TOXICOLOGICAL SCIENCES **125(1)**, 209–218 (2012)
doi:10.1093/toxsci/kfr252
Advance Access publication October 5, 2011

The Chemokine CCL2 Protects Against Methylmercury Neurotoxicity

David Godefroy,* Romain-Daniel Gosselin,† Akira Yasutake,‡ Masatake Fujimura,§ Christophe Combadière,¶ Régine Maury-Brachet,|| Muriel Laclau,|| Randeep Rakwal,||| Stéphane Melik-Parsadaniantz,|||| Jean-Paul Bourdineaud,|| and William Rostène*,[1]

**INSERM UMRS 968, Institut de la Vision, Université Pierre et Marie Curie Paris 6, 75012 Paris, France; †Department of Anesthesiology, University Hospital Center and University of Lausanne, Lausanne, Switzerland; ‡Graduate School of Medicine, Kumamoto University, Kumamoto 860-8555, Japan; §Department of Basic Medical Science, National Institute for Minamata Disease, Minamata City, Kumamoto, Japan; ¶INSERM UMRS 543, Hôpital Pitié-Salpêtrière, Université Pierre et Marie Curie Paris 6, 75013 Paris, France; ||CNRS UMR 5805, Station Marine d'Arcachon, Université de Bordeaux 1, Arcachon, 33120, France; |||School of Medicine, Showa University, Shinagawa-Ku, Tokyo 142-8555, Japan; and ||||INSERM UMRS 975, Hôpital Pitié-Salpétrière, Université Pierre et Marie Curie Paris 6, 75013 Paris, France*

[1]To whom correspondence should be addressed at INSERM-UPMC UMRS 968, Institut de la Vision, 17 rue Moreau, 75012 Paris, France. Fax: 33-0153462502. E-mail: william.rostene@inserm.fr.

Received June 16, 2011; accepted September 20, 2011

Industrial pollution due to heavy metals such as mercury is a major concern for the environment and public health. Mercury, in particular methylmercury (MeHg), primarily affects brain development and neuronal activity, resulting in neurotoxic effects. Because chemokines can modulate brain functions and are involved in neuroinflammatory and neurodegenerative diseases, we tested the possibility that the neurotoxic effect of MeHg may interfere with the chemokine CCL2. We have used an original protocol in young mice using a MeHg-contaminated fish-based diet for 3 months relevant to human MeHg contamination. We observed that MeHg induced in the mice cortex a decrease in CCL2 concentrations, neuronal cell death, and microglial activation. Knock-out (KO) CCL2 mice fed with a vegetal control food already presented a decrease in cortical neuronal cell density in comparison with wild-type animals under similar diet conditions, suggesting that the presence of CCL2 is required for normal neuronal survival. Moreover, KO CCL2 mice showed a pronounced neuronal cell death in response to MeHg. Using *in vitro* experiments on pure rat cortical neurons in culture, we observed by blockade of the CCL2/CCR2 neurotransmission an increased neuronal cell death in response to MeHg neurotoxicity. Furthermore, we showed that *sod* genes are upregulated in brain of wild-type mice fed with MeHg in contrast to KO CCL2 mice and that CCL2 can blunt *in vitro* the decrease in glutathione levels induced by MeHg. These original findings demonstrate that CCL2 may act as a neuroprotective alarm system in brain deficits due to MeHg intoxication.

Key Words: **methylmercury neurotoxicity; chemokines; CCL2/CCR2; fish diet; neuroprotection; microglia; neuronal cell death.**

Climate changes, ecological modifications due to pollution, in particular chemical/industrial pollution, bring forth scientific, political, and health issues. Among the most polluting compounds known in the industrial world are heavy metals such as mercury (Hg). Methylmercury (MeHg) is an environmental poison that has been shown to drastically affect various organs and in particular the brain. Major actions have been taken to reduce the use and emission of mercury in the environment in the 1950s, following the Minamata disaster in Japan that was caused by a dramatic industrial pollution of the sea by MeHg (Eto, 2000). Nonetheless, such a contamination remains a serious problem in many countries raising a controversial major concern for the environment with implications for public health.

