p75NTR regulates brain mononuclear cell function and neuronal structure in Toxoplasma infection-induced neuroinflammation

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Neurotrophins mediate neuronal growth, differentiation, and survival via tropomyosin receptor kinase (Trk) or p75 neurotrophin receptor (p75NTR) signaling. The p75NTR is not exclusively expressed by neurons but also by certain immune cells, implying a role for neurotrophin signaling in the immune system. In this study, we investigated the effect of p75NTR on innate immune cell behavior and on neuronal morphology upon chronic Toxoplasma gondii (T. gondii) infection-induced neuroinflammation. Characterization of the immune cells in the periphery and central nervous system (CNS) revealed that innate immune cell subsets in the brain upregulated p75NTR upon infection in wild-type mice. Although cell recruitment and phagocytic capacity of p75NTRexonIV knockout (p75−/−) mice were not impaired, the activation status of resident microglia and recruited myeloid cell subsets was altered. Importantly, recruited mononuclear cells in brains of infected p75−/− mice upregulated the production of the cytokines interleukin (IL)-10, IL-6 as well as IL-1α. Protein levels of proBDNF, known to negatively influence neuronal morphology by binding p75NTR, were highly increased upon chronic infection in the brain of wild-type and p75−/− mice. Moreover, upon infection the activated immune cells contributed to the proBDNF release. Notably, the neuroinflammation-induced changes in spine density were rescued in the p75−/− mice. In conclusion, these findings indicate that neurotrophin signaling via the p75NTR affects innate immune cell behavior, thus, influencing the structural plasticity of neurons under inflammatory conditions.

KEYWORDS
brain mononuclear cells, chronic Toxoplasma gondii infection, dendritic morphology, microglia, neuroinflammation, neurotrophins, p75 neurotrophin receptor, pro-neurotrophins

1 INTRODUCTION

Neuronal growth, differentiation, survival, and function are orchestrated in the central nervous system (CNS) by neurotrophins—secreted proteins involved in shaping neuronal connectivity and in repairing the CNS after injury (Kaplan & Miller, 2000). Neurotrophins are initially synthesized as pro-neurotrophins and then cleaved to produce mature proteins. The family of mature neurotrophins includes nerve growth factor (NGF), brain...
derived neurotrophic factor (BDNF), Neurotrophin-3 (NT-3), and Neurotrophin-4/5 (NT-4/5). They signal through the tropomyosin receptor kinase (Trk) receptors TrkA, TrkB, TrkC, and the p75 neurotrophin receptor (p75NTR) being a member of the tumor necrosis factor (TNF) receptor family. Neurotrophins are critical mediators of neuronal survival (Chao, 2003). They regulate both the architecture and plasticity of mature CNS neurons and are necessary for learning processes (Zagrebelsky & Korte, 2014). Recently, also the role and function of neurotrophin precursors have been explored with more detail suggesting their important role in injury and disease (Ibáñez & Simi, 2012). Several neurotrophin precursors have been explored with more detail suggesting (Zagrebelsky & Korte, 2014). Notably, mature neurotrophins can also influence the immune system, however, little is known about the specific functions in this context. They have been shown to modulate monocyte chemotaxis, to participate in tissue-healing mechanism, suppression of nitric oxide release by microglia (Samah, Porcheray, & Gras, 2008) and to enhance macrophage phagocytic activity (Hashimoto et al., 2005). BDNF produced by microglia cells and T cells (Krusse, Cetin, Chan, Gold, & Lüder, 2007) was able to modulate monocyte and macrophage function, for example, by regulating their differentiation towards tissue macrophages. Vega et al. detected that NGF and BDNF influenced cytokine expression in peripheral blood mononuclear cells (Vega, Garcia-Suarez, Hannestad, Perez-Perez, & Germana, 2003). Furthermore, the conditional depletions of hippocampal BDNF decreased the number of cortical microglia (Braun, Kalinin, & Feinstein, 2017). In this context, p75NTR is of special interest. It is expressed by neurons and also by certain types of immune cells, thus, possibly mediating the interaction between cells of the CNS and the innate immune system under pathological conditions (Meeker & Williams, 2014). However, the role of p75NTR signaling in neuro-immuno-interactions during neuroinflammation has still not been fully elucidated.

The intracranial parasite Toxoplasma gondii (T. gondii) infects a wide range of hosts worldwide (Hill, Chirukandoth, & Dubey, 2005; Montoya & Liesenfeld, 2004; Munoz, Liesenfeld, & Heimesaat, 2011). Being able to infect all nucleated cells, T. gondii spreads throughout the host’s body during the acute phase of infection. Eventually, the parasites reach immune-privileged regions such as the CNS. During the chronic phase of infection cysts are predominantly formed in infected neurons enabling the parasites to persist lifelong within the host (Dubey, 1998; Wilson & Hunter, 2004). Chronic infection with T. gondii is followed by a Th1 type inflammatory response and cell recruitment to the brain (Biswa et al., 2017; Blanchard, Dunay, & Schlüter, 2015).

Basal neuroinflammation is associated with the latent infection (Hermes et al., 2008). Behavioral changes were reported in T. gondii-infected mice, however, the underlying mechanisms are not fully understood (Parlog et al., 2014; Parlog, Schlüter, & Dunay, 2015; Vyas, Kim, Giaconmini, Boothroyd, & Sapolsky, 2007). Several factors may be responsible for these alterations such as the specific neuroinflammatory milieu, changes in the neurotransmitter balance affecting neuronal connectivity, or possibly the preference of cysts to specific neuron subtypes. Over the past decades, chronic Toxoplasma infection-induced neuroinflammation has been studied extensively and can, therefore, be employed as a suitable model to investigate immune cell dynamics in the CNS and the interaction between immune cells and neurons.

In a previous study, our research group could highlight the distinct alterations in cortical and hippocampal neurons of mice chronically infected with T. gondii (Parlog et al., 2014) showing reduced neuronal connectivity, decreased dendritic complexity, and changes in the synaptic protein expression upon infection. Recently, we further revealed the alterations in the synaptic protein composition induced by chronic T. gondii infection (Lang et al., 2018). Moreover, our group was able to show the crucial involvement in host defense by recruited myeloid-derived mononuclear cell subsets to the brain upon chronic toxoplasmosis in addition to tissue resident microglia (Biswa et al., 2015; Möhle et al., 2016; Möhle, Parlog, Pahnke, & Dunay, 2014).

