evaporated at 20°C, and the resulting plugs were lyophilized overnight, then sliced at 90 μm on a cryostat. Slices were cut to trapezoid-shape (parallel sides, 2–3 × 4–5 mm; height, 4–5 mm). Following craniotomy under isoflurane anesthesia, pieces of Elvax were placed on the surface of both occipital cortices. TUNEL assay. The FragEL DNA Fragmentation Detection Kit (Calbiochem) was used for the TUNEL assay. The procedures were performed according to the manufacturer’s instructions.

Antibodies. For immunoblotting, mouse monoclonal anti-PD-95 (catalog #K28/43; NeuroMab), anti-TrkB antibody (catalog PT16020; BD Biosciences), anti-phospho-TrkB (catalog ab51187; Abcam), anti-SAPF102 (synapse-associated protein 102, kindly provided by Dr. Johannes Hell, UC Davis, Davis, CA), anti-HA tag (catalog #3724; Cell Signaling Technology), and anti-phospho-(Ser) PKC substrate (catalog #2261; Cell Signaling Technology) antibodies were used. For immunohistochemistry, rabbit anti-PD-95 (catalog #2507; Cell Signaling Technology) was used.

Plasmid construction. The 2A cleavage sequence from Thosoa asigna virus together with the nucleotide sequences encoding PKMζ pseudosubstrate or its scrambled peptide were attached by PCR to the TagRFP-T sequence using the following primers (Szymczak et al., 2004; Trichas et al., 2008): universal forward primer, gtcaatgaatttgaagggcacatcggattagaa; first PCR reverse primer, gttagacagctctgctctactcactcactatcgtgccctctgctctgag; second PCR reverse primer, ctgggggcacaggtcctgcggcccgtgaatag; first PCR reverse primer, gttagacagctctgctctactcactcactatcgtgccctctgctctgag; third PCR reverse primer for pseudo-PKMζ substrate, gttagatcacatcagctctgcggcccgtgaatag; reverse primer for scramble peptide, gttagatcacatcagctctgcggcccgtgaatag; EcoRI adapter sequence, tatacactgctctgctctgcggcccgtgaatag.

The modified TagRFP-T sequences were inserted under the CAG promoter of the pCACIG plasmid by replacing the IRES and GFP sequences. TagRFP-T was a gift from the laboratory of R. Tsien (UCSD, San Diego CA); pCACIG was originally from the laboratory of the C. Cepko (Harvard Medical School, Boston, MA).

Synaptosome fractionation, immunoblotting, immunoprecipitation. Identification of visual cortex (VC) was based on the Paxinos atlas (Paxinos and Franklin, 2001). The VC tissues were collected by cutting the occipital one-third of the cortex along the anteroposterior axis and 3 mm from the midline along mediolateral axis. Whole lyases, synaptosome preparation, and immunoblotting were performed as described previously (Yoshii et al., 2003). Protein concentration of each sample was measured using the Pierce BCA Protein Assay Kit (Thermo Scientific), and 10 μg of sample was loaded in each lane for SDS-PAGE separation. Following immunoblotting, films were scanned, and band densities were quantified using NIH ImageJ. Full-length TrkB bands were constant between postnatal day 10 (P10) and P16; thus, phosphorylated TrkB (pTrkB) and PSD-95 band densities were normalized to the TrkB band. Control samples at P16 showed highest levels of PSD-95 and pTrkB; thus, fold changes at each time point were calculated relative to the protein level at P16 control on the same gels (Fig. 1G–I, M). Results are reported as mean ± SEM.

All immunoblot analyses used three sets of protein samples from three different litters. Two gels were run for each sample and blotted (N = 6).

Primary neuronal culture and lipofection. Primary neuronal culture and lipofection were performed as described previously (Li et al., 2005; Yoshii and Constantine-Paton, 2007).

Metabolic labeling with 3H palmitic acid and immunoprecipitation. Primary VC cultures were prepared from embryonic day 16 (E16) mouse brains. Cultured visual cortical neurons (6 × 10⁶ cells/plate; 21–28 d in vivo) were preincubated for 30 min in serum-free Neurobasal medium with fatty acid-free bovine serum albumin (10 mg/ml Sigma), and were then labeled for 4 h in neurobasal media containing 2 μCi/ml 3H palmitic acid (PerkinElmer) with or without BDNF and/or various blockers. Labeled neurons were washed with PBS. BDNF and/or inhibitors were added from the preincubation period through the end of the 4 h incubation period.

To observe PSD-95 palmitoylation, we scraped labeled neurons using 0.5 ml of lysis buffer A (20 μs Tris-HCl, pH 7.4, 1 μm EDTA, 100 μM NaCl, and 1% SDS), and after 5 min extraction, 1% Triton X-100 was added to a final volume of 1 ml. The suspensions were centrifuged at 20,000 × g for 10 min, and supernatants were incubated with anti-PD-95 antibody for 1 h and then incubated for 1 h with 30 μl of protein A-Sepharose (PharMaco) slurry at 4°C. Immunoprecipitates were washed three times with buffer containing 20 μs Tris-HCl, pH 7.4, 1 μM EDTA, 100 μM NaCl, and 1% Triton X-100, and were resuspended in 33 μl of SDS-PAGE sample buffer. We used 0.3 μl for autoradiography and the remaining 3 μl for immunoblotting. The ratios of palmitoylated PSD-95 densities in autoradiographs to total PSD-95 densities in corresponding immunoblots were calculated. Each experiment was repeated four times.