Exposure to MeHg has been shown to disrupt normal brain development and cerebral activity in adult humans as well as in various animal species and to produce neurotoxicity in selective brain areas such as the cerebral cortex and the cerebellum in adults (Auger *et al.*, 2005; Eto, 2000). It was extensively reported that neuronal cells were highly susceptible to MeHg toxicity (Rush *et al.*, 2009). Neuronal cell death by MeHg has been attributed in part to oxidative stress (Ceccatelli *et al.*, 2007; Huang *et al.*, 2008), a mechanism well described in a variety of pathological brain processes including neurodegenerative diseases and neuroinflammation (Huang *et al.*, 2008). However, several of the previous studies carried out to study the toxic effects of MeHg have used high doses of MeHg not directly relevant to current contamination in humans, in particular due to ingestion of contaminated fish (Bourdineaud *et al.*, 2008, 2011).

Chemokines are small proteins (6–10 KDa) that were initially thought to be responsible for the maturation and trafficking of leukocytes, in particular in inflammatory diseases (Ransohoff, 2009). Recently, the possibility has been raised that they are constitutively present in the brain in both glial cells and neurons and might act as neurotransmitters or neuromodulators (Rostène *et al.*, 2007). In particular, the CC chemokine CCL2 (also known as MCP-1: monocyte chemoattractant protein1) has been

extensively described in the central nervous system (CNS), where it is located, as well as its cognate receptor CCR2, in neurons in selective brain regions such as the cerebral cortex (Banisadr *et al*., 2005a,b). A recent report on gene expression profiling has shown a CCL2 messenger RNA modulation in mouse cerebellum following MeHg treatment (Hwang *et al*., 2011).

Here by means of both *in vivo* and *in vitro* approaches, we report that the chemokine CCL2 can be released by neurons and may prevent cortical neuronal cell death induced by a low contamination with MeHg present in a food pellet diet containing 0.1% of dry flesh from MeHg-contaminated *Hoplias aimara* fish (Bourdineaud *et al*., 2008). Furthermore, *in vitro* blockade of CCL2/CCR2 neurotransmission or *in vivo* blockade obtained in mice invalidated for the CCL2 gene, demonstrate a higher neurotoxic effect of MeHg. This protective effect of CCL2, via its CCR2 receptor, may be associated with the regulation of oxidative stress and/or CCL2-MeHg chemical interaction. These results are the first to show that chemokines, such as CCL2, may have a crucial role in the neuroprotective mechanisms that respond to MeHg contamination.

MATERIALS AND METHODS

Ethics Statement

Experiments on mice were performed in accordance with the European Community council directive no. 8616091 EEC agreement no. 75-108 (05/02/2001) to W.R. from Paris Prefecture. The experiments were conducted according to the agreement of the University Pierre et Marie Curie committee no. A75-19-01.

In vivo *Experiments*

Preparation of the mice diets. Adult 3-week-old male mice of the C57Bl/6 Jico inbred strain (IFFA Credo, Lyon, France) or mice deficient in CCL2 (B6.129S4-Ccl2tm1Rol/J) on the same C57Bl/6 background (Lu *et al*., 1998) were purchased from Jackson Laboratory (Bar Harbor, ME). Young mice were used because they grow quickly and are more sensitive to MeHg than older animals. In order to be close to human contamination by fish ingestion, a low dose of MeHg contamination was obtained with a food pellet diet containing 0.1% of dry flesh from MeHg-contaminated *H. aimara* fish (aimara groups) (Bourdineaud *et al*., 2008, 2011). Total Hg content in the aimara groups was 5.4 ± 0.5 ng Hg/g of food pellet (manufactured by Dietex). The control RM1 diet was 100% vegetal (RM1 diet; Dietex, Saint-Gratien, France) and contained 1.4 ± 0.2 ng Hg/g. Another control was carried out in order to avoid a possible effect of the fish flesh itself with noncontaminated farmed salmon flesh (1.55 ± 0.15 ng Hg/g). Mice were fed for 3 months with the control or MeHg-contaminated diets (Bourdineaud *et al*., 2008). The amount of polyunsaturated fatty acids ω3, ω6, and ω9 was similar for aimara and salmon flesh and represented less than 0.003% of the diets (Bourdineaud *et al*., 2008, 2011). The nutritional as well the metal composition of the various diets are given in the supplemental data (Supplementary table 1).