In this study, we set out to investigate the impact of p75NTR signaling on the function of immune cells during cerebral toxoplasmosis and to elucidate the role of p75NTR in mediating the changes in neuronal morphology upon Toxoplasma-induced neuroinflammation. Flow cytometric analysis revealed the upregulation of p75NTR surface expression by innate immune cells in the periphery and CNS of wild-type (WT) mice. Although cell recruitment and phagocytic capacity of p75NTRexonIV knockout (p75NTR−/−) mice were not altered, the activation status of innate immune cells was modified as indicated by differences in their phenotypic properties. Accordingly, cytokine production by recruited myeloid cells in brains of T. gondii-infected p75NTR−/− mice was changed as the anti-inflammatory IL-10 and proinflammatory IL-6 and IL-1α and were upregulated. Applying Western blot analysis to whole brain lysate we could show a strong increase of proBDNF protein levels in infected WT and p75NTR−/− animals. Finally, changes in spine density were rescued in infected p75NTR−/− mice when compared to WT controls. Taken together, these findings indicate that proBDNF-mediated signaling via the p75NTR affects immune cell activation and neuronal morphology in the brain upon inflammation.

2 | MATERIALS AND METHODS

2.1 | Animals

The experiments were performed using age-matched 2- to 4-month-old female wild-type (WT), Thy1-eGFP-M transgenic (Feng et al., 2000) or p75NTRexonIV knockout (p75NTR−/−) C57BL/6 mice. The p75NTR−/− mice were generated in the laboratory of Prof. Georg Dechant (University of Innsbruck, Austria) and were genotyped as previously described (von Schack et al., 2001). C57BL/6 WT mice were obtained from Janvier (Cedex, France). Thy1-eGFP-M transgenic mice and p75NTR−/− mice and littermate controls were obtained from animal facility at the TU Braunschweig. All animal care was in accordance with institutional guidelines. Food and water were available ad libitum and experiments were performed in accordance to National Institutes of Health (NIH) Guidelines for the Care and Use of Laboratory Animals with local government approval.
2.2 | Infection

For the infection of mice with *T. gondii*, cysts of the type II strain ME49 were first collected from brains of female NMRI mice infected with *T. gondii* cysts 10–12 months earlier as described before (Möhl et al., 2016). Each animal was infected with a dose of 2 cysts intraperitoneally while naive control animals were mock infected with sterile Phosphate buffered saline (PBS). Mice were sacrificed 4 weeks post infection (p.i.).

2.3 | Tissue preparation and analysis of neuronal morphology

All mice were transcardially perfused with 4% Paraformaldehyde (PFA), the brain was postfixed and the hemispheres were sliced at 300 μm (for reconstruction of the dendrites) or 150 μm (for spine density analysis) with a vibratome (VT 1200S; Leica) and mounted with an anti-fading mounting medium. To analyze dendritic architecture, hippocampal CA1 neurons were imaged using a 20x (NA 0.8) objective for acquiring z-stacks (step size 1 μm). Only isolated, not overlapping eGFP expressing hippocampal CA1 neurons were chosen. Morphological analysis was performed using Neurolucida® (Microbrightfield Bioscience) to trace the dendritic tree and perform a Sholl analysis of dendritic complexity (Sholl, 1953). To analyze dendritic spine density, z-stacks of mid-apical dendrites from hippocampal CA1 and cortical layer V/VI pyramidal neurons were acquired using a 40x oil objective (NA 1.3) with z-steps of 0.5 μm. The number of spines and the dendritic length was analyzed on three-dimensional images using ImageJ software using the multipoint tool and the segmented line respectively. The experimenter was blind to the genotype and treatment throughout all phases of the experiment and analysis.

2.4 | Immunohistochemistry

After fixation by perfusion, as above, the hippocampi were dissected, postfixed in 4% PFA and subsequently cryoprotected. The hippocampi were cryo-sectioned at 30 μm and after a blocking and permeabilization step the sections were incubated overnight with anti-iba1 primary antibodies (dilution of 1:1,000; Synaptic Systems, #234003), then with a Cy3-conjugated goat anti-rabbit IgG (1:500, Dianova) and mounted using an anti-fading mounting medium. For analyzing changes in microglia density z-stacks of 3 to 5 regions of interest (ROIs) per mouse were imaged using a 20x objective (NA 0.8) at a z-step of 1 μm. The number of microglia was counted using the multipoint tool of ImageJ and is expressed as number of cells per mm³ of tissue. For analyzing the enwrapping of microglia around neuronal cell bodies, confocal images of at least 10 randomly selected eGFP-expressing CA1 pyramidal neurons were analyzed with a BX61WI FluoView 1000 (FV1000) Olympus confocal microscope. Stacks were acquired using a 40x oil objective (NA 1.3), z-steps of 1 μm. The neuron profile as well as the length of Iba1 positive microglia processes contacting the neuronal cell body were measured using the freehand tool from ImageJ for each z-plane and summed to obtain one value of overlap per each neuron (expressed in % of the neuronal perimeter).

2.5 | Cell isolation

Blood of mice was collected and prepared as described before (Biswas et al., 2015). Brains were collected from mice previously perfused intra-cardially with sterile PBS. Obtained samples were homogenized in a buffer containing HBSS (Gibco), 1M HEPES (pH 7.3, Thermo Fisher) and 45% glucose before sieving through a 70 μm cell strainer. The homogenate was fractioned on a discontinuous 30–70% Percoll gradient (GE Healthcare) and collected cells were washed in PBS and used subsequently for further experiments. To isolate peripheral immune cells, spleens of mice were passed through a 40 μm cell strainer followed by a lysis of erythrocytes in RBC lysis Buffer (eBioscience). Cells were pelleted and stored in –80 °C until further use.

2.6 | Flow cytometric analysis

For flow cytometric analysis of cell phenotypes, isolated cells were first incubated with Zombie NIR™ or Zombie Violet™ fixable dye (Biolegend) for live/dead discrimination and with anti-FcγIII/II receptor antibody (clone 93) to prevent unspecific binding of antibodies. Cells were further stained with fluorochrome-conjugated antibodies against cell surface markers in FACS buffer containing 2% fetal bovine serum and 0.1% sodium azide. CD45 (30-F11), CD11b (M1/70), Ly6C (HK1.4), MHCII I-A/I-E (M5/114.15.2), CD4 (GK1.5), CD8 (53–6.7), CD11c (N418), CD80 (16-10A1), and F4/80 (BM8) were all purchased from eBioscience. Ly6G (1A8), CD3 (17A2), and CD25 (3C7) were purchased from Biolegend and p75NTR (MLR2) was bought from Thermo Fisher. Fluorescence Minus One (FMO) controls were used to determine the level of autofluorescence.