Immunohistochemistry. After 4% paraformaldehyde perfusion and vibratome sectioning at 50 μm, coronal brain sections were permeabilized using pepsin (Gene Tex; catalog #GTX28194) at 37°C for 30 min and then rinsed twice with PBS. The sections were reacted overnight at room temperature with mouse anti-PD-95 in PBS containing 4% donkey serum (Jackson ImmunoResearch) and 0.2% Triton X-100. Thereafter, they were incubated in Alexa-488-tagged antibody (Invitrogen) and then washed with PBS three times (15 min each). Images were captured using a 40× objective lens under identical settings with a Nikon PCM 2000 confocal microscope. The visual cortex was identified on coronal sections using the Paxinos atlas. The Z-series of optical sections taken at intervals of 0.5 μm through 20 μm of tissue were reconstructed.

In utero electroporation. Following laparotomy on timed pregnant mice, the uterus was externalized. Approximately 0.5–0.6 μl of solution containing PSD-95-GFP construct (2 μg/μl) was injected into the forebrain ventricle at E15.5 through the uterine wall. In later experiments, constructs encoding red fluorescent protein (RFP)-tagged pseudosubstrate and/or HA-tagged ZDHHC8 were added at 0.01 μg/μl. Using an ECM 830 apparatus (Harvard Apparatus), brains were electroporated with five pulses of 28 V for 50 ms at intervals of 950 ms. After recovery, pregnancies continued, and pups were delivered and nursed normally.

Cortical injection. The PKMζ inhibitory pseudosubstrate and scrambled peptide were dissolved in PBS to a concentration of 10 nmol/ml. Under isoflurane anesthesia, the skin was opened. The skull was thinned with a drill. A pulled capillary pipette connected to a Nanoject II (Drummond Scientific) was inserted into the brain using an stereotaxic atlas and/or HA-tagged ZDHHC8 were added at 0.01 μg/μl. Using an ECM 830 apparatus (Harvard Apparatus), brains were electroporated with five pulses of 28 V for 50 ms at intervals of 950 ms. After recovery, pregnancies continued, and pups were delivered and nursed normally.
Cholera-toxin B conjugated with Alexa-647 (Invitrogen) were injected over 1 min. In each animal, injections were made in four different sites of the visual cortex. The eyes were opened immediately after the surgery at P13. For each experiment described, data were acquired from three experimental animals and three controls.

Imaging analysis. Sections containing PSD-95–GFP–expressing neurons were imaged at successive depths of 0.5 μm using a Nikon PCM 2000 confocal microscope. In each experiment, data were acquired from three experimental animals and three controls. The same laser intensity was used between treatment and control groups, and all analyzed neurons included the cell’s nucleus indicated by a “halo” pattern of GFP signal in somata. Neurons with a soma showing fluorescence either saturated (intensity value of 255 throughout the nucleus in ImageJ) or dim (intensity value 150 in ImageJ) were excluded from the analyses. Total pixel intensities were analyzed with ImageJ. Secondary branches of apical dendrites located between 60–150 μm from the soma were selected with 40 x 20 μm rectangles. For each cell analyzed, a threshold was set by eye during the initial evaluation so as to represent PSD-95–GFP puncta and exclude diffuse labels in dendritic shafts (see Fig. 3C). The same threshold was applied to all neurons in the same experiment. Total pixel intensity

Figure 1. TrkB blockade suppresses developmental increase of PSD-95 synthesis. A, Chemical structure of 1NM-PP1 (left) and Bph-PP1 (right). B, PSD-95 level significantly increased 6 h AEO compared to BEO at P13 in synaptosomal fractions from mouse visual cortex. C, Among three different concentrations, Elvax containing 1NM-PP1 at 25 μm showed the highest suppression of PSD-95 at P12, P14, and P16 compared to Bph-PP1 containing Elvax. The inset diagram (top) in this figure and those in the following figures illustrate the sequence of procedures for the experiments. D, The TUNEL assay showed no apoptosis in VC under the 1NM-PP1-Elvax (left) or Bph-PP1-Elvax (middle). As a positive control, slices were treated with DNase (right). Scale bar, 10 μm. E, During the period bracketing eye opening, in whole lysates of WT mouse VC, PSD-95 and pTrkB increased, whereas full-length TrkB (FL-TrkB) levels remained constant. F, Both pTrkB and PSD-95 levels were suppressed in whole lysates of VC when TrkB was blocked with 1NM-PP1. FL-TrkB levels in the same lanes are used to normalize because their levels remained constant. G, H, Both pTrkB and PSD-95 levels were suppressed in whole lysates of VC when TrkB was blocked with 1NM-PP1. When TrkB was blocked in VC over the interval encompassing the eye opening (P10–P16), both phosphorylated TrkB (K) and PSD-95 (K, M) increased normally in the same animals’ superficial visual layers of the superior colliculus (sSC), indicating that the blocking effect was restricted to cortex. The blots in C–F and K were first probed for pTrkB, then stripped and probed for PSD-95 and FL-TrkB. *p < 0.05; **p < 0.01; ***p < 0.001. Error bars represent SEM.
was also increased AEO as compared to BEO (pTrkBAEO/pTrkB
1.8
synaptic PSD-95 in 1NM-PP1-treated VC (Fig. 1C). We found a
dependent decrease in phospho-TrkB (data not shown) and
(Fig. 1D). TrkB phosphorylation (Fig. 1E–G) and in
PSD-95 levels (Fig. 1F,H) over the EO
interval (P12–P14). The different patterns of increase in Figure 1, G and H, suggest
that in VC whole lysates, more TrkB is activated after EO when the cortex
becomes driven by high-contrast vision
(Heimel et al., 2010), whereas PSD-95 levels increase from before EO (P12) through
at least 3 d afterward.