Brain measurement of CCL2 and total Hg determination in mice brain. At the end of the 3-month feeding period, mice were killed by decapitation, and the cortex was taken at three different levels: anterior (from bregma + 2.96 mm to + 1.18 mm corresponding mainly to the frontal cortex), medial (from bregma + 0.86 mm to −2.3 mm corresponding to the sensorimotor cortex), and posterior (from bregma −2.46 mm to −4.36 mm corresponding to the visual cortex) (Franklin and Paxinos, 1997). CCL2 was extracted by sonication for few seconds in 250 µl of assay diluent (cat No 51-2641KC; BD Biosciences, Le Pont de Claix, France). Samples were centrifuged at 10,000 rpm for 15 min at 4°C, and the supernatant was collected. CCL2 was measured with an enzyme-linked immunoadsorbent assays (ELISA) kit (mouse CCL2 ELISA set, BD OptEIA cat no. 555260; BD Biosciences). Total Hg concentrations in mice tissues and diets were determined by flameless atomic absorption spectrometry (Bourdineaud *et al*., 2008).

Neuronal Cell death measurement in mice brain. For determination of neuronal cell number, 20-µm brain sections were cut with a cryostat (Leica CM 3050 S) from bregma −1.46 mm to −2.06 mm according to the atlas of Franklin and Paxinos (1997) and mounted on glass slices. Preliminary experiments using a human anti-HuD antibody (1:8000) (Szabo *et al*., 1991) and TUNEL determination on sections pretreated for 15 min with paraformaldehyde (PFA) 4% confirm that the cell death we observed was mainly apoptotic and selective for neurons (Banisadr *et al*., 2005a). Neuron quantification was carried out on nonfixed sections pretreated for 5 min with 70° ethanol. The sections were then dipped in cresyl violet (5g/l) and 0.0006 N acetic acid, washed with distilled water (20 s), and dipped again in 70° ethanol and acetic acid 0.0003 N (5 s), 95° ethanol (5 s), 100° ethanol (5 s), and xylene (2 × 5 min). All sections were mounted with entellan (Electron Microscopy Science, Hatfield, PA; ref 14800). Neuronal cells were measured at different layers of the parietal/sensorimotor cortex with an image analyzer (Mercator; Explora Nova, La Rochelle, France). Two determinations on the same surface (20,000 μm^2) were carried out on each section in the various layers, and mean values calculated for each animal.

Microglia immunocytochemistry. For microglia determination, PFA 4% pretreated sections were mounted on glass slices, washed with PBS 1× (3 × 5 min), and incubated overnight at room temperature with an anti-Iba1 rabbit antibody (1:400 dilution) (Wako Pure Chemical Industries Ltd., code no: 019-19741). After incubation, sections were rinsed with PBS 1× (3 × 5 min) and incubated at room temperature for 2 h with an Alexa 488–conjugated anti-rabbit antibody (Molecular Probe; Invitrogen, France; ref A11-008) at a 1:200 dilution. The sections were washed with PBS 1× (3 × 5 min) and mounted with mountant permafluor (Labovision; ThermoFisher Microm, France; ref TA-030-FM). Iba-1 fluorescence was determined with a fluorescent microscope (Leica DM400B). Microglia were measured in the parietal/sensorimotor cortex. Two determinations on the same surface (200,000 μm^2) were carried out by image analysis on each section, and mean values calculated for each animal.

Sod ***gene expression in mice cortex.*** Total RNAs were extracted from 40 mg of fresh parietal/sensorimotor cortex using the Absolutely RNA Miniprep Kit (Stratagene, France). First strand cDNA was synthesized from 5 µg total RNA using the StrataScript First Strand cDNA Synthesis Kit (Stratagene). Specific primer pairs were determined for *sod1* and *sod 2* genes. Real-time PCR reaction was performed in a LightCycler (Roche) according to the manufacturer's instructions. PCR amplification, reaction specificity, and gene expression normalized to β-actin were carried out as previously described (Bourdineaud *et al*., 2008).

In vitro *Experiments*

Primary neuronal cultures. Rat embryos were collected in cold PBS (1×) from impregnated females at embryonic day 14. Briefly, fetal cortex was dissected in cold PBS (1×) under sterile conditions, and cells were mechanically dissociated by pipetting, in Neurobasal medium (Gibco Invitrogen Corporation, France), collected by centrifugation (800 × g, 5 min), and gently resuspended in serum-free medium (see below). Cell viability was estimated by Trypan Blue exclusion. Cells were plated (density 1.10^5 cells/well [48-well plates] for cell death experiments and 2.10^5 cells/well [24-well plates] for glutathione [GSH] determination) on wells previously coated with poly-L-lysine (15 µg/ml). Cultures were maintained for 7 days at 37°C in a humidified incubator (95% O_2/5% CO_2). At days 1 and 2, aracytine (AraC) was added at 25 and 50µM, respectively, to prevent glial proliferation. The culture serum free medium used was Neurobasal medium (Gibco Invitrogen Corporation) supplemented with 0.5mM L-glutamine, 50 µg/ml streptomycin, 50 U/ml penicillin, and B27 complement (Gibco Invitrogen Corporation). Medium was changed 1/3 at days 2, 5, and 7. In the presence of AraC and of Neurobasal medium supplemented with B27, the percentage of GFAP-positive astrocytes was 0.4 ± 0.2%, and no Iba-1 microglial–positive cells were