For flow cytometric analysis of intracellular cytokines and proteins, single cell suspensions of brains from infected animals were re-stimulated with 0.21 μg/μl Toxoplasma lysate antigen in a 96-well plate (5 × 10⁵ cell/well) for 6 hr. After 2 hr of incubation, Brefeldin A (10 μg/ml, GolgiPlug, BD Biosciences) and Monensin (10 μg/ml GolgiStop, BD Biosciences) were added. Thereafter, cells were incubated with ZOMBIE NIR™ or Violet™ fixable dye and anti-FcγIII/II receptor antibody. Next, surface staining was performed on the cells with antibodies for CD45 (30-F11), CD11b (M1/70), Ly6C (HK1.4), Ly6G (1A8), CD3 (17A2), CD4 (GK1.5), CD8 (53–6.7) in FACS buffer. Cells were fixed in 4% paraformaldehyde and then permeabilized using Permeabilization Buffer (Biolegend). Intracellular cytokines and proteins were stained with fluorochrome-conjugated antibodies: IL-1α (ALF-161), IL-1β (NJ TEN3), IL-6 (MP5-20F3), IL-10 (JESS-16E3), IL-12 (C17.8), purchased from eBiosciences); iNOS (BD Biosciences, 610330) in Permeabilization Buffer. Matched isotype controls were used to assess the level of unspecific binding.

A minimum of 100,000 cells were acquired using the BD FACS Canto II and Thermo Fisher Attune NxT flow cytometer. Obtained data were analyzed using FlowJo software (Version 10 Tree Star).

2.7 | Ex vivo phagocytosis assay

Isolated cells from brains of infected mice were transferred into wells of a 96-well plate (4 × 10⁵ cells/well) and incubated at 37 °C for 1 hr. Negative controls were set up by treatment of cells with cytochalasin D
and were considered significant, with the software (Version 10 Tree Star).

2.8 | In vitro migration assay

Isolated blood cells were washed in RPMI (Gibco) medium containing 10 mM HEPES (Sigma) and 0.1% bovine serum albumin (pH 7.4) before being transferred into a Transwell insert (3 x 10^5 cells/well. Costar Corning) previously coated with recombinant human Fc-tagged murine VCAM (5 μg/ml, R&D systems) in PBS. The inserts were then placed on a 24-well plate filled with RPMI medium (10 mM HEPES, 0.1% BSA, pH 7.4), with or without stimulation of mCCL2 (20 ng/ml, R&D systems). After 2 hr incubation at 37 °C and 5% CO₂, cells were isolated from the lower compartment and counted under a light microscope.

2.9 | Western blot analysis

For Western blot analysis, proteins were either isolated from whole mouse brains or spleenocytes obtained previously. In the case of brain samples, collected tissue was immediately snap frozen in liquid nitrogen and stored in −80 °C until further preparation. In all cases, samples were lysed on ice in RIPA lysis buffer containing protease inhibitors, 50 mM Tris/HCl (pH 7.4); 150 mM NaCl; 1% IGEPAL CA-630; 0.25% Na-deoxycholate; 1 mM NaF. Proteins were separated by SDS-polyacrylamide gel electrophoresis (12.5%) and transferred to nitrocellulose. Membranes were incubated overnight at 4 °C in 1:500 dilution of anti-β-Tubulin-III antibody (Sigma, #T8660) or, for face expression of the neurotrophin receptor (Ly6C hi monocytes: 21.4 ± 1.3%; upon infection, the amount of microglia and recruited myeloid cells expressing p75NTR increased (microglia: 21.4 ± 1.3% vs. 94.2 ± 1.2%; myeloid cells: 37.3 ± 5.3% vs. 85.0 ± 1.3%; p < .04). Among the myeloid cell subsets, Ly6Chi monocytes and Ly6Cint brain DCs displayed similar surface expression of the neurotrophin receptor (Ly6Cint monocytes: 20.3 ± 12.8% vs. 86.8 ± 1.2%; p < .04 / Ly6Cint brain DCs: 47.9 ± 11.4% vs. 87.1 ± 1.0%; p < .04) and the subset of Ly6Cint macrophages increased their p75NTR surface expression the greatest (47.4 ± 2.8% vs. 94.7 ± 1.3%; p < .04) but the receptor was not detected on recruited lymphocytes (1.8 ± 0.6% vs. 6.2 ± 0.8%; p < .04). When comparing the median fluorescence intensity (MFI) of the p75NTR expression level between microglia and recruited myeloid cells in the CNS under steady state condition (data not shown) the corresponding flow cytometric histograms are not representative (Figure 1d). In control brains a small proportion of microglia cells expressed p75NTR (21.4 ± 1.3%). Upon infection, the amount of microglia and recruited myeloid cells expressing p75NTR increased (microglia: 21.4 ± 1.3% vs. 94.2 ± 1.2%; myeloid cells: 37.3 ± 5.3% vs. 85.0 ± 1.3%; p < .04). Among the myeloid cell subsets, Ly6Chi monocytes and Ly6Cint brain DCs displayed similar surface expression of the neurotrophin receptor (Ly6Cint monocytes: 20.3 ± 12.8% vs. 86.8 ± 1.2%; p < .04 / Ly6Cint brain DCs: 47.9 ± 11.4% vs. 87.1 ± 1.0%; p < .04) and the subset of Ly6Cint macrophages increased their p75NTR surface expression the greatest (47.4 ± 2.8% vs. 94.7 ± 1.3%; p < .04) but the receptor was not detected on recruited lymphocytes (1.8 ± 0.6% vs. 6.2 ± 0.8%; p < .04). When comparing the median fluorescence intensity (MFI) of the p75NTR expression level between microglia and recruited myeloid cells in the CNS we could show that expression of p75NTR was similar between peripheral innate immune cells and brain resident immune cells (Figure 1e). Taken together, our results indicate the upregulation of p75NTR by innate immune cells in the blood and CNS upon T. gondii infection.