As expected, ratios of phospho-TrkB
to total TrkB in these lysates were signifi-
cantly reduced in TrkB-suppressed
(1NM-PP1-treated) VCs compared to
to control (Bph-PP1-treated) VCs (Fig. 1F,J). Ratios of PSD-95 to total TrkB levels
were also suppressed in TrkB-blocked
VCs from P12 through P16 (Fig. 1F,J).

In contrast to the VC, PSD-95 levels
were not perturbed in the visual layers of
the superior colliculus or the dorsal thala-
mas, indicating that 1NM-PP1 from cor-
tically placed Elvax was not affecting lower levels of the visual
pathway (Fig. 1K–M).

Synaptic analyses in TrkB
2
616A
mice
We found previously in rat that PSD-95 increases in synaptic
fractions immediately after EO were not seen in whole lysates and
did not require protein synthesis (Yoshii et al., 2003), suggesting
that EO and pattern vision onset acutely trigger trafficking of
PSD-95 to the synapse with no new protein synthesis of the scaf-
dfold during this interval.

In mouse VC treated with Bph-PP1-Elvax (control), synap-
tosome PSD-95 levels increased after EO (Fig. 2A) (synaptosome
PSD-95 level change at P14 relative to P12, 1.35 ± 0.05; N = 6).
However, 1NM-PP1-Elvax (TrkB blocking) placed on VC sup-
pressed the increase of PSD-95 in the synaptosome compared to
the Bph-PP1 after EO (synaptosome PSD-95 level change at P14
relative to P12, 1.01 ± 0.05; N = 6; control vs 1NM-PP1, p < 0.05).
While synaptosome PSD-95 in control was enriched compa-
red to levels in control whole lysates (Fig. 2A), TrkB-blockade
with 1NM-PP1-Elvax also suppressed the PSD-95 synaptosome
enrichment over whole lysates during the same 2 d interval (Fig.
2A) (synaptosome enrichment for PSD-95 level in synaptosome/PSD-
95 level in whole lysate: 1.78 ± 0.06 in control, 1.15 ± 0.05
in TrkBblock: p < 0.01; N = 6).

We previously documented BDNF/TrkB-driven PSD-95
transport in dendrites of cultured neurons from mouse VC (Yo-
shii and Constantine-Paton, 2007). As a first step in determining
whether TrkB-mediated transport from somata and proximal
dendrites to synapses occurred in mouse cortical neurons in vivo,
we used immunocytochemistry to examine changes in endoge-

Figure 2. TrkB blockade suppresses the synaptosome increases and endogenous dendritic PSD-95 after eye opening. A, When TrkB
signaling was suppressed, synaptosomal PSD-95 level as compared to control was neither increased after EO nor enriched
compared to whole lysates (WL). B, Immunohistochemistry of PSD-95 in layer 2/3 VC from two different animals implanted with
Bph-PP1 Elvax to the left hemisphere and 1NM-PP1 Elvax to the right. After eye opening, the punctate distribution of PSD-95 seen
in the TrkB-blocked cortices (1NM) compared to the contralateral Bph-treated cortices show reductions in endogenous, immuno-
stained, PSD-95 puncta but enhanced staining in somata. Dashed lines indicate the pial surface. A dashed square shows the size of
the quantified area for total pixel intensity of PSD-95-positive immunolabels. Scale bar, 10 μm.
uous PSD-95 (Fig. 2B). Mice with control Bph-Elvax on one VC and 1NM-PP1 Elvax on the other were maintained over the EO interval, and, after animals were killed and tissue and slices were processed, the local distribution of endogenous PSD-95 was examined in VC layer 2/3 neurons of both cortices. Suppression of TrkB signaling caused a marked reduction in the number and intensity of PSD-95 puncta among the dendrites of these neurons, and layer 2/3 cell bodies were filled by diffuse anti-PSD-95 immunoreactivity. Pixel intensities of PSD-95-positive immunolabels in 20 \times 20 \mu m areas (Fig. 2B, dashed square) were sampled and quantified (50,100 \pm 1700 A.U.; N = 20). Control neurons in the other VCs of the same mice showed the converse distribution: high densities of PSD-95 throughout the superficial dendrites with PSD-95 immunoreactivity barely visible in layer 2/3 cell bodies (83,900 \pm 3600 A.U.; N = 20; p < 0.001).

