Perilesional Treatment with Chondroitinase ABC and Motor Training Promote Functional Recovery After Stroke in Rats

Lisa Gherardini[1,2,], Mariangela Gennaro[1] and Tommaso Pizzorusso[1,3]

[1]Institute of Neuroscience, CNR, Pisa 56124, Italy, [2]Institute of Clinical Physiology, CNR, Siena 53100, Italy and [3]NEUROFARBA Dept, University of Florence, Florence 50135, Italy

Address correspondence to Dr Tommaso Pizzorusso, Institute of Neuroscience, CNR, via Moruzzi, 1, 56124 Pisa, Italy. Email: tommaso@in.cnr.it
Lisa Gherardini and Mariangela Gennaro contributed equally.

Ischemic stroke insults may lead to chronic functional limitations that adversely affect patient movements. Partial motor recovery is thought to be sustained by neuronal plasticity, particularly in areas close to the lesion site. It is still unknown if treatments acting exclusively on cortical plasticity of perilesional areas could result in behavioral amelioration. We tested whether enhancing plasticity in the ipsilesional cortex using local injections of chondroitinase ABC (ChABC) could promote recovery of skilled motor function in a focal cortical ischemia of forelimb motor cortex in rats. Using the skilled reaching test, we found that acute and delayed ChABC treatment induced recovery of impaired motor skills in treated rats. vGLUT1, vGLUT2, and vGAT staining indicated that functional recovery after acute ChABC treatment was associated with local plastic modification of the excitatory cortical circuitry positive for VGLUT2. ChABC effects on vGLUT2 staining were present only in rats undergoing behavioral training. Thus, the combination of treatments targeting the CSPG component of the extracellular matrix in perilesional areas and rehabilitation could be sufficient to enhance functional recovery from a focal stroke.

Keywords: penumbra, perineuronal nets, plasticity, skilled reaching

Introduction

Stroke takes an extremely heavy toll on affected individuals and their families. Survivors are often chronically impaired in their movements and left with long-term disability (Schwab 2010). Several interventions using anti-inflammatory treatments (Wang et al. 2012), antioxidant and antiapoptotic agents (Ikeda-Matsuo et al. 2011), and neuroprotective gene therapy (Chu et al. 2007; Al-Jamal et al. 2011) have been investigated; however, physical rehabilitation therapy (Steinle and Corbaley 2011) remains the first-line intervention strategy to attenuate chronic impairment of sensory-motor function (Arya et al. 2011). Experimental and clinical evidence indicates that functional recovery by rehabilitation therapy is based on the ability to alter brain organization in adaptive ways after damage (Nudo 2011). Studies in both animals and patients have demonstrated that stroke-induced neuronal plasticity drives the formation of new local circuits, intracortical connections, and descending projection remodeling, suggesting that promoting neuronal plasticity in the affected brain can enhance functional recovery. This observation provided a rationale to studies testing whether treatments promoting plasticity could facilitate functional recovery from stroke effects. For example, inosine, which acts through a direct intracellular mechanism to stimulate axon growth in several types of neurons (Smith et al. 2007; Zai et al. 2011), Nogo-A antibodies (Buchli and Schwab 2005), or agents that block signaling through the Nogo receptor (Papadopoulos et al. 2006; Kilic et al. 2010; Tsai et al. 2011) promoted functional recovery in animal models. Interestingly, behavioral effects of these treatments were associated with enhanced plasticity of corticospinal axons in the spinal cord.

One alternative strategy to enhance plasticity in the adult brain is to recreate a tissue environment free from growth inhibiting molecules forming perineuronal nets such as chondroitin sulfate proteoglycans (CSPGs). By digesting CSPG side chains, chondroitinase ABC (ChABC) modifies extracellular matrix and allows axonal sprouting (Bruckner et al. 1998; Crespo et al. 2007). Moreover, ChABC was found to facilitate plasticity in the adult visual cortex (Pizzorusso et al. 2002, 2006), and after spinal cord injury (Barritt et al. 2006; Houle et al. 2006; Garcia-Alias et al. 2009; Tom et al. 2009; Lee et al. 2010; Carter et al. 2011). Recently, ChABC has been tested in models of brain trauma (Harris et al. 2010), however the therapeutic potential of ChABC after stroke is only partially explored (Nakamura et al. 2009; Hill et al. 2012; Soleman et al. 2012). Importantly, it is not known whether selective targeting of cortical perilesional areas is sufficient to promote behavioral amelioration and synaptic plasticity. To answer these questions, we investigated whether the treatment with ChABC restricted to the ipsilesional cortex could promote functional recovery from the effects of focal ischemia of the motor cortex containing the representation of the forelimb. We evaluated the effects of rehabilitation training and timing of ChABC delivery on behavioral recovery and cortical synaptic plasticity. We found that the synergic effect of ChABC treatment and specific rehabilitation training re-established motor function of the affected limb and caused synaptic plasticity, supporting the possibility that interventions enhancing plasticity in the perilesional cortex could promote functional recovery from stroke-induced impairments.

Materials and Methods

Animals

All procedures were performed according to the guidelines of the Italian Ministry of Health for care and maintenance of laboratory animals (law 116/92) and in strict compliance with the European Communities Council Directive 86/609/EEC. Adult Long Evans rats (300–400 g) were housed with a 12 h/12 h light/dark cycle with food and water available ad libitum. Animals were reared in a standard environment (3 adult rats in 30 cm × 40 cm × 20 cm laboratory cages). For the duration of the protocol of the skilled reaching test (SRT), rats were fed ~20 g of Purina rat chow once a day after the daily tests (Whishaw and Pellis 1990) in addition to the food pellets they obtained while performing the SRT (Bio-Serv dustless precision pellets product F0021). The weight of the rats was maintained at about 90–100% of their expected body weight.

Focal Ischemic Lesion and Treatment

After SRT completion, rats were anesthetized with avertin prior to surgery. The head was fixed in a stereotaxic frame and the scalp retracted. Body temperature was monitored throughout the procedure using a rectal probe and maintained at 37 °C with a homeothermic blanket (Harvard Apparatus Ltd, Edenbridge, Kent, UK). Unilateral lesions were performed in the hemisphere contralateral to the dominant forelimb. The 2 sites of injection were identified in correspondence to the forelimb motor cortex (A-P 0 mm, M-L 2.5 mm; A-P 2.5 mm, M-L 2.3 mm). A 1-mm burr hole was drilled through the scalp at the 2 sites while continuously applying saline over the area to prevent damage to the brain. The underlying dura was pierced during microinjections by a glass micropipette (0.03 mm tip). Two 0.75 µL injections of ET-1 (Sigma; 40 pmol/µL in sterile saline) were delivered via a glass micropipette connected to a syringe, at a depth of 0.7 mm from the brain surface at each injection site. ET-1 was delivered at a rate of 0.5 µL/min with a 1-min interval before retract the micropipette from the tissue.

After induction of focal ischemia, the protocol for acute ChABC treatment was initiated. Animals received the first dose of ChABC (40 mU/µL; 1 µL for each site) or saline immediately after injury. An equivalent second dose of ChABC or saline was delivered in a subsequent surgery session 1 week later through the already existing apertures in the skull. At the end of any surgical session and prior to suturing, lidocaine gel was gently applied on animal skulls. Animals were allowed to recover from anesthesia in a recovery box until fully conscious and paracetamol (100 mg/kg) was administered in the water.

The protocol for delayed ChABC treatment was initiated 2 weeks after stroke induction. At this time, animals underwent surgical preparation as described and were injected with a first dose of ChABC. The second dose of ChABC treatment was delivered a week later.

Behavioral Testing

Animals were handled every day for 1 week before the onset of the experiment while let familiarizing with the arena box used for in the SRT (pretraining). All behavioral testing was carried out by an experimenter blind to group membership of the animals. Animals were trained on a single pellet-reaching task modified from Whishaw and Pellis 1990. The boxes were made of clear Plexiglas with dimensions of 45 cm × 14 cm × 35 cm. In the center of the front wall, there was a vertical slit, 1 cm wide. On the outside of the wall, in front of the slit, a 2-cm-wide shelf was mounted 3 cm above the floor. Two indentations on the surface of the shelf were located 1 cm from the inside of the wall and were aligned with the edges of the slit (1 cm apart) where rats could reach the pellet with either paw. A pellet was placed in the indentation contralateral to the limb which the rat preferred for reaching. The lateral placement of the food pellet prevented the rats from using the tongue to lap the pellet also preventing them from successfully using the nonpreferred paw to grasp the food (Whishaw and Pellis 1990). A metal bar is located in front of the slit at circa 1 cm from the horizontal shelf preventing the animal to drag the food after reaching, avoiding performing a full correct movement of grasping.

Training

Training was performed as previously described (Gharbawie and Whishaw 2006). The first 5 days consisted in a shaping phase during which a number of food pellets were placed on the shelf to attract the animals. At the end of this period, rats reliably retrieved the food from the shelf using the preferred limb on each trial. Then, a single pellet was placed in the food-indentation contralateral to the rat preferred paw and the training phase consisting in 25 trials repeated 3 times in each daily session for 7 days was performed prior to receiving surgery. If the rat obtained a pellet and subsequently consumed it without dropping it, a success was scored (Gharbawie and Whishaw 2006).