3.2 | Knockout of p75NTR does not affect cell recruitment during T. gondii infection

To elucidate the effect of p75NTR on the behavior of immune cells we utilized p75NTRexonIV knockout (p75+/−) mice. Due to the strong expression of the neurotrophin receptor on peripheral blood mononuclear cells we first aimed to analyze the potential effect of p75NTR on immune cell trafficking. Thus, we infected p75+/− and WT mice with T. gondii and analyzed the composition of immune cells in the hippocampus and cortex by flow cytometry (Figure 2a–c). When compared to WT animals, no difference was observed in the composition of brain resident microglia cells in cortex (WT: 22.5 ± 2.3% vs. p75+/−:...
Flow cytometric analysis of p75\textsubscript{NTR} surface expression on immune cells upon infection with \textit{T. gondii}. Cells were isolated from blood and brains of noninfected and \textit{T. gondii}-infected mice then analyzed by flow cytometry. (a, a') Representative gating strategy for myeloid cells from blood of animals infected with \textit{T. gondii}. Cells were selected based on the forward-scatter/side-scatter plot (FSC/SSC), dead cells were excluded and only single cells were selected for further analysis (not shown). (a) Neutrophil granulocytes (CD11b\textsuperscript{+}Ly6G\textsuperscript{+}) in the blood were excluded (upper gate) and monocytes remained as CD11b\textsuperscript{+}Ly6G\textsuperscript{−} cells (lower gate). (a') Monocytes were further divided with respect to the surface expression of Ly6C into CD11b\textsuperscript{+}Ly6C\textsuperscript{hi} inflammatory monocytes (upper gate), CD11b\textsuperscript{+}Ly6C\textsuperscript{int} blood monocytes (middle gate) and CD11b\textsuperscript{+}Ly6C\textsuperscript{low} resident macrophages (bottom gate). (b, b') Representative gating strategy for immune cells isolated from the brain of animals infected with \textit{T. gondii}. After FSC/SSC gating, dead cells were excluded and only single cells were selected for further analysis (not shown). (b) Based on the expression of CD45 and CD11b, CD45\textsuperscript{+}CD11b\textsuperscript{lo} lymphocytes (upper left gate), CD45\textsuperscript{+}CD11b\textsuperscript{hi} myeloid cells (upper right gate)
and CD45<sup>int</sup>CD11b<sup>int</sup> microglia (lower right gate) were identified. Next, neutrophil granulocytes were excluded from the myeloid cell population by their expression of CD11b and Ly6G (not shown). (b) Myeloid cells were further divided into CD11b<sup>Ly6C<sup>m</sup>+</sup> inflammatory monocytes (upper gate), CD11b<sup>Ly6C<sup>int</sup></sup> monocyte-derived DCs (middle gate) and CD11b<sup>Ly6C<sup>lo</sup></sup> monocyte-derived macrophages (bottom gate; Biswas et al., 2015). The lymphocyte population was subdivided into CD3<sup>+</sup>CD4<sup>+</sup> T cells and CD3<sup>CD8<sup>+</sup></sup> T cells (data not shown). Surface expression of p75<sup>NTR</sup> was analyzed on blood cells (c) and brain cells (d) of noninfected mice and on blood cells (c') and brain cells (d') of animals infected with <i>T. gondii</i>. Cell populations were selected as described above and histograms show the representative expression level of p75<sup>NTR</sup> by the cell population in the respective population. (e) Flow cytometric analysis of p75<sup>NTR</sup> surface expression on cells isolated from brains of naive and <i>T. gondii</i>-infected mice. Cell populations were selected as described above and bar charts display the median fluorescence intensity (MFI; ±SEM). Differences between groups were analyzed by one-way ANOVA with post hoc Tukey's HSD test (*p < .05; ***p < .001; ****p < .0001).

3.3 | Phenotypic characterization of innate immune cells in the CNS of p75<sup>−/−</sup> mice upon <i>T. gondii</i>-induced neuroinflammation

Although no change was detected in the composition of immune cells in the brains of p75<sup>−/−</sup> mice, we characterized phenotype and activation status of the cell subsets upon <i>T. gondii</i>-induced neuroinflammation. Flow cytometric analysis was performed to assess the expression level of distinct surface markers by immune cell subsets isolated from infected brains of WT and p75<sup>−/−</sup> mice. When compared to WT, brain resident microglia from p75<sup>−/−</sup> animals showed a significantly reduced MFI for Major Histocompatibility complex (MHC) class II surface expression (p < .02), CD11c (p < .01) and co-stimulatory CD80 (p < .03), as indicated in Figure 3a–d. The histograms show that the subsets expressing the indicated markers were similar between the experimental groups for MHC class II (WT: 95.8 ± 0.5% vs. p75<sup>−/−</sup>: 98.6 ± 0.5%; p < .09) and CD11c (WT: 89.9 ± 2.9% vs. p75<sup>−/−</sup>: 91.4 ± 1.1%; p < .86). Yet CD80 was found to be expressed by fewer cells in p75<sup>−/−</sup> samples (WT: 94.5 ± 0.4% vs. p75<sup>−/−</sup>: 88.6 ± 1.2%; p < .02; Figure 3a–d). In contrast to microglia, Ly6C<sup>hi</sup> monocytes showed no differences between p75<sup>−/−</sup> and WT animals with respect to MFI values or expressing cell fractions for the surface markers MHC II, CD11c, F4/80, and CD80 (Figure 3e–h). As we reported previously, peripheral Ly6C<sup>hi</sup> inflammatory monocytes enter the parenchyma and differentiate into Ly6C<sup>int</sup> brain dendritic cells (DCs) and
Ly6C\textsuperscript{low} macrophages (Biswa et al., 2015). Interestingly, Ly6C\textsuperscript{int} brain DCs in p75\textsuperscript{−/−} animals displayed a significant reduction in the MFI of CD11c (\(p < .002\)) although the fraction of expressing cells was not changed (WT: \(83.9 \pm 0.1\%\) vs. p75\textsuperscript{−/−}: \(78.0 \pm 1.4\%\); \(p < .1\); Figure 4c). In accordance to this, knockout of p75\textsuperscript{NTR} also resulted in a diminished MFI for CD11c (\(p < .03\)) and F4/80 (\(p < .001\)) surface expression levels on Ly6C\textsuperscript{low} macrophages (Figure 4e–h) but not in cells positively expressing the respective surface receptors (CD11c: \(p > .1\); Figure 4d).
WT: 97.5 ± 0.3% vs. p75−/−: 92.7 ± 1.0%; p < .1 / F4/80: WT: 97.9 ± 0.4% vs. p75−/−: 86.6 ± 0.7%; p < .24). We further investigated the CD4+ and CD8+ T cell lymphocyte populations and quantified their activation status in infected brains of WT and p75−/− animals by flow cytometric analysis (Supporting Information 1A–C).