To quantify TrkB effects on the distribution of PSD-95 in single neurons, PSD-95-GFP constructs were electroporated into newly generated 2/3 VC neurons of TrkB \textit{F616A} mice at embryonic day 15.5. At either P9 or P11, 1NM-PP1-Elvax or Bph-PP1-Elvax was placed on their VCs. All animals survived 3 d of Bph-PP1 or 1NM-PP1 treatment. Pups implanted at P9 were killed for cortical analyses at P12 before EO. Eyes of pups implanted on P11 were opened on P13, and pups were killed on P14. We analyzed PSD-95-GFP puncta in littermates after EO (P14) and before EO (P12).

At P14 (after P11 Elvax implantations), PSD-95-GFP-expressing control neurons had many protrusions supporting PSD-95 puncta, whereas neurons treated with 1NM-PP1 had fewer PSD-95 puncta (Fig. 3A). This difference in numbers of PSD-95-positive protrusions was much more significant for apical dendrite puncta (Fig. 3B) than basal dendrite puncta (data not shown; p < 0.05 in only 2 of 13 segments; N = 17 neurons).

Consequently, we focused on apical dendrites and estimated the density of PSD-95-GFP in synaptic puncta by selecting fixed lengths of dendrite at the point of secondary branching (Fig. 3A, boxed areas) and thresholding the images (Fig. 3C) to best represent synaptic PSD-95-GFP. All pixel intensities in the thresholded segments from each neuron in the control and TrkB-blocked treatment groups were summed separately to give the total pixel intensity for each group (Yoshii and Constantine-Paton, 2007). The pooled pixel intensity in apical dendrites with TrkB blocked (8540 \pm 900 A.U.) was highly significantly reduced relative to the apical dendrite pixel intensities (30,100 \pm 3900 A.U.) in control neurons (N = 34 for each group; p < 0.001).

A Sholl analysis examining differences in numbers of PSD-95 puncta at different distances from somata between Bph-PP1 and 1NM-PP1 treatments of apical dendrite anatomical puncta is shown in Figure 3B and shows significant differences across the apical dendritic tree (N = 17 neurons). Total PSD-95-GFP pixel intensities across 34 basal dendrites of these same neurons were also reduced in 1NM-PP1- compared to Bph-PP1-treated cells; however, the significance was less robust (24,700 \pm 5900 A.U. in control vs 26,500 \pm 1000 A.U. in 1NM-PP1; p < 0.05). Thus, an effect of TrkB blockade on dendritic protrusions is consistent with the previous report using a dominant-negative TrkB mutant mouse (Chakravarthy et al., 2006).

In the Sholl analysis, the total dendritic branching was marginally different between TrkB-blocked neurons and controls (p < 0.05 in only 1 of 15 segments at 70 \mu m from the somata; N = 17). Cell body sizes were also only modestly altered (165 \pm 15 \mu m^2 in control vs 140 \pm 5 \mu m^2 in 1NM-PP1; p < 0.05; N = 17). These findings are in contrast with data from...
Figure 4. Immunoprecipitation experiments demonstrate that BDNF/TrkB signaling regulates PSD-95 palmitoylation through PLCγ and PKMζ in VC cultures. A, Palmitoylation of PSD-95 was increased in cultured VC neurons by BDNF (50 ng ml⁻¹) and decreased by TrkB block (1NM-PP1, 1 μM; N = 4). B, VC cultures with TrkB block (1NM-PP1, 1 μM) in the presence of BDNF (50 ng ml⁻¹) showed a reduction in PSD-95 palmitoylation ratio compared to control (Bph-PP1, 3 μM; N = 4). C, VC cultures treated with blockers of the PLC pathway (U73122, 1 μM), but not the MAPK (PD98059, 50 μM) or PI3K (wortmannin, 100 nM) pathways, in the presence of BDNF (50 ng ml⁻¹) showed a decrease in PSD-95 palmitoylation (N = 4). D, VC cultures treated with the broad PKC blocker (chelerythrine, 2.5 μM) in the presence of BDNF (50 ng ml⁻¹) showed decreased palmitoylation (N = 4). E, VC cultures treated with PKMζ inhibitory peptide (a pseudosubstrate, 1 μM) or the scrambled peptide (1 μM) in the presence of BDNF (50 ng ml⁻¹) showed a decrease only with the pseudosubstrate (N = 4). Cultures in B–E were pretreated with BDNF (50 ng ml⁻¹). The signaling blocked is indicated for each lane below the blots. All immunoprecipitates (B–E) were resuspended in 33 μl of SDS-PAGE sample buffer; 30 μl were used for autoradiography (PSD-95 [¹H Palm]), and the remaining 3 μl for immunoblotting (PSD-95 [IB]). **p < 0.01; ***p < 0.001. Error bars represent SEM.