Histological Procedure

After anesthesia with an overdose of chloral hydrate, the thoracic cavity was open to expose the heart. A needle was inserted in the left ventricle, and the right atrium was cut open. By means of a peristaltic pump, vessels were washed with PBS, and then the animal was perfused in a 4% w/v solution of freshly prepared paraformaldehyde in 0.1 M phosphate buffer (PB), pH 7.4. The brain was then quickly removed, postfixed by immersion in the same fixative solution for 24 h, then cryoprotected overnight in 30% w/v sucrose in 0.1 M PB. Finally, brains were frozen by immersion in isopenthane and stored at −80 °C; 12 h before cutting, samples were put at −20 °C. Free-floating brain coronal sections of about 50 µm thickness cut with a cryostat (Leica Microsystems) were collected in PBS and distributed for further analysis.

Volume Measurement

Brains were sectioned using a cryostat in 50-µm sections, and cresyl violet staining was performed. Images were acquired on a camera-mounted Zeiss Axioskop microscope, and lesion area was measured using the Metamorph software (Molecular Devices, Downingtown, Pennsylvania). The lesion area was identified and measured in all sections that contained ischemic lesion and a volume measurement computed by summation of areas multiplied by the interslice distance. The experimental group of any treatment consisted of at least 5 animals.

Expression of Synaptic Markers

Glutamate vesicular transporter 1 and 2 (vGLUT1 and 2), and the GABA vesicular transporter (vGAT) were immunostained as described (Mainardi et al. 2010). Coronal sections covering the primary motor cortex (50 µm) collected free-floating in PBS were blocked in 10% BSA, 0.3% Triton X-100 in PBS for 2 h at room temperature, then incubated overnight at 4 °C in 1% BSA, 0.1% Triton X-100, and 1:1000 rabbit anti-vGLUT1 or -2 and vGAT (1:5000) primary antibody (Synaptic Systems) in PBS. The signal was detected by incubation in 1% BSA, 0.1% Triton X-100, and 1:400 anti-rabbit secondary antibody conjugated to Alexa Fluor-568 fluorophore (Molecular Probes, Eugene, OR) for 2.5 h at room temperature, unless otherwise specified. Sections were mounted on glass slides using VectaShield mounting medium (Vector Laboratories, Burlingame, CA, USA).

Images of vGLUT1–2 and vGAT immunoreactivity in the selected areas of the cortex were acquired with a confocal laser scanning microscope (Leica BM6000). Optimal acquisition parameters (photomultiplier gain, intensity offset, and laser excitation intensity) were adjusted at the beginning of each acquisition session and held constant. Acquired images were analyzed offline using a dedicated software (Imaris, CH). A 63× oil objective (N.A. = 1.4) was used, with a 2.5 digital zoom. To achieve an optimal resolution on the z-axis, 15 sequential focal planes, spaced 0.125 µm apart, were acquired. Each focal plane was then saved as a single TIFF file in an 8-bit gray-scale mode. For vGAT and vGLUT1-2 immunoreactive puncta analysis, the image stacks were processed using the "spots" function of Imaris software (Bitplane, CH). A double threshold was applied to images to select puncta: the 'spot quality threshold' parameter that threshold pixels above a certain value of luminance, and the 'minimum spot diameter' parameter that select puncta above a certain dimension. In pilot analyses, we manually adjusted both parameters to optimize puncta detection. As a compromise between automation and optimization, we choose to keep the "minimum spot diameter" constant for all cases with a value of 1 µm. To adjust for the different brightness of sections, the "spot quality threshold" was changed by the operator blind to the experimental case to optimize puncta detection.

The expression of these markers was detected in layers I–III-selected regions of the brain cortex: for each slice section, areas of interest were defined as 1) lesion, where the damage was present, 2) penumbra, the area bordering with the lesion, 3) ipsilateral, a cortical area distant from the lesion area in the same hemisphere (Par1), 4) contralateral, the homotopic area of the motor cortex in the opposite hemisphere. For each slide, one image of each of these areas was collected representative of the fluorescence signal of the marker under investigation. For each animal, at least 6 slides were analyzed and images collected.

Anterograde Tracing of Thalamocortical Projection and Colocalization Analysis

To label thalamocortical pathway projecting into the primary motor cortex (M1), 5 adults Long Evans rats were anesthetized by intraperitoneal injection of avertin (1 mL per 100 g body weight) and stereotaxically injected with 2 µL of AAV8-GFP viral vector (9.9 E+11 genomic copies/mL) solution into the ventrolateral–ventromedial (VL-VM) thalamic motor nuclei (−3.0 mm posterior to Bregma; 1.8 mm lateral to the midline, 6.00 mm depth) by pressure through a glass micropipette attached to Picospritzer (PDES-02 TX, npi electronic system, GmbH, Germany). The mixture containing the AAV8-GFP was delivered at a rate of 0.05 µL/min, and the tip of the micropipette was held in place for 10 min after the injection and was then slowly withdrawn. During the same surgery, all the animals underwent the focal ischemia induction injury by ET-1 intracortical injections, and the ChABC or saline solution 0.9% perilesional treatment given both immediately after injury and 1 week later, as previously described. After SRT recall, rats were perfused and coronal sections covering the primary motor cortex (50 µm thickness) were prepared for immunostaining for vGLUT2 and vGLUT1 as described. A rabbit anti-GFP (1:400) primary antibody (Molecular Probes, Invitrogen) was added to the solution containing either vGLUT1 or vGLUT2 primary antibody. The signal was detected by incubation in 1% BSA, 0.1% Triton X-100, 1:400 anti-rabbit secondary antibody conjugated to Alexa Fluor-488 fluorophore (Molecular Probes, Eugene, OR) and 1:400 anti-guinea pig secondary antibody conjugated to Alexa Fluor-568 fluorophore (Molecular Probes, Eugene, OR) for 2.5 h at room temperature. After rinsing twice in PBS, sections were mounted on glass slides using Vectashield mounting medium (Vector Laboratories, Burlingame, CA). Images of GFP and vGLUT1–2 immunoreactivity in the perilesional area of the cortex were acquired (the 2 channels acquired separately to minimize cross-talk) with a confocal laser scanning microscope (Leica BM6000). Synaptic marker-positive puncta overlapping with GFP were counted offline using Imaris by an operator blind to the synaptic marker under analysis.

Wisteria Floribunda Agglutinin and CSPG Stubs Staining

Three days after stroke 4 ChABC-treated rats were perfused with cold 4% paraformaldehyde and postfixed overnight. About 50 µm sections were blocked in 3% goat or donkey serum 3% bovine serum albumin, in Tris buffered saline with 0.2% triton X-100. Wisteria Floribunda Agglutinin (WFA) histochemistry was performed by incubating sections in biotinylated WFA (20 mg/ml, Sigma, Haverhill, UK) overnight at 4 °C (Hobohm et al. 2005). Labeling was revealed using TRITC-labeled Streptavidin (Sigma) and images were acquired at the confocal microscope. An additional group of 3 animals were perfused with cold 4% paraformaldehyde and postfixed overnight. About 50 µm sections were blocked in 10% BSA, 0.3% Triton X-100 in PBS for 1 h at room temperature, then incubated overnight at 4 °C in 1% BSA, 0.1% Triton X-100 and monoclonal 2B6 antibody (MD Bioproducts, CH) primary antibody (1:100) in PBS. The signal was detected by incubation in 1% BSA, 0.1% Triton X-100, 1:400 anti-mouse secondary antibody conjugated to Alexa Fluor-568 fluorophore (Molecular Probes, Eugene, OR) for 2 h at room temperature. After rinsing twice in PBS, sections were mounted on glass slides using Vectashield mounting medium (Vector Laboratories, Burlingame, CA). Images of 2B6 immunoreactivity in injured hemisphere were acquired with a confocal laser scanning microscope (Leica BM6000).

Analysis of Reactive Astrogliosis

Two groups of animals ($N = 4$ each) treated with ChABC or control were perfused 3 days after stroke with cold 4% paraformaldehyde and postfixed overnight. About 50 µm sections were blocked in 10% normal goat serum NGS, 0.3% Triton X-100 in PBS for 1 h at room temperature, then incubated overnight at 4 °C in 1% NGS, 0.1% Triton X-100 and monoclonal mouse anti-GFAP (1:500) primary antibody (Sigma Aldrich) in PBS. The signal was detected by incubation in 1% NGS, 0.1% Triton X-100, 1:400 anti-mouse secondary antibody conjugated to Alexa Fluor-568 fluorophore (Molecular Probes, Eugene, OR, USA) for 2 h at room temperature. After rinsing twice in PBS, sections were mounted on glass slides using Vectashield mounting medium (Vector Laboratories, Burlingame, CA). Images of GFP

immunoreactivity in injured hemisphere were acquired with a confocal laser scanning microscope (Leica BM6000). Six fields (700 × 700 µm) were acquired in the penumbra area for each slice, and 4 slices were analyzed for each rat. For each image, we first choose a fluorescence intensity threshold to exclude background. Then, the area of the image containing pixels above threshold was multiplied by their average fluorescence to obtain the integrated fluorescence.