detected, suggesting that the cells grown under these conditions represent neuronal cortical cells as confirmed with HuD staining (Szabo *et al.*, 1991). In some experiments, cortical cells were also prepared without AraC in order to obtain mixed glial and neuronal cell populations (Supplementary figure 1). Cells were stained with a rabbit CCL2 antibody (Torrey Pines Biolabs; cat: TP209) at a final concentration 1/400 in PBS 1× supplemented with 0.05% Triton.

Cell exposure. After 7 days of culture, MeHg (methylmercury chloride; Sigma-Aldrich, St Louis, MO, ref: 442534-5G-A) was added at various concentrations (50nM–5μM) for 1, 2, 3, and 5 days depending on the experiment. For 5 days exposure to MeHg, medium was changed 1/3 at day 2. In order to block the *in vitro* effects of CCL2, a blocking rabbit anti-CCL2 antibody (Torrey Pines Biolabs cat TP209, East Orange, NJ) was added in the incubation medium at days 1 and 3 (for 5 days MeHg treatment) at 0.5 μg/ml. We previously observed that this antibody totally trapped CCL2 leading to an undetectable level of the chemokine in the incubation medium (data not shown). A nonpeptide CCR2 receptor antagonist, INCB3344, was also added at 10μM (Brodmerkel *et al.*, 2005) at the same times as above. In some experiments, CCL2 (rat CCL2, ref: 400-12; Preprotech Inc., Rocky Hill, NJ) was added in the culture medium at concentrations ranging from 1 to 50nM at days 1 and 3.

Cell death counting. At the end of the experiments, neuronal cells were washed with PBS supplemented with Triton X 100 (0.1%) and fixed with filtered 4% PFA for 5 min. Cells were washed again with PBS. DAPI (4,6-diamidino-2-phenylindole) solution (Chimie, ref 32671; Sigma-Aldrich) was applied on cells at 0.1 μl/ml for 10 min. Condensed nuclei were considered as apoptotic and counted among the whole cell population labeled with a blue homogeneous staining. Measurement was carried out on 50 cells/area with an inverted Nikon Diaphot 300 epifluorescence microscope.

GSH measurement in neuronal cells. Cells were suspended in 150 μl ice-cold PBS for protein analysis and GSH measurement. Protein levels were analyzed using bovine serum albumin as external standard. For GSH analysis, a 100 μl aliquot of the PBS suspension was diluted twice with ice-cold 5% perchloric acid containing 1mM EDTA to precipitate protein and centrifuged for 1 min at 12,000 rpm. The total cellular GSH levels were determined by the enzymatic recycling method reported by Tietze (1969) using the supernatant fraction.

Statistical analysis. Data are expressed as means ± SEM. All *in vitro* experiments were carried out at least in triplicate. The number of animals for the *in vivo* experiments is mentioned in the results. One-way ANOVA was performed, followed by a Student-Newman-Keuls test or by a Kruskal-Wallis test. Student's *t*-test was used when only two groups were compared. A two-way ANOVA at two levels with unequal numbers of samples was used when more than one treatment was studied, followed by a Student-Newman-Keuls test (Harvey, 1966; Winer, 1971). The threshold of significance was $p < 0.05$. Statistical software was used (SigmaStat version 3.5; Jandel Scientific, San Jose, CA).