The frequencies of CD4+ T cells (WT: 50.8 ± 1.2% vs. p75−/−: 52.0 ± 2.3%; p < .74) and CD8+ T cells (WT: 46.4 ± 1.3% vs. p75−/−: 45.1 ± 2.2%; p < .86) in T. gondii-infected brains were not differing.

FIGURE 4 Phenotypic analysis of activated Ly6Cint brain DCs and Ly6Clow macrophages from brains of T. gondii-infected WT and p75−/− mice. The surface expression of activation markers on cells isolated from infected brains of WT and p75−/− mice was determined by flow cytometric analysis. Cell populations were selected as described in Figure 1b, b’. (a–h) Histograms show the representative expression level of the surface marker by cells (WT mice tinted, p75−/− mice without tint) in comparison to the corresponding FMO control and bars mark cells positively expressing the surface marker. Numbers above bars represent the percentage of cells (±SEM) in the respective population. (a’–h’) Bar charts display the MFI (±SEM) for the specific surface marker. Differences between groups were analyzed by Mann–Whitney test (* p < .05, ** p < .01, *** p < .001)
between p75−/− and WT mice. Interestingly, significantly less CD4+ T cells in p75−/− mice were expressing the IL-2 receptor alpha chain CD25 (WT: 13.6 ± 0.2% vs. p75−/−: 11.4 ± 0.1%; p < .03) which also resulted in a significantly lower MFI (p < .03). CD8+ T cells of both experimental groups expressed CD25 equally (WT: 12.2 ± 1.2% vs. p75−/−: 9.9 ± 0.8%; p < .34) and did not show significant differences in MFI. In conclusion, the phenotypic analysis of brain resident and recruited peripheral immune cells during cerebral toxoplasmosis revealed several differences between p75−/− and WT animals implying a modified activation of the immune cells in knockout animals.

3.4 Knockout of p75NTR has no effect on phagocytic capacity but alters intracellular cytokine production by innate immune cells

To further examine whether the function of immune cells in p75−/− mice could also be affected, an ex vivo phagocytosis assay was performed. For that reason, resident, and recruited immune cells from infected brains were isolated and subsequently incubated with FITC-fluorescent latex beads. The MFI of each population in the FITC detection channel was determined by flow cytometry and results were compared between WT and p75−/− mice (Figure 5a). The results reveal, that phagocytic activity of microglia or recruited myeloid cell populations in p75−/− mice and WT cells was not distinct.

Next, the morphological activation of microglia was assessed by analyzing their structural alterations and density. Under steady state conditions, in both WT and p75−/− mice the microglia in the CA1 region of the hippocampus showed the ramified morphology, typical for resting cells (Figure 5b above). Upon T. gondii infection, microglia transformed their morphology to an activated amoeboid form with hypertrophic processes that tightly wrap around the cell bodies and main dendrites of eGFP-positive CA1 pyramidal neurons (Figure 5b below and 5b). We further quantified the overlap between Iba1+ microglial processes and the perimeter of eGFP expressing pyramidal neurons and observed a significant increase upon T. gondii infection (Figure 5c; WT: p < .001; p75−/−: p < .001). The increase in microglia/neuron overlap was not significantly different in p75−/− when compared to WT infected mice (Figure 5c). Finally, microglia density was quantified and showed an equally significant increase in the number of Iba1+ microglia cells in the CA1 region of p75−/− and WT infected mice (Figure 5d; WT p < .001; p75−/− p < .001). Taken together, the results show a strong activation of microglia upon T. gondii infection that does not significantly differ between WT and p75−/− mice.

In the next step, we focused on the flow cytometric analysis of cytokine expression by immune cell populations in brains of T. gondii-infected animals. Upon in vitro re-stimulation with Toxoplasma lystate antigen (TLA) the production of IL-1α, IL-6, and IL-10 by microglia from WT and p75−/− mice did not differ (Figure 6a–d). Interestingly, a significantly higher percentage of Ly6Cint brain DCs reported significantly higher fluorescence intensities for IL-10 (p < .03) and also IL-6 (p < .03) in infected p75−/− animals while the frequency of secreting cells did not differ (Figure 7a–d). We also discovered an increased percentage of Ly6Cint macrophages from p75−/− mice secreting IL-1α (WT: 26.3 ± 1.7% vs. p75−/−: 38.6 ± 3.2%; p < .0004), resulting in significantly higher median fluorescence (p < .03). In addition, significantly elevated MFIs were also detected for IL-6 (p < .03) and IL-10 (p < .3) when compared to WT samples while positively expressing cell fractions were not altered (Figure 7e–h).

Levels of IL-12 and inducible nitric oxide synthase (iNOS) in microglia and recruited mononuclear cells were analyzed upon T. gondii infection (Supporting Information 2A–H). Here no differences were observed in MFI values or cells positively producing these proteins. To address the question whether the altered cytokine milieu in infected brains of p75−/− mice would affect the survival of cells, we performed an apoptosis assay via flow cytometry (Supporting Information 3A, B). While the frequencies of living cells and apoptotic cells did not differ between WT and p75−/− animals, necrotic cells were significantly reduced in KO mice (p < .03).

In summary, we found that knockout of p75NTR leads to a higher secretion of proinflammatory mediators and anti-inflammatory IL-10 by myeloid cell populations but had no effect on brain resident microglia.