Results

Skilled Reaching Task Learning

SRT, which is a complex motor cortex-dependent behavior, was analyzed in the single pellet retrieval task. This test is normally used to assess the ability of rats to perform forelimb grasping fine movements (Starkey et al. 2011). Animals were trained to successfully retrieve a food pellet from a tray through a narrow window using their preferred forelimb. For each animal, the grasping ability was measured during the training period (day 1–6) when animals learned to perform the task, improving steadily their retrieving rate (Fig. 1A; $n = 57$ 1-way ANOVA repeated measures, $P < 0.001$). After completion of the SRT training, rats were randomly assigned to one of the experimental groups.

Effects of ChABC Cortical Administration on CSPGs and Astroglia

Before assessing ChABC effects on motor behavior, we assessed the spatial coverage of CSPG glycosaminoglycan (GAG) digestion by ChABC using WFA staining. Intracortical injection of ChABC into the adult rat motor cortex resulted in a reduction of WFA staining in an area covering almost all the mediolateral extent of the treated cortex and affecting all cortical layers. The area devoid of WFA staining did not spread into the contralateral hemisphere. Similar results were obtained using 2B6 antibody that labels the CSPG stubs left by ChABC digestion (Fig. 1B).

It has been suggested that ChABC could reduce glial scar formation assessed by GFAP immunostaining after severing nigro-striatal pathway (Li et al. 2013). We analyzed GFAP staining 3 days after stroke in saline and ChABC-treated rats. Our data show a trend of borderline statistical significance toward reduced GFAP staining in ChABC-treated animals (Fig. 1C).

Rats Treated with ChABC Show Motor Impairment at the Beginning of the Recall Phase

Fine movement impairment induced by the focal stroke was analyzed by comparing animal performance in the SRT before and after damage. The effects of intracortical ChABC treatment were studied applying 2 different protocols (Fig. 1D): an acute protocol, in which ChABC was administered immediately after lesion and 7 days later, or a delayed protocol in which the 2 ChABC injections began 2 weeks after lesion. Motor function was assessed 1 week after the last ChABC administration. All animals continued to use the preferred limb even if the corresponding cortex was lesioned.

To induce a cortical focal lesion we injected ET-1, a potent vase constrictor at2 sites targeting the forelimb motor cortex (Gilmour et al. 2004). M1 focal ischemia caused a significant reduction of successful retrievals in the SRT on the first day of recall. This impairment was present both in ChABC and control rats regardless of the timing of application of the
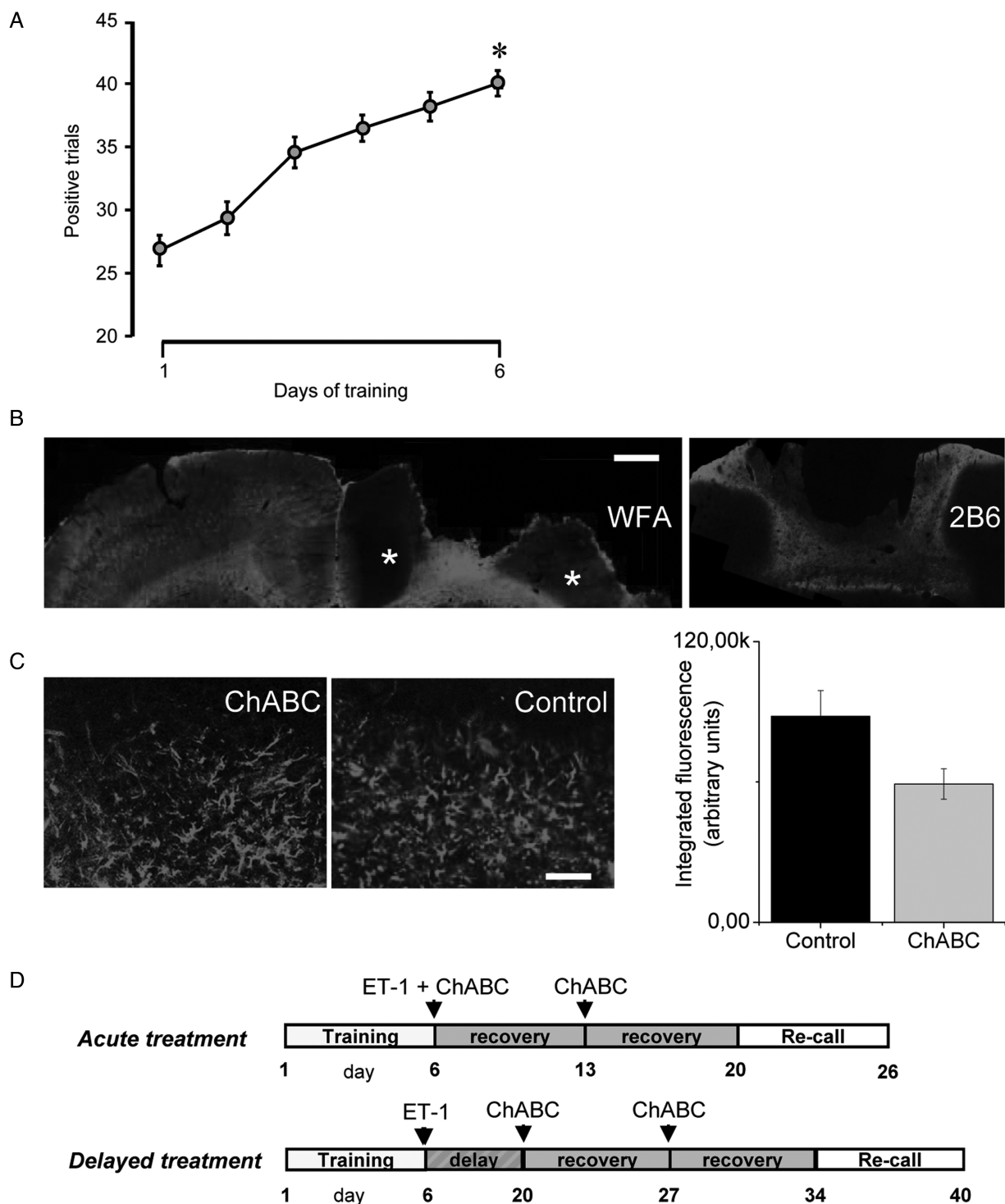
Figure 1. (A) Learning curve of the SRT test. Positive retrieves were measured during the training period (day 1–6, $n = 57$ 1-way ANOVA repeated measures, $P < 0.001$). (B) Visualization of the area of digestion by ChABC. Left: WFA staining in an ET-1-injected brain perfused 3 days after lesion shows 2 perilesional areas of digestion (marked by asterisks). Right: immuno staining for CSPG stubs using 2B6 antibody in a different rat. Calibration bar = 1 mm in left picture, 0.6 mm in right picture. (C) GFAP staining at the border of the lesion site (dark area at the top of pictures). Quantitation of the integrated GFAP staining fluorescence did not show a statistical difference between ChABC-treated ($N = 4$) and control ($N = 4$) rats 3 days after lesion (t-test, $P = 0.06$). Calibration bar = 40 µm. (D) Treatment protocols. SRT was administered during Training and Recall sessions.

treatment. Indeed, on day 6 of the acute protocol, controls performed 37.8 ± 2.7 correct retrievals ($n = 16$) while the mean value of the correct retrievals measured the first day of retraining (day 20) was significantly decreased (18.5 ± 2.7 correct retrievals, paired t-test, $P < 0.005$). Similarly, the ChABC acute

group managed 41.0 ± 2.5 positive trials ($n = 16$) on day 6, but only 27.1 ± 2.8 positive trials on day 20 (paired t-test, $P < 0.005$).

Performance after lesion was also affected in control and ChABC rats treated adopting the delayed protocol: in controls,

corrected retrievals at day 6, last day before lesion, were 39.4 ± 2.4 whereas at day 35, the first day of assessment after lesion, they were significantly reduced to 25.0 ± 2.3 ($n = 11$, paired t-test, $P < 0.005$). In ChABC rats, corrected retrievals at day 6 were 40.5 ± 1.2 whereas they were 28.1 ± 3.2 at day 35 ($n = 13$, paired t-test, $P < 0.005$). Thus, motor ability learned before lesion was lost after stroke and was not preserved by ChABC treatment.

Acute and Delayed ChABC Treatment Promotes Motor Learning After Cortical Stroke

SRT performance of the acute ChABC and control groups dramatically diverged during recall (Fig. 2A and B). Indeed, at the end of the recall phase the number of successful pellet retrieval recovered to prelesion values (paired t-test, day 6 vs., day 25, paired t-test $P = 0.38$) in ChABC-treated rats. Conversely, in control rats, performance at the end of the recall period remained significantly lower than the prelesion level (paired t-test; day 6 vs., day 25, paired t-test $P < 0.001$). To better visualize postlesion behavioral recovery in ChABC-treated rats we also plotted the data normalized to the prelesion performance of each animal (Fig. 2C and D). This analysis nulls between-subject variability in the final level of prelesion learning. Using this processing of the data, it is even more evident how stroke rats treated with ChABC were able to relearn the motor task.