TrkB-PLCγ-PKMζ regulates PSD-95 palmitoylation
Palmitoylation of PSD-95 can be triggered by glutamate (El-Husseini Ael et al., 2002) and is crucial for this scaffold's trafficking and insertion at postsynaptic sites (El-Husseini et al., 2000b). Our previous work suggested that in young cortical neurons, NMDA receptor currents activate BDNF/TrkB signaling and drive movement of PSD-95 from the ER to the Golgi apparatus in cell bodies before dendritic transport (Yoshii and Constantine-Paton, 2007). However, PSD-95 is synthesized by cytoplasmic ribosomes, implying that it must be palmitoylated to allow association with ER and Golgi membranes. Therefore, we hypothesized that BDNF-TrkB signaling might also trigger palmitoylation, and this might be a trigger for PSD-95 palmitoylation to enable the scaffold's membrane association and microtubule-based vesicular transport to synapses. Despite recent progress in purification of palmitoylation using chemical probing, metabolic labeling with a radioisotope is the standard procedure for identification of palmitoylated proteins (Fukata and Fukata, 2010), but radioactive labeling of whole mouse pups was not feasible. Therefore, we dissociated cortical neurons from TrkBPKMζ knock-out mice (Xu et al., 2000). The short-duration block of TrkB in our experiments compared to prolonged absence of the receptor in the knock-out mice could explain these differences.

To determine whether the effect on apical puncta change was due to EO and not simply due to the presence of Elvax on cortex, we performed a similar experiment on the layer 2/3 VC neurons that had also been exposed to 1NM-PP1 for the same duration but not over the EO interval. Before EO, similar low-density distributions of PSD-95-GFP puncta were present in both 1NM-PP1- and Bph-PP1-treated neurons (Fig. 3D,E). Total pixel intensities at P12 were 6980 ± 750 A.U. in control VC neurons treated with Bph-PP1 (N = 20) and 6850 ± 1050 A.U. in VC neurons treated with 1NM-PP1 (N = 20; p = 0.33).

TrkB-PLCγ-PKMζ regulates PSD-95 palmitoylation
Palmitoylation of PSD-95 can be triggered by glutamate (El-Husseini Ael et al., 2002) and is crucial for this scaffold’s trafficking and insertion at postsynaptic sites (El-Husseini et al., 2000b). Our previous work suggested that in young cortical neurons, NMDA receptor currents activate BDNF/TrkB signaling and drive movement of PSD-95 from the ER to the Golgi apparatus in cell bodies before dendritic transport (Yoshii and Constantine-Paton, 2007). However, PSD-95 is synthesized by cytoplasmic ribosomes, implying that it must be palmitoylated to allow association with ER and Golgi membranes. Therefore, we hypothesized that BDNF-TrkB signaling might also trigger palmitoylation, and this might be a trigger for PSD-95 palmitoylation to enable the scaffold’s membrane association and microtubule-based vesicular transport to synapses. Despite recent progress in purification of palmitoylation using chemical probing, metabolic labeling with a radioisotope is the standard procedure for identification of palmitoylated proteins (Fukata and Fukata, 2010), but radioactive labeling of whole mouse pups was not feasible. Therefore, we dissociated cortical neurons from TrkBPKMζ knock-out mice and labeled them with [³H]palmitic acid.

Subsequently, we immunoprecipitated PSD-95 from lysates of cultures with no treatment or with either BDNF or 1NM-PP1 added. Palmitoylation of PSD-95 from cultures treated with BDNF was higher than without treatment (palmitoylated PSD-95 ratio relative to control, 1.25 ± 0.05; p < 0.01; N = 4), and palmitoylation of PSD-95 from cultures treated with 1NM-PP1 was the lowest (palmitoylated PSD-95 ratio relative to control, 0.45 ± 0.11; p < 0.001; N = 4) (Fig. 4A). In addition, immunoprecipitation of PSD-95 from the lysates revealed that levels of palmitoylated PSD-95 were significantly greater in cultures treated with Bph-PP1 compared to 1NM-PP1-treated cultures (palmitoylated PSD-95 ratio relative to Bph-PP1 treatment, 0.37 ± 0.11; p < 0.001; N = 4) (Fig. 4B). Neuronal cultures were subsequently exposed to antagonists of the three pathways downstream of TrkB: mitogen-activated protein kinase (MAPK), phosphoinositide 3 kinase (PI3K), and phospholipase C (PLCγ) (Huang and Reichardt, 2003). The PLC blocker U73122 significantly reduced PSD-95 palmitoylation (palmitoylated PSD-95 ratio relative to control, 0.35 ± 0.17; p < 0.001; N = 4), while blockers of MAPK (PD98059; palmitoylated PSD-95 ratio relative to control, 1.15 ± 0.21; p = 0.38; N = 4) and PI3K (wortmannin; palmitoylated PSD-95 ratio relative to control, 1.03 ± 0.1; p = 0.21; N = 4) did not (Fig. 4C). PLCγ is known to regulate PKC. Consequently, we applied chelerythrine, a broad PKC blocker. This treatment also suppressed PSD-95 palmitoylation (palmitoylated PSD-95 ratio relative to control, 0.39 ± 0.08; p < 0.001; N = 4) (Fig. 4D). PKMζ is a brain-specific variant of PKC. It is an important mediator of late, protein synthesis-dependent LTP in hippocampus (Sajikumar et al.,
PKMζ blockade causes reduction in PSD-95 puncta

We next examined the contribution of PKMζ to synaptic localization of PSD-95 in vivo. At P13, before EO, we injected either the PKMζ pseudosubstrate or the scrambled pseudosubstrate into the VC of animals expressing PSD-95-GFP in layer 2/3 neurons. We added Alexa-647-conjugated cholera toxin B (ACTB), a non-toxic and broad neuronal tracer, to the injected peptide solutions. Eyes were opened immediately after the peptide/ACTB injection, and 24 h later the animals were killed, and VC layer 2/3 neurons were examined for PSD-95 total pixel intensity compared with neurons treated with the scrambled peptide.