3.5 Chronic infection with T. gondii increases proBDNF levels in WT and p75−/− mice

Previously, we reported that infection with T. gondii induces changes in the morphology of noninfected neurons and also leads to modified brain connectivity in rodents (Parlog et al., 2014) possibly explaining the behavioral changes observed in infected rats (Berdoy, Webster, & Macdonald, 2000). With regards to this, related studies have reported a link between changes in neurotrophin levels and the progression of neurodegenerative diseases such as schizophrenia and Alzheimer’s disease (Capsoni, Brandi, Arisi, D’Onofrio, & Cattaneo, 2011; Green, Matheson, Shepherd, Weickert, & Carr, 2011). To obtain more information about possible changes in neurotrophin expression levels within the CNS of WT and p75−/− mice upon the infection with T. gondii we performed Western blot analysis. Isolated proteins from brain lysate of noninfected and infected WT and p75−/− mice were analyzed for NGF, BDNF, and proBDNF levels (Figure 8a–d). Neither infection with T. gondii nor knockout of p75NTR was found to have an effect on NGF or BDNF levels which remained at baseline (NGF: WT control vs. WT inf.: p < .99; p75−/− control vs. p75−/− inf.: p < .74 / BDNF: WT control vs. WT inf.: p < .75; p75−/− control vs. p75−/− inf.: p < .99; Figure 8b, c). Remarkably, proBDNF which was detectable in small quantities in control WT and p75−/− mice increased strongly upon T. gondii infection (WT control vs. WT inf.: p < .0001; p75−/− control vs. p75−/− inf.: p < .0001; Figure 8d). Assuming that this observed upregulation of proBDNF was possibly facilitated by the recruited immune cell populations due to T. gondii infection, we set out to confirm our hypothesis. To this end, peripheral immune cells were isolated from spleens of control and infected WT mice and proBDNF expression was analyzed by Western blot (Figure 8e, f). While protein levels of the proneurotrophin were detectable at lower
FIGURE 5  Ex vivo phagocytosis assay of immune cells isolated from brains of WT and p75<sup>−/−</sup> mice infected with <i>T. gondii</i>. (a) The phagocytic capability of immune cells isolated from <i>T. gondii</i>-infected brains of WT and p75<sup>−/−</sup> mice was assessed ex vivo by a phagocytosis assay. Isolated cells were incubated together with FITC-fluorescent latex beads and analyzed by flow cytometry. Cell populations were selected as described above and Bar charts display the MFI (±SEM) in the FITC detection channel. Differences between groups were analyzed by Mann–Whitney test. (b) The images above show a typical resting Iba1<sup>+</sup> microglia (red) under control conditions for hippocampal CA1 region of WT (left) and p75<sup>−/−</sup> mice (right). Below are typical images of activated Iba1<sup>+</sup> microglia (red) upon chronic <i>T. gondii</i> infection for hippocampal CA1 region of WT (left) and p75<sup>−/−</sup> mice (right). In green are eGFP-labeled CA1 pyramidal neurons. Scale bars are 50 μm. (b') The images show a higher magnification (scale bar is 10 μm) of eGFP<sup>+</sup> CA1 pyramidal cell bodies and Iba1<sup>+</sup> microglia processes under control conditions (above) and chronic <i>T. gondii</i> infection (below) for WT (left) and p75<sup>−/−</sup> mice (right). (c) Bar charts show the quantification for the overlay (in %) between Iba1<sup>+</sup> microglia processes and eGFP expressing cell bodies for WT and p75<sup>−/−</sup> mice under control conditions and upon chronic <i>T. gondii</i> infection. (d) Bar charts show the quantification for Iba1<sup>+</sup> microglia density for WT and p75<sup>−/−</sup> mice under control conditions and chronic <i>T. gondii</i> infection. Differences between groups were analyzed by Student’s <i>T</i>-test. All values are shown as mean ± SEM (*** <i>p</i> < .001).
FIGURE 6  Flow cytometric analysis of intracellular cytokines in microglia and Ly6C\textsuperscript{hi} monocytes from brains of T. gondii-infected WT and p75\textsuperscript{−/−} mice. Isolated cells from brains of T. gondii-infected WT and p75\textsuperscript{−/−} mice were re-stimulated with Toxoplasma lysate antigen in vitro and intracellular proteins were stained for flow cytometric analysis. Cell populations were selected as described above. (a–h) Histograms show the representative intracellular expression level of the molecules by cells (WT mice tinted, p75\textsuperscript{−/−} mice without tint) in comparison to the corresponding isotype control. Bars mark cells positive for the particular protein and numbers above bars show the percentage of cells (±SEM) in the respective population. (a’–h’) Bar charts display the MFI (±SEM) for the respective fluorochrome-conjugated antibody for the particular protein. Differences between groups were analyzed by Mann–Whitney test (*p < .05)
FIGURE 7 Flow cytometric analysis of intracellular cytokines in Ly6C<sup>int</sup> brain DCs and Ly6C<sup>low</sup> macrophages from brains of T. gondii-infected WT and p75<sup>−/−</sup> mice. Isolated cells from brains of T. gondii-infected WT and p75<sup>−/−</sup> mice were re-stimulated with Toxoplasma lysate antigen in vitro and intracellular proteins were stained for flow cytometric analysis. Cell populations were selected as described above. (a–h) Histograms show the representative intracellular expression level of the molecules by cells (WT mice tinted, p75<sup>−/−</sup> mice without tint) in comparison to the corresponding isotype control. Bars mark cells positive for the particular protein and numbers above bars show the percentage of cells (±SEM) in the respective population. (a′–h′) Bar charts display the MFI (±SEM) for the respective fluorochrome-conjugated antibody for the particular protein. Differences between groups were analyzed by Mann–Whitney test (*p < .05)
quantities in control mice, T. gondii infection significantly increased the levels of proBDNF (WT control vs. WT inf.: \( p < .03 \)) supporting our previous findings in brain homogenate. Taken together we could show that protein levels of NGF and BDNF were neither affected by our previous findings in brain homogenate. Taken together we could show that protein levels of NGF and BDNF were neither affected by p75NTR KO nor by T. gondii infection. In contrast, proBDNF levels were found highly increased in the brain and periphery of infected mice.