ChABC-delayed treatment similarly improved the reaching skills of treated animals (Fig. 3). Successful retrieval at the end of the recall phase was significantly lower than prelesion values in control rats (at day 6 39.27 ± 2.36 retrieved pellets, at day 41 25.0 ± 2.30 retrieved pellets, paired t-test, $P < 0.001$). On the contrary, ChABC-delayed treatment induced a complete recovery of skilled reaching. Indeed, correct successful retrieval values at the end of the recall phase in the delayed ChABC group was not different from preinjury levels (at day 6 40.5 ± 1.17 retrieved pellets, at day 41 36.21 ± 11.51 retrieved pellets, paired t-test $P = 0.44$). This profile is clearly visualized when normalized results are examined (Fig. 3C and D). Thus, local cortical treatment with ChABC promotes functional restoration of impaired forepaw use in stroke injured rats even if performed 2 weeks after injury.

ChABC Treatment Does Not Affect Damage Size in Ischemic Rats

We controlled whether ChABC might have influenced lesion size. The effect of the acute and delayed ChABC treatments was evaluated measuring the volume of the lesion in the brain of animals sacrificed at the end of the behavioral protocol. The lesion volume comprised most of the primary forelimb motor cortex. For both the acute (control 0.99 ± 0.21 mm^3 $n = 8$; ChABC treated 0.75 ± 0.15 mm^3 $n = 10$, t-test, $P = 0.34$) and the
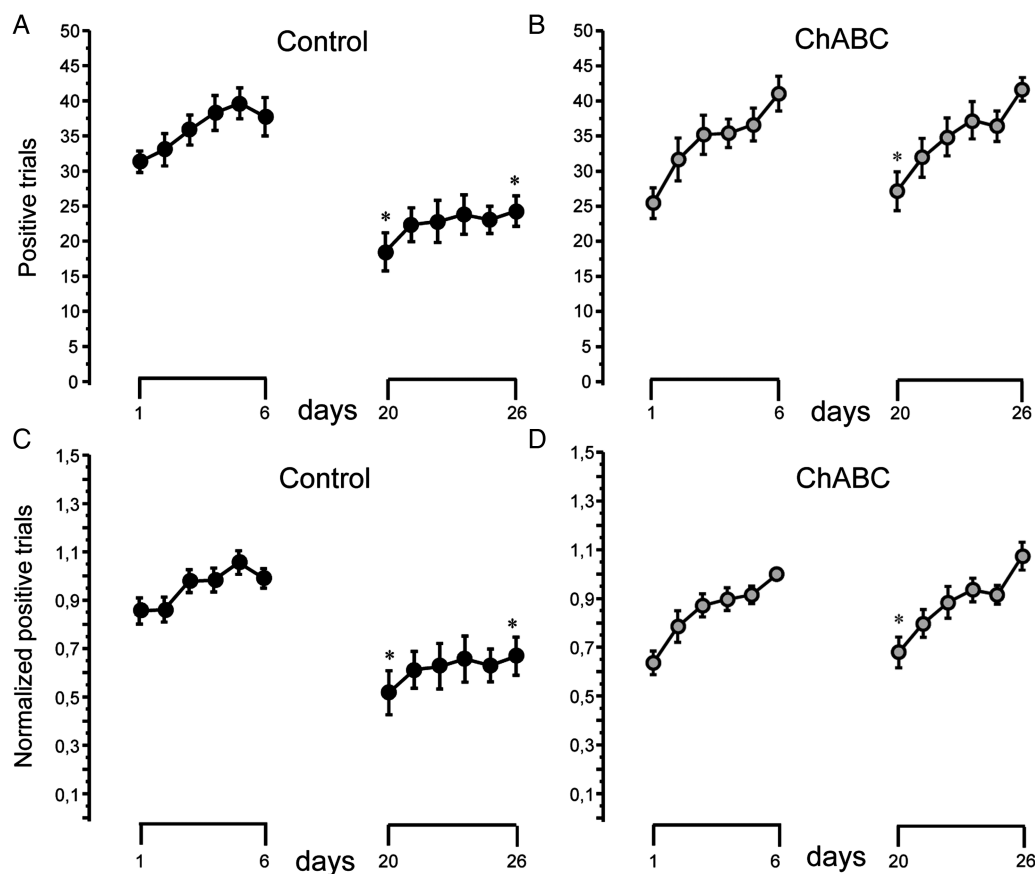

Figure 2. Acute ChABC treatment promotes SRT re-learning after stroke. Learning curves of the control and ChABC groups did not statistically differ [2-way ANOVA, $N = 16$ for both treatment groups, no significant effect of the treatment group ($P = 0.41$) or time $\times$ treatment group interaction was observed ($P = 0.21$). The factor time was significant (factor time $P < 0.001$)]. Stroke caused significant fine movement impairment in both control (A) and ChABC-treated animals (B) measured on the first day of re-training (day 20). After re-training, control animals failed to reach full recovery while ChABC-treated animals fully recovered reaching motor skills. Data normalized to the prelesion level of learning (average of the last 3 days of prelesion training) show a similar profile for control (C) and ChABC-treated (D) rats. *$P < 0.05$ with respect to prelesion level (paired t-test).
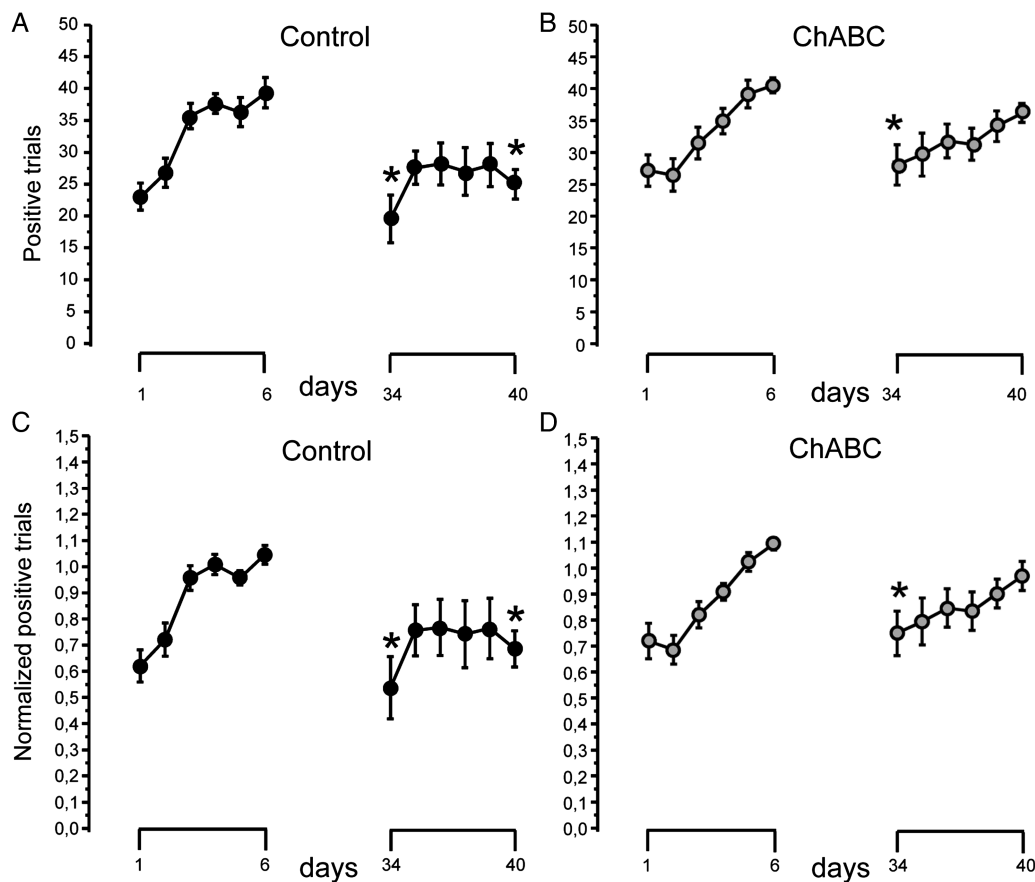
Figure 3. Delayed ChABC treatment promotes SRT re-learning after stroke. Fine forelimb movement is impaired in both control (*A*) and ChABC-treated animals (*B*) measured on the first day of re-training (day 34). After re-training, control animals failed to reach full recovery while ChABC-treated animals fully recovered reaching motor skills. Data normalized to the prelesion level of learning (average of the last 3 days of prelesion training) show a similar profile for control (*C*) and ChABC-treated (*D*) rats. *$P < 0.05$ with respect to prelesion level (paired *t*-test).

delayed protocol (control 2.32 ± 0.83 mm³ $n = 5$; ChABC treated 2.24 ± 0.83 mm³ $n = 5$, *t*-test, $P = 0.1$), the measurement of stroke volume revealed no significant differences between groups (Fig. 4*A*). No correlation was observed between volume of the lesions and skilled reaching motor performance in any of the experimental groups (Fig. 4*B*, Pearson Product Moment Correlation, $P > 0.050$ for all groups).