RESULTS

Impact of Fish-Contaminated Diets on Brain Hg Bioaccumulation and CCL2 Content in Mouse Cortex

We recently demonstrated (Bourdineaud *et al.*, 2008, 2011) that we could mimic human food contamination with MeHg by giving to mice food pellets at a concentration as little as 5 ng/g Hg (containing less than 2 ng/g MeHg) brought by dry fish flesh supplementation obtained from contaminated aimara fish. Male C57Bl/6 mice were thus contaminated for 3 months with such diet and compared with control mice provided 100% vegetal RM1 or farmed salmon diets. Aimara diet induced a 10-fold increase in total Hg content in the brain (0.0312 ± 0.006 vs. 0.0026 ± 0.0003 μg Hg/g dry weight in RM1 and farmed salmon diets; means ± SEM, $n = 8$/group). The highest amounts of total Hg with the aimara diet were found in the kidneys (0.907 ± 0.063 μg Hg/g dry weight; means ± SEM, $n = 8$/group) and in the hairs (0.47 ± 0.06 μg Hg/g dry weight; means ± SEM, $n = 8$/group). In mice submitted to such Hg contamination, a significant decrease in CCL2 content was observed in the cortex, in particular in the sensorimotor and visual cortex (Table 1).

TABLE 1
Effect of MeHg Contamination *In Vivo* on CCL2 Concentration in Mice Cortex

	Concentration of CCL2 (pg/mg protein)		
	Frontal cortex	Sensorimotor cortex	Visual cortex
Control RM1	4.36 ± 0.7	4.06 ± 0.7	4.46 ± 0.67
Control salmon	4.44 ± 0.8	4.51 ± 0.8	4.85 ± 0.7
MeHg aimara	3.37 ± 0.46	2.14 ± 0.1*	2.99 ± 0.24*

Note. Mice were fed for 3 months with pellets prepared from MeHg-contaminated aimara fish (Aimara group) or salmon flesh (control salmon) and compared with mice fed with 100% vegetal RM1 food (control group), $n = 24$ for each group. MeHg treatment induced a decrease in CCL2 content in the mouse cortex. A Student's *t*-test was used for comparison with each control group. Values indicate means ± SEM.

*$p < 0.05$ versus respective controls.

Consequence of MeHg-Contaminated Diet on Neuronal Cell Death in the Mouse Cortex

Cell counting carried out in the different layers of the sensorimotor cortex demonstrated a significant loss of neuronal cells following 3 months diet with aimara-contaminated food (Fig. 1a). Quantitative measurement by image analysis showed that this decrease affected all layers of the cortex from the surface (cortex I–II) till the deep layer (cortex VI) (Fig. 1a). No effect was observed with the non–Hg-contaminated fish flesh obtained from farmed salmon diet. Interestingly, as shown in Figure 1b, a loss in neuronal cell density was already observed in knock-out (KO) CCL2 mice in comparison with the wild-type animals fed with the control RM1 diet, in particular in the deep layers of the cortex. Furthermore, quantitative measurements and statistical analysis using a two-way ANOVA (Harvey, 1966; Winer, 1971) demonstrated a significant difference between groups but no significant interaction between the diet and the presence or absence of CCL2. However, KO CCL2 mice subjected to the aimara-contaminated food showed a significant higher neuronal cell death in the cortical deeper layers in response to MeHg contamination. These *in vivo* data suggested that CCL2 was not directly involved in the mechanism of neurotoxicity induced by MeHg but had a neuroprotective effect against MeHg contamination (Fig. 1b).