### 3.6 | Role of p75NTR in mediating the effect of a chronic T. gondii infection on dendritic architecture

Chronic infection with T. gondii was shown to result in a significant reduction in neuronal morphology and connectivity both in the cortex and hippocampus of C57BL/6 mice (Parlog et al., 2014). Interestingly, the p75NTR was reported to specifically mediate negative structural changes at pyramidal neurons (Zagrebelsky et al., 2005) and its expression levels are modulated upon neuroinflammation (Meeker & Williams, 2014). Thus, we addressed whether knocking out p75NTR might rescue neuronal morphology upon T. gondii infection. While at a qualitative level dendritic complexity of CA1 pyramidal neurons is clearly reduced in WT mice upon chronic T. gondii infection (Figure 9a), no obvious differences in dendritic architecture can be observed in infected p75−/− mice (Figure 9a'). Further, Sholl analysis was applied to quantify dendritic complexity relative to the distance from the cell body. When comparing control (open circles) and infected WT mice (black circles) a significantly lower dendritic complexity along the entire length of both the apical (Figure 9b; \( F(1.38) = 4.677; p < .05 \)) but not the basal (Figure 9c) dendritic trees was detected upon T. gondii infection. When p75−/− mice were analyzed no significant difference in dendritic complexity could be observed along the entire length of the apical dendrite (Figure 9b') upon T. gondii infection (black circles) compared to noninfected p75−/− mice (open circles). On the contrary, dendritic complexity for the basal dendrites of CA1 pyramidal neurons of p75−/− mice was significantly lower in the proximal part (Figure 9c'; \( F(1.52) = 4.283; p < .03 \)) during infection (black circles). The analysis of total dendritic complexity confirmed the observations above and showed a slight decrease in WT mice upon T. gondii infection for the apical but not for the basal dendrites (Figure 9b'; c'; Table 1). Interestingly, total dendritic complexity was not significantly decreased for both apical and basal dendrites of infected p75−/− mice when compared to controls (Figure 9b'', c'; Table 1). Taken together these results confirm previous findings showing a significant loss in neuronal complexity in WT mice upon T. gondii infection and indicate that deletion of p75NTR prevents the T. gondii-induced changes in dendritic architecture of CA1 pyramidal neurons. Next, we compared dendritic spine density changes in WT and p75−/− cortical and hippocampal pyramidal neurons upon T. gondii infection. Both for CA1 and for Layer V/VI pyramidal neurons, dendritic spine density was significantly reduced during infection in WT mice (Figure 9d-e'; CA1 apical dendrites \( p < .05 \); CA1 basal \( p < .01 \); LV/VI apical \( p < .01 \); LV/VI basal \( p < .001 \)). In p75−/− mice, dendritic spine density upon T. gondii infection was only slightly, but not significantly lower than in noninfected mice for both compartments of CA1 pyramidal neurons and for the basal dendrites of Layer V/VI pyramidal neurons (Figure 9d-e'; Table 1). The only exceptions were the LV/VI apical dendrites showing a significantly lower spine density.
density than controls upon infection (Figure 9e; p < .05). For the CA1 basal dendrites dendritic spine density was significantly higher for infected p75−/− mice versus infected WT mice (Figure 9d; Table 1: CA1 basal p < .05). Thus, deletion of p75NTR results in a complete rescue of the decrease in dendritic spine density induced by T. gondii infection for the CA1 pyramidal neurons and a partial one for Layer V/VI pyramidal neurons.

4 | DISCUSSION

We recently detected significant alterations in dendritic complexity and dendritic spine density in CNS principal neurons upon cerebral toxoplasmosis (Parlog et al., 2014). In addition, Western blot analysis revealed decreased levels of the presynaptic protein Synaptophysin and the postsynaptic protein PSD-95 indicating a significant modification of brain connectivity upon T. gondii infection (Parlog et al., 2014). Moreover, our results indicate distinct modifications in the synaptic protein composition (Lang et al., 2018). We previously reported that the chronic infection causes activation of resident microglia and recruitment of mononuclear immune cell subsets to the CNS (Biswas et al., 2015, 2017; Möhle et al., 2016). Thus, we hypothesized that activated immune cells possibly interact with neurons upon infection and modify their morphology and function. However, the molecular and cellular mechanisms mediating such interaction remained unexplored (Parlog et al., 2015). Neurotrophin signaling has been shown to modulate the immune system activity at different levels (Minnone, de Benedetti, & Bracci-Laudiero, 2017; Vega et al., 2003). Therefore, we investigated the role of p75NTR signaling in modulating neuronal architecture and immune cell function in the CNS. We showed that p75NTR influences immune cell activation, function, and cytokine production possibly contributing to the rescue of neuronal structure. Moreover, we revealed that infection-induced decrease in dendritic complexity observed upon T. gondii infection could be rescued by p75NTR knockout.

In addition to neurons, the expression of p75NTR was also detected on a variety of immune cells such as B cells and peripheral mononuclear blood cells (Morgan, Thorpe, Marchetti, & Perez-Polo, 1989). Based on those previous observations, we aimed at investigating whether p75NTR expression is altered on peripheral blood mononuclear cell subsets during T. gondii infection. Our results already showed a prominent expression of p75NTR on mononuclear cells in the blood of control mice under steady state conditions. Infection with T. gondii led to an increased receptor expression that was found on Ly6C+ inflammatory monocytes and Ly6C− resident macrophages. These results are in line with results by Choi and Friedman (2009) who reported an increase of p75NTR expression in astrocytes and neurons as a response to high levels of IL-1β and TNF. Noteworthy, these cytokines have also been shown to be important mediators in the course of T. gondii infection (Chang, Grau, & Pechère, 1990; Dimier & Bout, 1993; Schlüter et al., 1999; Yap, Scharton-Kersten, Charest, & Sher, 1998).

Next, we examined p75NTR expression by resident and recruited immune cells in the CNS upon infection-induced neuroinflammation. While lymphocytes did not express this receptor, resident microglia cells and myeloid-derived mononuclear cell subsets upregulated p75NTR. Importantly, Ly6C− macrophages revealed the most
prominent upregulation of p75NTR suggesting a potential effect on their function.

Previously we have described the crucial involvement of recruited peripheral myeloid cells in host defense against T. gondii infection (Dunay et al., 2008). In the murine model of cerebral toxoplasmosis we found that Ly6Cin inflammatory monocytes were recruited from the blood to the brain in a CCL2-dependent manner to exert anti-parasitic activities (Biswas et al., 2015). First, recruited Ly6Cin inflammatory monocytes produced proinflammatory mediators such as IL-1α, IL-6, and inducible nitric oxide synthase (iNOS) but were also able to secrete regulatory IL-10. Second, Ly6Cin inflammatory monocytes further differentiated into Ly6Cint brain DCs and Ly6Clow macrophages upon arrival in the CNS and, thus, contributed to antigen presentation and to parasite control.

Due to the high p75NTR expression on Ly6Cin inflammatory monocytes in the blood, we investigated whether knockout of p75NTR would affect the recruitment of monocytes to the CNS upon T. gondii infection. Previous in vitro studies have reported beneficial effects of NGF-associated neurotrofin signaling on macrophage chemotaxis (Kobayashi & Mizisin, 2001; Samah et al., 2008) but in contrast, animal models of experimental autoimmune encephalomyelitis demonstrated a reduced CNS infiltration of blood monocytes caused by NGF overexpression (Flügel et al., 2001). Here, we did not detect significant differences in the frequencies of myeloid cells in cortex or hippocampus of p75−/− mice. Furthermore, the in vitro migratory response of leukocytes towards CCL2 stimulation was not changed. The observed differences can possibly be explained by the difference in the model of neuroinflammation and by the circumstance that NGF protein levels were not affected by KO of p75NTR. Recent findings by Lee et al. (2016) reported reduction in CNS trafficking of inflammatory monocytes after applying a p75NTR blocking antagonist. However, this study only tested the effects of the p75NTR antagonist on other members of the TNF receptor family with cysteine-rich domains. Thus, they did not exclude interactions of this antagonist with other extracellular receptors which may be an explanation for the altered cell recruitment and activation (Delbary-Gossart et al., 2016).