ChABC and Behavioral Training Altered Expression of Synaptic Markers

As ChABC is known to promote cortical plasticity in the adult CNS after sensory deprivation (Pizzorusso et al. 2006; Nakamura et al. 2009; Carulli et al. 2010) and in the spinal cord after damage (Garcia-Alias et al. 2009), we investigated whether the cortical treatment with ChABC could promote plasticity of synaptic connections. Therefore, at day 26 of the acute protocol, we performed an immunohistochemical analysis of synaptic markers in control and ChABC-treated rats. At this time point, ChABC-treated rats show complete functional recovery and are maximally different from control animals.

To assess synaptic connectivity, we measured punctate staining for markers of glutamatergic (vGLUT1 and vGLUT2) and GABAergic (vGAT) presynaptic terminals in different brain regions. Punctate marker staining was measured in the lesioned area (Les), in the penumbra (Pen), an area bordering with the lesion where maximal plasticity has been reported to

occur after damage, and in a cortical area located in parietal area Par1 ipsilateral to the lesion (Ipsi) and not damaged by stroke. We also measured marker expression in the homotopic area contralateral (Contra) to the lesion (Fig. 5*A*).

For all proteins, expression was extremely scarce in the lesion area of both control and ChABC-treated animals due to the loss of neuronal cells occurring after damage in either treated or control animals (Fig. 5*B* and *D*; Table 1). vGLUT1 and vGAT puncta density was not significantly affected by ChABC treatment coupled with behavioral training in none of the other analyzed areas (Table 1). On the contrary, ChABC-treated rats showed a significant higher density of vGLUT2-positive puncta in the penumbra area (Fig. 5*B*) with respect to the other areas of the same animals. This effect was specific for the ChABC-treated penumbra, indeed vGLUT2-positive puncta density in trained ChABC rats was higher than both trained control rats or untrained ChABC-treated rats (*t*-test, $P < 0.05$). Therefore, training in the SRT coupled with ChABC is able to promote plasticity of vGLUT2-positive terminals in the penumbra area surrounding the stroke lesion.

VGLUT2 has been described to be expressed primarily by afferent thalamic fibers. To check whether the increase in vGLUT2-positive puncta was associated with thalamic axons also in ChABC-treated and SRT-trained rats, we traced thalamic fibers ascending from the VL/VM thalamic nuclei by microinjection of AAV carrying a GFP expression cassette into VL/VM
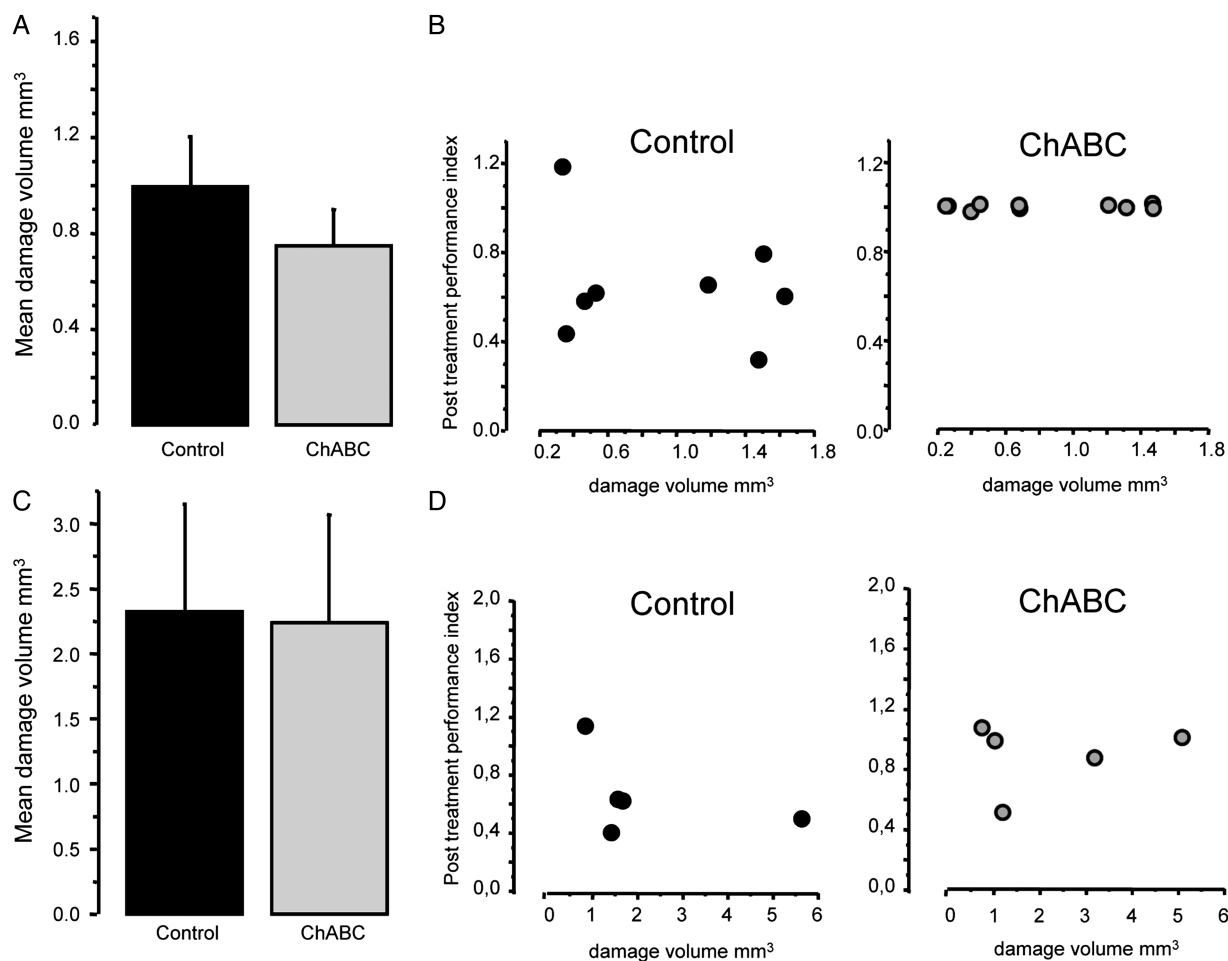
Figure 4. Lack of effect of acute and delayed ChABC treatment on lesion volume. No significant difference in lesion volume was measured between control and acute (*A*) or delayed (*C*) ChABC-treated animals. No correlation was present between the volume and the retrieval performance in controls- and ChABC-treated rats treated with the acute or the delayed protocol (*B* and *D*). Retrieval performance index was calculated as the mean performance during the last 3 days of the recall phase on normalized graphs shown in Figures 3 and 4.

nuclei. We then counted vGLUT2-positive puncta colocalizing with GFP-positive fibers present in the penumbra area. vGLUT1 puncta were also counted to assess specificity of the colocalization for vGLUT2. The results showed a significantly higher colocalization for vGLUT2 than for vGLUT1 (Fig. 5*E*) suggesting that VL/VM thalamic fibers predominantly express vGLUT2 also in chABC plus SRT rats.

Lack of Synaptic Marker Alteration in Untrained Rats Treated with ChABC

To dissect out the role of ChABC administration from SRT training in promoting cortical synaptic plasticity, we measured the expression of vGAT, vGLUT1, and vGLUT2 throughout the Les, Pen, Ipsi, and Contra cortical areas of animals that underwent the acute treatment with ChABC or control, but did not receive any SRT training.

Consistently with our previous results, the expression of vGLUT1, vGLUT2, and vGAT was reduced in the lesion area regardless of the treatment (Fig. 5*C* and Table 2). Moreover, vGLUT1 and vGAT puncta density did not change throughout the different areas of the cortex in both ChABC and control rats. At difference with the results obtained in trained rats,

vGLUT2 was also unaffected in the penumbra of ChABC-treated, untrained rats. In these animals, vGLUT2-positive puncta density remained similar to the levels measured in Ipsi and Contra areas of the same animals and in the penumbra area of control animals.

The lack of increase in penumbral vGLUT2 punctate staining after ChABC treatment suggests that ChABC per se is not sufficient to sustain presynaptic plasticity in the motor cortex after focal ischemic damage.