We ensured that the pseudosubstrate was the active agent in the cells analyzed by building pseudosubstrate and scrambled peptide DNA constructs tagged with RFP (RFP-2A-pseudo and RFP-2A-scr, respectively) DNA (Fig. 6A). First, we confirmed that endogenous PSD-95 puncta were reduced in cultured cortical neurons expressing the pseudosubstrate-RFP (N = 22 dendrites in 9 cells; mean, $7.10 \pm 1.0$ puncta per 100 µm dendrite) compared to the scrambled-peptide-RFP (N = 24 dendrites in 9 cells; mean, $10.2 \pm 0.9$ puncta per 100 µm dendrite; pseudosubstrate-RFP vs scrambled-peptide-RFP, p < 0.05) (Fig. 6B). To better discern the PSD-95 puncta changes, we next either co-electroporated the pseudosubstrate-RFP or the scrambled-peptide-RFP construct with PSD-95-GFP into separate cortices at E15.5 and examined PSD-95 puncta in VC layer 2/3 24 h after EO (Fig. 6C,D). Neurons expressing the pseudosubstrate-RFP showed significantly lower total puncta intensity (33,900 ± 3500) than neurons expressing the scrambled-peptide-RFP (24,500 ± 2800; N = 18 for each group; p < 0.01).

Finally, we asked whether any palmitoylation enzyme(s) were regulated by PKMζ. Protein palmitoylation is accomplished by the ZDHHC family of PATs. However, there are over 20 known PATs (Fukata and Fukata, 2010). We reasoned that the putative PAT(s) should be phosphorylated by PKMζ. We transfected HA-tagged ZDHHCs 2, 3, 7, 8, 15, and 17 (gifts from M. Fukata, National Institute for Physiological Sciences, Okazaki, Aichi, Japan) in sets of primary cortical neuronal cultures, and, for each PAT, cultures were treated with either scrambled peptide or pseudosubstrate. Subsequently, we pulled down the PATs from culture lysates using an anti-HA antibody and immunoblotted to visualize HA-tagged ZDHHCs (Fig. 7A). As indicated by asterisks in Figure 7A, amounts of each PAT were equal between the two treatment groups (ZDHHC2 pseudo/ZDHHC2 scr = 1.02 ± 0.02;}

**Figure 5.** Cortical injection of PKMζ inhibitory pseudosubstrate suppresses synaptic increase of PSD-95 in vivo after eye opening. A, Overlays depict blue-stained cell bodies of neurons that absorbed either a scrambled or pseudosubstrate peptide solution containing an ACTB, a cell-tracking agent. B, Visual cortical neurons treated with PKMζ inhibitory pseudosubstrate had a reduction in PSD-95 total puncta intensity compared with neurons treated with the scrambled peptide.
Genetically encoded PKMζ inhibitory pseudosubstrate suppresses synaptic increase of PSD-95 in vivo after eye opening. A, Nucleotide and amino acid sequences of the 2A cleavage motif followed by either the scrambled peptide or the PKMζ pseudosubstrate peptide in the expression plasmids of TagRFP-T. B, Endogenous dendritic PSD-95 puncta are decreased in neurons expressing the pseudosubstrate but not in neurons expressing scrambled peptide or untransfected neurons (data not shown). C, Visual cortical neurons electroporated at E15.5 with constructs coding for either the pseudosubstrate-RFP or the scrambled-peptide-RFP plus PSD-95-GFP. Insets depict pseudosubstrate-RFP or scrambled-peptide-RFP. The diagram (top) illustrates the sequence of in vivo experiments. D, Visual cortical neurons expressing PKMζ inhibitory pseudosubstrate showed a significant reduction in PSD-95 puncta intensity compared with neurons expressing the scrambled peptide. Scale bars: 10 μm.

ZDHHC3pseudo/ZDHHC3act = 1.05 ± 0.08; ZDHHC7pseudo/ZDHHC7act = 1.02 ± 0.03; ZDHHC8pseudo/ZDHHC8act = 0.98 ± 0.03; ZDHHC15pseudo/ZDHHC15act = 1.0 ± 0.02; ZDHHC17pseudo/ZDHHC17act = 0.95 ± 0.08. We then reprobed the blotting membranes with an antibody against phosphorylated-serine PKC family substrates and found that only ZDHHC8 showed a pronounced phosphorylation band in the scrambled pseudosubstrate-treated control cultures, whereas the phosphorylation band was absent when cultures were treated with the PKMζ pseudosubstrate (Fig. 7B).