Early studies revealed that neurotrophin signaling affects several functions of immune cells such as inhibition of MHC class II expression, phagocytosis and proliferation (Elkabes, DiCicco-Bloom, & Black, 1996; Neumann, Misgeld, Matsumuro, & Wekerle, 1998). As the immune cell activation status reflects their functional properties, we characterized the phenotype of immune cells in the brains of p75−/− mice upon Toxoplasma-induced neuroinflammation. Here, we found that brain resident microglia and subsets of recruited peripheral myeloid cells in knockout mice displayed lower levels of MHC class II, CD11c, F4/80, and CD80 surface receptors implying an altered activation and function. Therefore, we analyzed the phagocytic capacity of these immune cells but did not find differences when compared to WT animals. Besides phagocytosis, the production of inflammatory mediators is another functional aspect of the cellular immune response toward inflammation. Accordingly, we analyzed cytokine production by microglia and recruited peripheral mononuclear cell subsets. Although p75NTR knockout did not affect microglia cells, myeloid cell subsets secreted increased amounts of proinflammatory IL-1α, IL-6, and regulatory IL-10. So far, few studies have reported about the effects of neurotrophins on the release of immunological mediators by immune cells and even less is known about the role of the p75NTR in this context. (Barouch et al., 2001) observed the secretion of nitric oxide by macrophages in an NGF-dependent activation of mitogen-activated protein kinases. In our experiments, we did not find alterations in the production of iNOS suggesting that the reported nitric oxide release could be rather a result of TrkA- instead of p75NTR-mediated signal transduction (Frossard, Freund, & Advenier, 2004; Stephens et al., 1994; Xie, Tisi, Yeo, & Longo, 2000).

The proinflammatory cytokine IL-1 was shown in many studies to be involved in memory processes, specifically those related to hippocampal functioning (Goshe & Yirmiya, 2007). Although most of the evidence gathered so far indicates that the effects of IL-1 on CNS neurons are detrimental, recent evidence suggests that under some circumstances IL-1 may actually be required for the normal physiological regulation of hippocampal function (Avital et al., 2003). Indeed, impairment of IL-1 signaling results in a reduced size of dendritic spines on hippocampal pyramid neurons (Goshe & Yirmiya, 2009). Also, application of IL-10 to hippocampal neurons has been shown to induce synapse formation (Lim et al., 2013). Taken together, the increase we observed in the secretion of IL-1α and IL-10 in p75−/− mice might at least in part contribute to the rescuing of neuronal structure upon T. gondii infection.

The multifunctional cytokine IL-6 was reported to be a promotor and inhibitor of inflammation (Scheller, Chalaris, Schmidt-Arras, & Rose-John, 2011; Tilg, Dinarello, & Mier, 1997; Xing et al., 1998) and has been associated with a variety of neurodegenerative disorders including Alzheimer’s and Parkinson disease (Dobbs et al., 1999; Wood et al., 1993). IL-6 was also found to induce neuroprotection and prevent neuron and oligodendrocyte degradation (Chucair-Elliott et al., 2014; Pizzi et al., 2004), thus contributing to its multifunctional aspects. Accordingly, our data showed an increased secretion of IL-6 by Ly6Cint brain DCs and Ly6Clow macrophages, supporting these previous findings. BDNF signaling has been shown to positively modulate dendritic spine and spine architecture in cortical and hippocampal neurons as well as structural plasticity both in vitro and in vivo (Kellner et al., 2014; Rauskolb et al., 2010; Zagrebelsky & Korte, 2014). We performed Western blot analysis of brain homogenates to compare BDNF protein levels. Here, we found that BDNF levels remained unaltered upon infection for both WT and p75−/− mice. Interestingly, the precursor protein proBDNF was strongly increased upon infection. Particularly, signaling of proBDNF via the p75NTR has been shown to promote spine pruning and to negatively affect dendritic spine density and synaptic plasticity (Orefice, Shih, Xu, Waterhouse, & Xu, 2016; Qiao, An, Xu, & Ma, 2017; Yang et al., 2014). In addition, our data imply that activated immune cells contribute to proBDNF production upon infection-induced inflammation since previous studies also observed the secretion of proBDNF by peripheral macrophages under certain inflammatory conditions (Luo et al., 2016; Wong et al., 2010). Thus, activated resident or recruited immune cells entering the CNS from the periphery during neuroinflammation possibly contribute to the elevated proBDNF levels in the CNS. Our results suggest that the rescue of the Toxoplasma infection-induced alterations of neuronal architecture observed in p75−/− animals may be due to the absence of
proBDNF-mediated signaling in neurons in combination with the altered immune response. Yet, it is not clear whether other cell types are also involved in this observed rescue of neuronal morphology. A study published by Cragnolinii, Huang, Gokin, and Friedman (2009) demonstrated that astrocytes are capable of expressing p75NTR upon seizures. Unfortunately, this study only addressed the impact of NGF on p75NTR signaling, leaving the effect of proneurotrophins on astrocyte activation unavowed. Accordingly, as for mature neurotrophins, only little is known about the final role of proneurotrophins in immune cell activation. Of note, two studies conducted on peripheral macrophages pointed out that proneurotrophins are able to alter the migratory behavior and phenotype of these cells (Williams, Killebrew, Clary, Seawell, & Meeker, 2015; Wong et al., 2010). Although the altered phenotype of immune cells in p75−/− mice could be caused by the lack of proneurotrophin signaling, it remains unclear why cytokine expression was different in infected myeloid cells but not in microglia. In addition, the question arises whether the high levels of proBDNF in infected peripheral immune cells can also mediate the activation of myeloid cells before entering the CNS. To this end, further experiments need to be carried out addressing the effect of mature neurotrophins and their precursor forms on immune cell activation in the brain and periphery during steady state and upon inflammatory conditions.

Taken together, our data provide evidence that neurotrophin signaling via the p75NTR alters innate immune cell behavior and contributes to function and structural rearrangements in the neuronal network upon chronic Toxoplasma infection-induced neuroinflammation.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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