Discussion

We showed that specific motor training combined with intracortical ChABC treatment promotes functional recovery from the effects of a focal cortical ischemia induced by ET-1 injection in the forelimb M1 area. Skilled forelimb motor behavior was tested using SRT, one of the most sensitive indicators of forelimb motor deficits during the chronic postinjury period (Adkins and Jones 2005). Both acute and delayed ChABC treatments were effective, albeit the final level of motor learning reached by the acutely treated rats was higher than that reached with the delayed ChABC treatment. This could be due to an additional effect of ChABC on counteracting
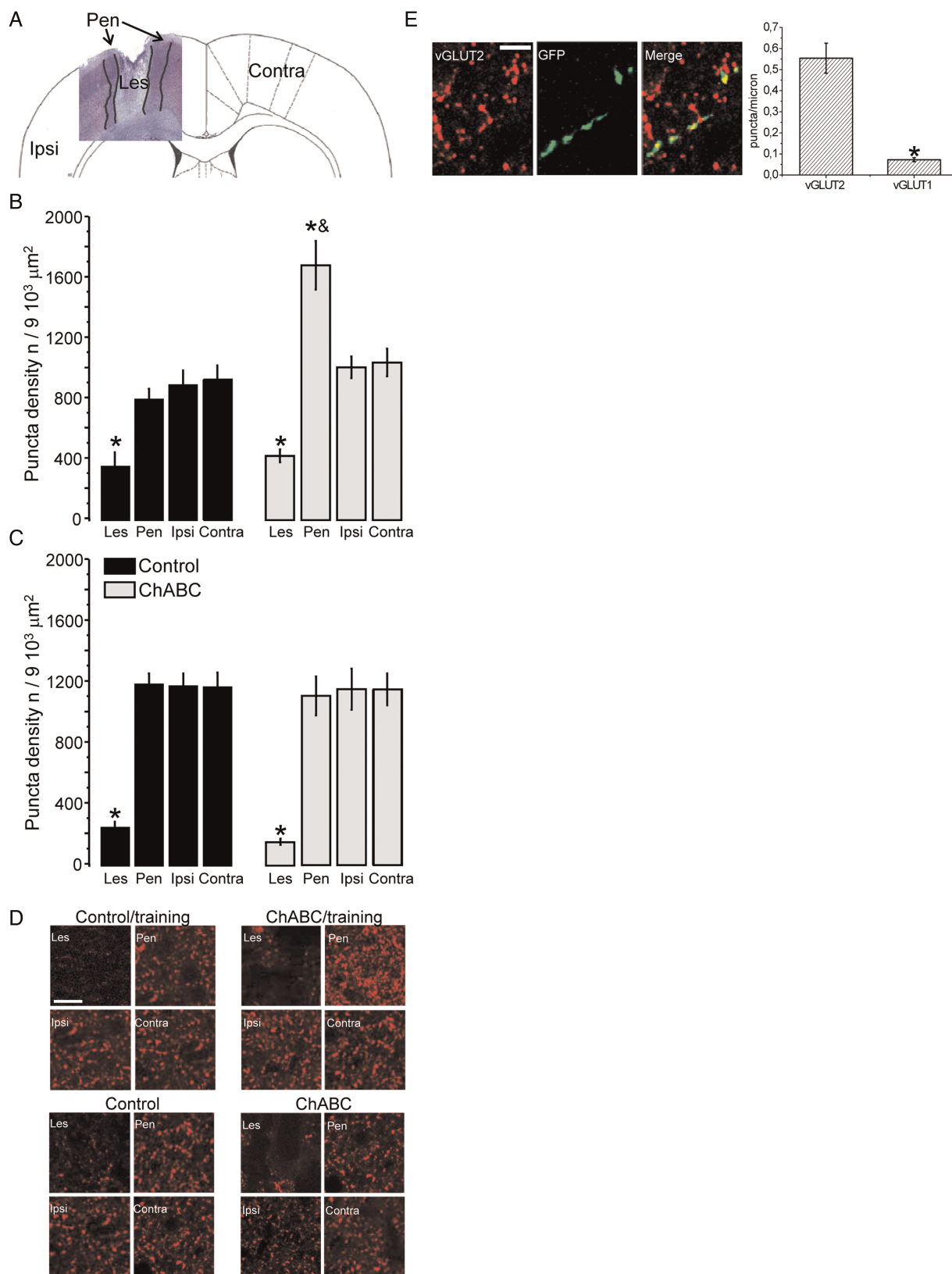
Figure 5. Punctate vGLUT2 staining is selectively increased in the Pen area of acutely ChABC-treated rats receiving SRT training. (*A*) Cresyl violet staining of the lesion showing the location of lesion (Les), penumbra (Pen), ipsilateral unlesioned (Ipsi), and homotopic contralateral areas (Contra) are also shown. (*B*) Quantitation of vGLUT2 puncta density in control and ChABC-treated rats trained in the SRT. In control-treated rats, the Les area significantly differed from the other areas (1-way RM ANOVA $P < 0.01$; Holm-Sidak post hoc test $P < 0.05$). Within ChABC-treated rats both the Les and the Pen areas significantly differed from all the other areas (1-way RM ANOVA $P < 0.01$; Holm-Sidak post hoc test, $P < 0.05$). The Pen area of controls and ChABC rats were significantly different (*t*-test, $P < 0.01$). * indicates $P < 0.05$ with respect to the other groups within the same treatment. & indicates $P < 0.05$ between Pen areas of ChABC- and control-treated rats. (*C*) Quantitation of vGLUT2 puncta density in control and ChABC-treated rats without training. Both in

Table 1
SRT training

	vGLUT1		vGAT	
	ChABC	Control	ChABC	Control
Les	216.3 ± 241	236.2 ± 35.1	366.6 ± 54.2	344.1 ± 64.2
Pen	1973.7 ± 65.6	1925.6 ± 96.5	1006.7 ± 93.9	1025.4 ± 31.7
Ipsi	2053.9 ± 84.5	2213.0 ± 94.5	1158.5 ± 146.3	1079.1 ± 112.4
Contra	1908.7 ± 107.4	2123.4 ± 79.6	1225.4 ± 84.3	982.8 ± 100.0

vGLUT1 and vGAT puncta density is altered exclusively in the Les area with respect to all other areas ($n = 6$ for ChABC and $n = 5$ for controls for both stainings, 1-way RM ANOVA, $P < 0.01$; post hoc Holm-Sidak test, $P < 0.05$)

Table 2
No SRT training

	vGLUT1		vGAT	
	ChABC	Control	ChABC	Control
Les	165.0 ± 36.1	145.9 ± 30.9	189.7 ± 13.2	206.7 ± 14.4
Pen	989.4 ± 67.5	1117.9 ± 167.0	1424.2 ± 72.2	1439.2 ± 33.7
Ipsi	1069.8 ± 92.8	1127.4 ± 118.8	1436.7 ± 55.2	1449.2 ± 69.3
Contra	1059.7 ± 128.3	1198.4 ± 155.8	1404.8 ± 52.8	1454.2 ± 45.3

vGLUT1 and vGAT puncta density is altered exclusively in the Les area with respect to all other areas ($n = 3$ for both treatments and stainings; 1-way RM ANOVA, $P < 0.01$; post hoc Holm-Sidak test, $P < 0.05$).

inflammatory and swelling reaction in the short time after stroke (Elkin et al. 2011) or to a facilitation of intrinsic plasticity mechanisms occurring during the first weeks after lesion and fading with time.

Mechanisms of Action of ChABC

ChABC digests the GAG chains of CSPGs into soluble disaccharides, and leaves behind the core protein. In several lesion models, this treatment has been shown to promote functional recovery (Tester et al. 2007; Garcia-Alias et al. 2009; Hyatt et al. 2010; Jefferson et al. 2011; Garcia-Alias and Fawcett 2012), suggesting that most of the inhibitory activity of CSPGs is mediated by their GAG moieties. Several molecular mechanisms have been proposed for the inhibitory activity of GAGs on functional recovery after lesion (Garcia-Alias et al. 2009). Receptor protein tyrosine phosphatase sigma (RPTPσ) has been identified as a CSPG receptor, through which CSPGs can trigger growth cone collapse when the GAG chains bind to the surface of the first immunoglobulin-like domain of the receptor (Shen et al. 2009). In addition, other mechanisms could also participate in the inhibitory nature of the CSPGs. For instance, the high negative charges of the sulfate groups can induce repulsive allosteric interaction with the axonal growth cone and with charged molecules and ions, impeding their growth on CSPG enriched areas (Gilbert et al. 2005), or CSPGs could mask some growth-promoting substrates, such as laminin (McKeon et al. 1995). Proteoglycans often act by attracting active molecules to their GAG chains, then forming a ternary complex with their receptor. During development, several

axon guidance molecules such as slits rely on this mechanism for their localization and action and, in the adult CNS, semaphorin3 family molecules bind to CSPGs and may rely on this for their inhibitory actions (Vo et al. 2013). Overall, all these mechanisms should impinge on the plasticity of the neuronal connections involved in functional recovery. Indeed, ChABC treatment was effective also in models that specifically involve plasticity mechanisms to achieve functional recovery such as recovery from amblyopia in the adult visual cortex (Pizzorusso et al. 2006). Furthermore, recent work indicates that ChABC can modulate plasticity mechanisms underlying learning and memory (Gogolla et al. 2009; Romberg et al. 2013). Thus, ChABC-facilitated plasticity could enhance functional recovery, either by enhanced sprouting of existing axons or by the formation of new connections at the injury site (Bradbury et al. 2002). Sprouting of axons in the perilesional cortex has been documented during early postcortical contusion (Carmichael et al. 2005; Harris et al. 2010) and postischemic (Carmichael et al. 2005) periods. We examined presynaptic markers of inhibitory and excitatory terminals and we found that ChABC enhanced density of vGLUT2-positive puncta only when its delivery was combined with motor training. Thus, sprouting of excitatory fibers in the cortical area close to the lesion could contribute to the skilled reaching learning observed in lesion animals treated with ChABC. On a functional level, the increase of glutamatergic presynaptic terminals might tip the excitatory/inhibitory balance in the penumbra areas toward excitation. This mechanism would counteract the decrease in excitability of the neuronal circuits in peri-infarct cortex due to the high levels of tonic GABA (Carmichael 2012), a factor shown to be important to hinder remapping of motor and sensory function after stroke.