These findings motivated us to test whether overexpression of ZDHHC8 could rescue the in vivo suppression of PSD-95 synaptic redistribution by PKMζ blockade in layer 2/3 VC neurons after EO. We electroporated constructs for PSD-95-GFP, RFP-tagged pseudosubstrate, and HA-tagged ZDHHC8 in utero and, 1 d after EO, killed the animals and stained the cortical slices with an anti-HA tag antibody followed by Alexa-647-conjugated secondary antibody. With this procedure, we determined whether a GFP- and RFP-containing neuron also overexpressed ZDHHC8 (Fig. 7C). We found that the addition of the WT ZDHHC8 gene completely restored total pixel intensity of PSD-95-GFP puncta, despite the pseudosubstrate inhibition of PKMζ (Fig. 7D,E) (33,000 ± 3600; N = 18; p < 0.01 between RFP-2A-pseudo and RFP-2A-pseudo + ZDHHC8). In the same slice, some neurons expressed PSD-95-GFP and RFP-tagged pseudosubstrate, but no detectable ZDHHC8. In these neurons, total pixel intensity of PSD-95-GFP puncta was suppressed, similar to neurons in Figure 6C (right).

Discussion
Transport of PSD-95 to synapses is dependent on pattern vision and mediated by activation of TrkB and PKMζ in mouse visual cortex
Previously, we reported that redistribution of PSD-95 to synapses is triggered by EO and the onset of the patterned vision in young rats (Yoshii et al., 2003). AMPAR increases at synapses follow within the next 24 h (Lu and Constantine-Paton, 2004). During this interval, more TrkB is associated with PSD-95 (Yoshii and Constantine-Paton, 2007). The current study confirms that the same activity-dependent transport occurs in mouse visual cortex and is dependent on the BDNF/TrkB signaling pathway. We show that EO induces increases of synaptosomal PSD-95 levels, while PSD-95 levels in whole lysates remain stable between P12 and P14 (Fig. 2A). The punctate distribution of PSD-95 in control visual cortex also increases after EO (total pixel intensity, ~30,000) compared with that before EO (total pixel intensity, ~7000) in visual cortex (Fig. 3C,D). In addition, TrkB phosphorylation gradually increases during development (Fig. 1G), over a period encompassing EO. The increase in TrkB phosphorylation is consistent with an increase in BDNF mRNA during this period (Castren et al., 1992).

Our data also indicate that specific TrkB blockade using a chemical genetic approach suppresses increases in PSD-95 synthesis in whole lysates during early development (Fig. 1F,J) and enrichment of PSD-95 at visual cortical synapses triggered by EO (Fig. 2A). Suppression of TrkB signaling also causes a reduction of endogenous PSD-95 puncta and increases endogenous PSD-95 immunolabeling in cell bodies, suggesting a decrease in PSD-95 transport to synapses (Fig. 2B). These results indicate that, in intact mouse visual cortex, TrkB signaling regulates the developmental increase in PSD-95 and that EO, the onset of pattern vision, facilitates TrkB activation as well as the synaptic redistribution of PSD-95.

Chemical genetic inactivation of TrkB signaling in the intact TrkB<sup>F<sub>0</sub>64Δ</sup> mouse has been shown to block the reinstatement of deprived eye synapses after brief monocular deprivation (Kaneko et al., 2008). In light of the present work, this is likely due to
failure to deliver PSD-95 to the synapses driven by the newly reactivated eye’s cortical inputs, because reduction or elimination of PSD-95 is known to decrease synapse number on young neurons (Beique et al., 2006; Elias et al., 2006; Yoshii and Constantine-Paton, 2007, 2010), and we have shown previously that 4 d of eye reclosure after EO causes PSD-95 levels in visual neuron synaptic fractions to decrease to pre-EO levels with a rapid recovery after eye reopening (Yoshii et al., 2003).

TrkB regulates excitatory synapse maturation and synaptic localization of PSD-95

The role of BDNF/TrkB signaling on inhibitory neurons in visual cortex has been well studied (Huang et al., 1999). Evidence for BDNF/TrkB functions in pyramidal neurons (Bracken and Turrigiano, 2009) and their developing spines is also abundant (Tyler and Pozzo-Miller, 2003; Chakravarthy et al., 2006; Tanaka et al., 2008). Furthermore, it has been established that PSD-95 at synapses is crucial to spine maturation (Kim and Sheng, 2004; van Zundert et al., 2004) and that BDNF/TrkB signaling plays a central role in facilitating glutamate synapse stabilization/maturation through the PSD-95 scaffold (Ji et al., 2005; Yoshii and Constantine-Paton, 2007, 2010). Our current results provide further evidence that BDNF/TrkB signaling regulates transport of PSD-95 to synapses in layer 2/3 pyramidal neurons, thus contributing to activity-dependent maturation of excitatory visual synapses.