Site of Action of ChABC

There is abundant literature on the use of ChABC in the spinal cord or in the cerebrospinal fluid in presence of spinal damage; however it was not clear whether a cortical ChABC treatment could be beneficial in stroke models. Recently, it was shown that spinal delivery of ChABC promotes functional recovery in aged rats (Soleman et al. 2012). Furthermore, intracerebral infusion of ChABC in medial cerebral artery occlusion rat model, resulting in a large lesion involving cortical and subcortical structures, also promoted functional amelioration (Hill et al. 2012). Our study demonstrates that ChABC treatment limited to cortical perilesional areas is sufficient for functional recovery and creates a permissive environment for training-induced synaptic reorganization.

An obvious target of our ChABC treatment is cortical connectivity. This possibility is strengthened by the plastic rewiring observed using presynaptic puncta staining in the perilesional areas of trained, ChABC-treated rats. Intriguingly, an enhancement of puncta density was present in vGLUT2-positive and not in vGLUT1 or vGAT-positive terminals. vGLUT2 is thought be present prominently on thalamic terminals present in cortical tissue (Kaneko and Fujiyama 2002; Fattorini et al. 2009), the mechanisms

control and in ChABC-treated rats, only the Les area significantly differed from the other areas (1-way RM ANOVA $P < 0.01$; Holm-Sidak post hoc test $P < 0.05$). The Pen area of controls and ChABC rats were not significantly different (t-test, $P = 0.64$). * indicates $P < 0.05$ with respect to the other groups within the same treatment. (D) Representative maximum projection images of vGLUT2 staining in control and ChABC-treated rats with and without SRT training. Calibration bar 15 μm. E. vGLUT2 puncta density in GFP-labeled thalamic fibers ($N = 37$ axons) is significantly higher than vGLUT1 puncta density ($N = 35$; t-test, $P < 0.001$). Left: picture of a GFP-positive fiber carrying vGLUT2-positive puncta. Calibration bar 6 μm.

involving this population in the effect of ChABC are still to be elucidated. Furthermore, lack of alteration of puncta density should be interpreted cautiously because vGLUT1 and vGAT-positive terminals could still participate to the plasticity process by changing their strength, localization, and postsynaptic partner.

Plasticity of cortical connectivity and enhanced glutamatergic input could preserve firing of descending neurons promoting plastic changes occurring also subcortically. Indeed, spared cortical descending fibers may strengthen their synaptic efficacy on those spinal neurons deprived of innervation. Lesioned spinal axons can sprout into denervated spinal domains; moreover, enhancement of this sprouting is associated with better behavioral recovery from stroke effects (Lee et al. 2004). Recently, lentivirus mediated gene expression of bacterial ChABC in the motor cortex was found to enhance sprouting of lesioned corticospinal neurons (Zhao et al. 2011). This effect could be mediated by the transport of ChABC into the spinal cord along axons of transduced corticospinal neurons as shown by the presence of digested CSPG stubs (Zhao et al. 2011).

It has been reported that, in presence of wide damaged areas including corpus callosum white matter and subcortical regions, structural and functional reorganization is not limited to spared areas of the injured hemisphere, but may occur in homotopic regions of the intact hemisphere (Jones and Schallert 1992). We investigated the presynaptic vesicular transporters expression in the homotopic contralateral region without finding any significant change in both glutamatergic and GABAergic transporters, thus making unlikely that plastic rearrangements of contralateral presynaptic terminals could be induced by ChABC in our model of focal ischemia. As following a cortical injury animals adjust forelimb movements to compensate for deficits in the affected limb (Whishaw et al. 2004), true recovery may be masked (Whishaw et al. 1991; Whishaw 2000), or even hindered (Alaverdashvili et al. 2007, 2008), by the use of alternative movement strategies, often resulting in postural compensation (Krasovsky and Levin 2010). Lack of plasticity in the contralateral motor cortex may preserve perilesional circuitry from minimal maladaptive interference, often invoked to justify inappropriate stimulation evoked movements.

The amelioration of skilled movements observed with cortical treatment with ChABC together with the lack of maladaptive forms of plasticity underscores the importance of cortical plasticity in functional recovery from stroke. Furthermore, treatments targeting CSPGs could be effective in restoring motor function not only after traumatic lesions of the spinal cord, but also in cortical stroke patients.

Funding

Notes

Conflict of Interest: None declared.

References

Adkins DL, Jones TA. 2005. D-amphetamine enhances skilled reaching after ischemic cortical lesions in rats. Neurosci Lett. 380:214–218.

Alaverdashvili M, Foroud A, Lim DH, Whishaw IQ. 2008. 'Learned baduse' limits recovery of skilled reaching for food after forelimb motor cortex stroke in rats: a new analysis of the effect of gestures on success. Behav Brain Res. 188:281–290.

Alaverdashvili M, Lim DH, Whishaw IQ. 2007. No improvement by amphetamine on learned non-use, attempts, success or movement in skilled reaching by the rat after motor cortex stroke. Eur J Neurosci. 25:3442–3452.

Al-Jamal KT, Gherardini L, Bardi G, Nunes A, Guo C, Bussy C, Herrero MA, Bianco A, Prato M, Kostarelos K et al. 2011. Functional motor recovery from brain ischemic insult by carbon nanotube-mediated siRNA silencing. Proc Natl Acad Sci U S A. 108:10952–7.

Arya KN, Pandian S, Verma R, Garg RK. 2011. Movement therapy induced neural reorganization and motor recovery in stroke: a review. J Bodyw Mov Ther. 15:528–537.

Barritt AW, Davies M, Marchand F, Hartley R, Grist J, Yip P, McMahon SB, Bradbury EJ. 2006. Chondroitinase ABC promotes sprouting of intact and injured spinal systems after spinal cord injury. J Neurosci. 26:10856–10867.

Bradbury EJ, Moon LD, Popat RJ, King VR, Bennett GS, Patel PN, Fawcett JW, McMahon SB. 2002. Chondroitinase ABC promotes functional recovery after spinal cord injury. Nature. 416:636–640.

Bruckner G, Bringmann A, Hartig W, Koppe G, Delpech B, Brauer K. 1998. Acute and long-lasting changes in extracellular-matrix chondroitin-sulphate proteoglycans induced by injection of chondroitinase ABC in the adult rat brain. Exp Brain Res. 121:300–310.

Buchli AD, Schwab ME. 2005. Inhibition of nogo: a key strategy to increase regeneration, plasticity and functional recovery of the lesioned central nervous system. Ann Med. 37:556–567.

Carmichael ST. 2012. Brain excitability in stroke: the yin and yang of stroke progression. Arch Neurol. 69:161–167.

Carmichael ST, Archibeque I, Luke L, Nolan T, Momiy J, Li S. 2005. Growth-associated gene expression after stroke: evidence for a growth-promoting region in peri-infarct cortex. Exp Neurol. 193:291–311.

Carter LM, McMahon SB, Bradbury EJ. 2011. Delayed treatment with chondroitinase ABC reverses chronic atrophy of rubrospinal neurons following spinal cord injury. Exp Neurol. 228:149–156.

Carulli D, Pizzorusso T, Kwok JC, Putignano E, Poli A et al. 2010. Animals lacking link protein have attenuated perineuronal nets and persistent plasticity. Brain 133:2331–2347.

Chu Y, Miller JD, Heistad DD. 2007. Gene therapy for stroke: 2006 overview. Curr Hypertens Rep. 9:19–24.

Crespo D, Asher RA, Lin R, Rhodes KE, Fawcett JW. 2007. How does chondroitinase promote functional recovery in the damaged CNS? Exp Neurol. 206:159–171.

Elkin BS, Shaik MA, Morrison B 3rd. 2011. Chondroitinase ABC reduces brain tissue swelling in vitro. J Neurotrauma. 28:2277–2285.

Fattorini G, Verderio C, Melone M, Giovedi S, Benfenati F, Matteoli M, Conti F. 2009. VGLUT1 And VGAT are sorted to the same population of synaptic vesicles in subsets of cortical axon terminals. J Neurochem. 110:1538–1546.

Garcia-Alias G, Fawcett JW. 2012. Training and anti-CSPG combination therapy for spinal cord injury. Exp Neurol. 235:26–32.

Garcia-Alias G, Barkhuysen S, Buckle M, Fawcett JW. 2009. Chondroitinase ABC treatment opens a window of opportunity for task-specific rehabilitation. Nat Neurosci. 12:1145–1151.

Gharbawie OA, Whishaw IQ. 2006. Parallel stages of learning and recovery of skilled reaching after motor cortex stroke: 'oppositions' organize normal and compensatory movements. Behav Brain Res. 175:249–262.

Gilbert RJ, McKeon RJ, Darr A, Calabro A, Hascall VC, Bellamkonda RV. 2005. CS-4,6 is differentially upregulated in glial scar and is a potent inhibitor of neurite extension. Mol Cell Neurosci. 29:545–558.

Gilmour G, Iversen SD, O'Neill MF, Bannerman DM. 2004. The effects of intracortical endothelin-1 injections on skilled forelimb use: implications for modelling recovery of function after stroke. Behav Brain Res. 150:171–183.

Gogolla N, Caroni P, Luthi A, Herry C. 2009. Perineuronal nets protect fear memories from erasure. Science. 325:1258–1261.

Harris NG, Mironova YA, Hovda DA, Sutton RL. 2010. Chondroitinase ABC enhances pericontusion axonal sprouting but does not confer robust improvements in behavioral recovery. J Neurotrauma. 27:1971–1982.

Hill JJ, Jin K, Mao XO, Xie L, Greenberg DA. 2012. Intracerebral chondroitinase ABC and heparan sulfate proteoglycan glypican improve outcome from chronic stroke in rats. Proc Natl Acad Sci U S A. 109:9155–9160.

Hobohm C, Gunther A, Grosche J, Rossner S, Schneider D, Bruckner G. 2005. Decomposition and long-lasting downregulation of extracellular matrix in perineuronal nets induced by focal cerebral ischemia in rats. J Neurosci Res. 80:539–548.

Houle JD, Tom VJ, Mayes D, Wagoner G, Phillips N, Silver J. 2006. Combining an autologous peripheral nervous system 'bridge' and matrix modification by chondroitinase allows robust, functional regeneration beyond a hemisection lesion of the adult rat spinal cord. J Neurosci. 26:7405–7415.

Hyatt AJ, Wang D, Kwok JC, Fawcett JW, Martin KR. 2010. Controlled release of chondroitinase ABC from fibrin gel reduces the level of inhibitory glycosaminoglycan chains in lesioned spinal cord. J Control Release. 147:24–29.

Ikeda-Matsuo Y, Tanji H, Narumiya S, Sasaki Y. 2011. Inhibition of prostaglandin E2 EP3 receptors improves stroke injury via anti-inflammatory and anti-apoptotic mechanisms. J Neuroimmunol. 238:34–43.

Jefferson SC, Tester NJ, Howland DR. 2011. Chondroitinase ABC promotes recovery of adaptive limb movements and enhances axonal growth caudal to a spinal hemisection. J Neurosci. 31:5710–5720.

Jones TA, Schallert T. 1992. Subcortical deterioration after cortical damage: effects of diazepam and relation to recovery of function. Behav Brain Res. 51:1–13.

Kaneko T, Fujiyama F. 2002. Complementary distribution of vesicular glutamate transporters in the central nervous system. Neurosci Res. 42:243–250.

Kilic E, ElAli A, Kilic U, Guo Z, Ugur M, Uslu U, Bassetti CL, Schwab ME, Hermann DM. 2010. Role of nogo-A in neuronal survival in the reperfused ischemic brain. J Cereb Blood Flow Metab. 30:969–984.

Krasovsky T, Levin MF. 2010. Review: toward a better understanding of coordination in healthy and poststroke gait. Neurorehabil Neural Repair. 24:213–224.

Lee H, McKeon RJ, Bellamkonda RV. 2010. Sustained delivery of thermostabilized ChABC enhances axonal sprouting and functional recovery after spinal cord injury. Proc Natl Acad Sci U S A. 107:3340–3345.

Lee JK, Kim JE, Sivula M, Strittmatter SM. 2004. Nogo receptor antagonism promotes stroke recovery by enhancing axonal plasticity. J Neurosci. 24:6209–6217.

Li HP, Komuta Y, Kimura-Kuroda J, van Kuppevelt TH, Kawano H. 2013. Roles of chondroitin sulfate and dermatan sulfate in the formation of a lesion scar and axonal regeneration after traumatic injury of the mouse brain. J Neurotrauma. 30:413–425.

Mainardi M, Scabia G, Vottari T, Santini F, Pinchera A, Maffei L, Pizzorusso T, Maffei M. 2010. A sensitive period for environmental regulation of eating behavior and leptin sensitivity. Proc Natl Acad Sci U S A. 107:16673–8.

McKeon RJ, Hoke A, Silver J. 1995. Injury-induced proteoglycans inhibit the potential for laminin-mediated axon growth on astrocytic scars. Exp Neurol. 136:32–43.

Nakamura M, Nakano K, Morita S, Nakashima T, Oohira A, Miyata S. 2009. Expression of chondroitin sulfate proteoglycans in barrel field of mouse and rat somatosensory cortex. Brain Res. 1252:117–129.

Nudo RJ. 2011. Neural bases of recovery after brain injury. J Commun Disord. 44:515–520.

Papadopoulos CM, Tsai SY, Cheatwood JL, Bollnow MR, Kolb BE, Schwab ME, Kartje GL 2006. Dendritic plasticity in the adult rat following middle cerebral artery occlusion and nogo-a neutralization. Cereb Cortex. 16:529–536.

Pizzorusso T, Medini P, Berardi N, Chierzi S, Fawcett JW, Maffei L. 2002. Reactivation of ocular dominance plasticity in the adult visual cortex. Science. 298:1248–1251.

Pizzorusso T, Medini P, Landi S, Baldini S, Berardi N, Maffei L. 2006. Structural and functional recovery from early monocular deprivation in adult rats. Proc Natl Acad Sci U S A. 103:8517–8522.

Romberg C, Yang S, Melani R, Andrews MR, Horner AE, Spillantini MG, Bussey TJ, Fawcett JW, Pizzorusso T, Saksida LM. 2013. Depletion of perineuronal nets enhances recognition memory and long-term depression in the perirhinal cortex. J Neurosci. 33:7057–7065.

Schwab ME. 2010. How hard is the CNS hardware? Nat Neurosci. 13:1444–1446.

Shen Y, Tenney AP, Busch SA, Horn KP, Cuascut FX, Liu K, He Z, Silver J, Flanagan JG. 2009. PTPsigma is a receptor for chondroitin sulfate proteoglycan, an inhibitor of neural regeneration. Science. 326:592–596.

Smith JM, Lunga P, Story D, Harris N, Le Belle J, James MF, Pickard JD, Fawcett JW. 2007. Inosine promotes recovery of skilled motor function in a model of focal brain injury. Brain. 130:915–925.

Soleman S, Yip PK, Duricki DA, Moon LD. 2012. Delayed treatment with chondroitinase ABC promotes sensorimotor recovery and plasticity after stroke in aged rats. Brain. 135:1210–1223.

Starkey ML, Bleul C, Maier IC, Schwab ME. 2011. Rehabilitative training following unilateral pyramidotomy in adult rats improves forelimb function in a non-task-specific way. Exp Neurol. 232:81–89.

Steinle B, Corbaley J. 2011. Rehabilitation of stroke: a new horizon. Mo Med. 108:284–288.

Tester NJ, Plaas AH, Howland DR. 2007. Effect of body temperature on chondroitinase ABC's ability to cleave chondroitin sulfate glycosaminoglycans. J Neurosci Res. 85:1110–1118.

Tom VJ, Kadakia R, Santi L, Houle JD. 2009. Administration of chondroitinase ABC rostral or caudal to a spinal cord injury site promotes anatomical but not functional plasticity. J Neurotrauma. 26:2323–2333.

Tsai SY, Papadopoulos CM, Schwab ME, Kartje GL. 2011. Delayed anti-nogo-a therapy improves function after chronic stroke in adult rats. Stroke. 42:186–190.

Vo T, Carulli D, Ehlert EM, Kwok JC, Dick G, Mecollari V, Moloney EB, Neufeld G, de Winter F, Fawcett JW et al. 2013. The chemorepulsive axon guidance protein semaphorin3A is a constituent of perineuronal nets in the adult rodent brain. Mol Cell Neurosci. 56C:186–200.

Wang W, Ye SD, Zhou KQ, Wu LM, Huang YN. 2012. High doses of salicylate and aspirin are inhibitory on acid-sensing ion channels and protective against acidosis-induced neuronal injury in the rat cortical neuron. J Neurosci Res. 90:267–277.

Whishaw IQ. 2000. Loss of the innate cortical engram for action patterns used in skilled reaching and the development of behavioral compensation following motor cortex lesions in the rat. Neuropharmacology. 39:788–805.

Whishaw IQ, Pellis SM. 1990. The structure of skilled forelimb reaching in the rat: a proximally driven movement with a single distal rotatory component. Behav Brain Res. 41:49–59.

Whishaw IQ, Pellis SM, Gorny BP, Pellis VC. 1991. The impairments in reaching and the movements of compensation in rats with motor cortex lesions: an endpoint, videorecording, and movement notation analysis. Behav Brain Res. 42:77–91.

Whishaw IQ, Piecharka DM, Zeeb F, Stein DG. 2004. Unilateral frontal lobe contusion and forelimb function: chronic quantitative and qualitative impairments in reflexive and skilled forelimb movements in rats. J Neurotrauma. 21:1584–1600.

Zai L, Ferrari C, Dice C, Subbaiah S, Havton LA, Coppola G, Geschwind D, Irwin N, Huebner E, Strittmatter SM et al. 2011. Inosine augments the effects of a nogo receptor blocker and of environmental enrichment to restore skilled forelimb use after stroke. J Neurosci. 31:5977–5988.

Zhao RR, Muir EM, Alves JN, Rickman H, Allan AY, Kwok JC, Roet KC, Verhaagen J, Schneider BL, Bensadoun JC et al. 2011. Lentiviral vectors express chondroitinase ABC in cortical projections and promote sprouting of injured corticospinal axons. J Neurosci Methods. 201:228–238.