PSD-95 palmitoylation is regulated by a trophic factor signaling pathway

Palmitoylation has been shown to be required for PSD-95 transport and synaptic insertion (Topinka and Bredt, 1998; El-Husseini et al., 2000b), and PSD-95 palmitoylation is known to require synaptic activity (El-Husseini Ael et al., 2002; Noritake et al., 2009). Considerably less is known about the signaling pathway that regulates this palmitoylation. Here, we document that the TrkB pathway regulates palmitoylation of PSD-95 through PLC and the PKC/PKM phosphorylation pathway (Fig. 4–7). We also show, for the first time, that PKM phosphorylates PSD-95, allowing the scaffold synthesized in cytoplasm to attach to PSD-95. Thus BDNF/TrkB signaling drives two synergistic regulations of these two palmitoylated synaptic proteins.

Several reports indicate that one mechanism through which PKM might work to maintain LTP and memory is to block the endocytosis of the AMPAR subunit GluR2 by interfering with N-ethylmaleimide-sensitive factor-mediated GluR2 endocytosis (Yao et al., 2008; Migues et al., 2010). GluR2 is also palmitoylated by GODZ (Golgi apparatus-specific protein with a DHHC zinc finger domain; or ZDHHC3) (Hayashi et al., 2005). However, palmitoylation of GluR2 was unchanged between control and TrkB-blocked samples (data not shown), indicating differential regulations of these two palmitoylated synaptic proteins.

Palmitoylation and vesicular transport: two critical components of PSD-95 trafficking

Neurotrophins and protein palmitoylation interact in key ways with diverse membrane-associated proteins and regulate their subcellular localizations and functions throughout the brain. ZDHHC8 has been shown to be localized in the Golgi apparatus and to palmitoylate PSD-95 (Mukai et al., 2008).

We previously used fluorescence recovery after photobleaching and in vitro immunocytochemistry to show that the PI3K–Akt pathway is required for the NMDAR driven, BDNF-induced trafficking of PSD-95 from visual cortical neuron somata to dendrites. The same report showed that TrkB signaling facilitates PSD-95 transport from the ER to the Golgi apparatus (Yoshii and Constantine-Paton, 2007). Our current work shows that EO-induced increase in visual activity, also operating through BDNF/TrkB signaling, up-regulates PLC signaling to induce ZDHHC8-dependent palmitoylation of PSD-95. Thus BDNF/TrkB signaling drives two synergistic pathways in parallel: (1) the PI3K–Akt pathway triggers PSD-95 vesicular transport systems in cell bodies and dendrites to bring the scaffold to the synapse; (2) the PLC pathway drives palmitoylation of PSD-95, allowing the scaffold synthesized in cytoplasm to attach to
plasma membranes and travel via the dendritic microtubule transport system as we have shown previously (Yoshii and Constantine-Paton, 2007). TrkB-induced increases in PSD-95 at synapses (Yoshii et al., 2003; Ji et al., 2005; Yoshii and Constantine-Paton, 2007) and the subsequent synaptic signaling mediated through this scaffold (Ehrlich et al., 2007; Yoshii and Constantine-Paton, 2007) are known to increase stabilization of young synapses, a precondition for many of the events involved in neural circuit maturation (McAlister et al., 1999; Poo, 2001; Huang and Reichardt, 2003; Minichiello, 2009; Yoshii and Constantine-Paton, 2010).

**Synaptic trafficking of PSD-95 is regulated by both TrkB signaling and PKMζ**

PLCγ-binding sites on TrkB have been shown to be crucial for maintaining late LTP (Minichiello et al., 2002) and also limbic epileptogenesis (He et al., 2010). It is widely accepted that PLCγ activates PKC and that PKMζ is a brain-specific PKC variant. In fact, BDNF has been shown to upregulate the expression and, because PKMζ is a constitutively active enzyme, the activity of PKMζ (Adasme et al., 2011). Furthermore, both TrkB and PKMζ are crucial for the maintenance of late-phase LTP, consolidation of long-term memory (Pastalkova et al., 2006; Minichiello, 2009), synaptic tagging (Barco et al., 2005; Sajikumar et al., 2005), and synaptic localization of PSD-95 (Yoshii and Constantine-Paton, 2007; Liu et al., 2009).

**Conclusion**

We have documented a new mechanism for trafficking synaptic molecules in vivo that is triggered by the developmental milestone of eye opening; namely, TrkB and PKMζ play significant, if not critical roles in the transport of PSD-95 to synapses after eye opening in layer 2/3 pyramidal neurons of mouse visual cortex. This mechanism involves the PSD-95 palmitoylation enzyme ZDHHC8, which is thus a prime candidate for effecting the critical palmitoylation known to bring PSD-95 to synapses. The same or a similar mechanism is likely to play a role in various forms of learning and memory as well as the developmental tuning of circuity as a result of environmentally induced activity.

Perhaps most significantly, the knowledge of a neurotrophin-pathway-dependent palmitoylation of PSD-95 can provide insights and eventual treatments for devastating developmental and psychiatric diseases such as autism spectrum disorders and schizophrenia, to name a few (Mukai et al., 2008; Fukata and Fukata, 2010; Yoshii and Constantine-Paton, 2010). This TrkB-triggered pathway is also involved in learning and memory, and also may be critical to the maintenance of memory and cognition in the aging brain (Shema et al., 2011).

**References**