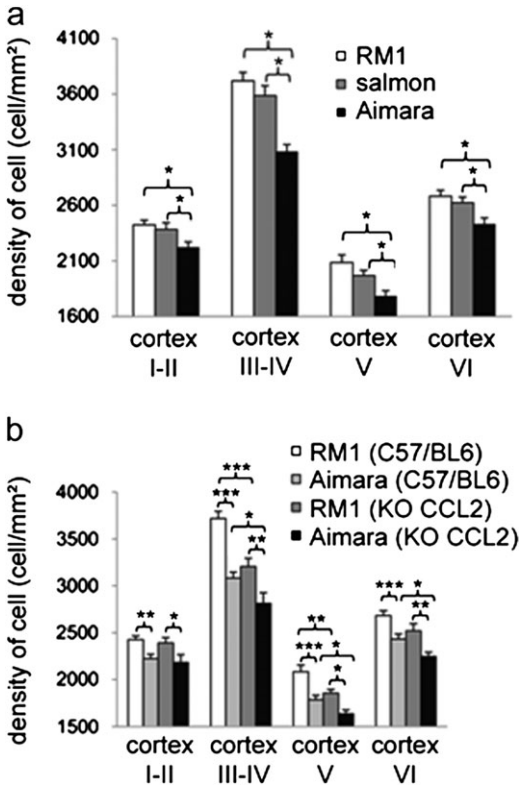

FIG. 1. Effect of MeHg-contaminated diet on neuronal cell death in the mouse cortex. Quantitative measurement by image analysis showing the loss of neurons in various layers of the sensorimotor cortex (a) in wild-type mice fed with the contaminated aimara fish food (■). No effect of salmon diet was observed (■). (b) A more pronounced effect can be seen in KO CCL2 animals in particular in the deeper layers of the cortex. $n = 24$/group for control vegetal RM1 food, salmon, and aimara groups and $n = 17$ for KO CCL2. A two-way ANOVA at two levels with unequal numbers was used for comparison (Harvey, 1966). Values indicate means. Error bars indicate SEM. *$p < 0.05$ was considered as significant. **$p < 0.01$; ***$p < 0.001$.

Consequence of MeHg-Contaminated Diet on Microglial Activation and Sod *Gene Expression in the Mouse Cortex*

As shown in Figure 2, aimara food diet in wild-type mice induced an increase in the number of microglial cells as stained with Iba-1 in the sensorimotor cortex. In contrast, the salmon diet had no effect on microglial activation (Figs. 2a–c). KO CCL2 mice presented a slight deficit in microglial cell number under control RM1 diet and did not show any significant increase in microglia under aimara food diet (Fig. 2d). Exposure of wild-type mice to aimara food diet for 3 months demonstrated a twofold upregulation in the expression of the superoxide dismutase-encoding genes *sod1* (cytoplasmic Sod enzyme) and *sod2* (mitochondrial Sod enzyme) (Table 2). In contrast, in the brain of KO CCL2 mice, the aimara diet did not trigger this increased expression of both *sod* genes. Moreover, in mice fed with the control RM1 diet, KO CCL2 brain displayed *sod* gene expression 60% higher than that in wild-type brain, indicating an increased oxidative level in the absence of CCL2. In addition, KO CCL2 mice fed with the aimara-containing diet demonstrated a significant decrease in the expression level of the *sod2* gene as compared with wild-type brain.

Dose- and Time-Dependent Neurotoxic Effects of MeHg In Vitro

In order to further study the neuroprotective effect of CCL2 in response to MeHg exposure, *in vitro* experiments were carried out. Pure rat cortical neurons in primary cultures were grown with various concentrations of MeHg (50nM–5μM) and over different durations from 1 to 5 days. Neuronal cells determined with a specific neuronal marker HuD (Szabo *et al.*, 1991) expressed CCL2 (Figs. 3a and 3b). Neuronal cells in culture were considered as apoptotic when presenting nuclei condensation when counterstained with DAPI as compared with the whole cell population (Fig. 3c). Increasing concentrations of MeHg induced a dose-dependent apoptotic neuronal cell death starting at 500nM following 1-day incubation with MeHg (Fig. 4a). Interestingly, the same concentration of MeHg, which was slightly neurotoxic after 1 day, was able to induce the same level of apoptosis (40–50%) than 1μM MeHg after 2 days of treatment. After 5 days, 80% of the cells died when exposed to 500nM MeHg, similarly to 5μM MeHg after 24 h of treatment (Fig. 4b). In complementary experiments, we observed that when primary cultures were grown in the absence of aracytine (AraC) which allowed glial proliferation and thus provided a neuron-glia co-culture model, only a slight significant neurotoxic effect of 500nM MeHg could be observed starting at day 5 (Supplementary figure 1). Therefore, the following *in vitro* experiments were carried out on pure rat cortical neurons in culture.

Neuroprotective Effect of the Chemokine CCL2 against MeHg Neurotoxicity

In order to study the role of CCL2, three different experiments were performed. First, we trapped the chemokine present in the culture medium by means of a blocking anti-CCL2 antibody resulting in an undetectable level of CCL2 in the incubation medium (data not shown). Under these conditions, an increase in neuronal cell death was observed as soon as 24 h. When the anti-CCL2 antibody was added in the presence of MeHg, more apoptotic cell death was observed (Fig. 5a). Second, we used a selective nonpeptide receptor antagonist to block the binding of CCL2 on its main receptor CCR2 (Brodmerkel *et al.*, 2005). Similar to what we observed with the blocking CCL2 antibody, blockade of CCR2 increased neuronal cell apoptosis and the neurotoxic effect of MeHg was significantly enhanced in the presence of the CCR2 antagonist after 5 days in culture (Fig. 5b). Third, instead of blunting the CCL2 effect, increasing concentrations of CCL2 were introduced into the incubation medium (Fig. 5c). Under our experimental

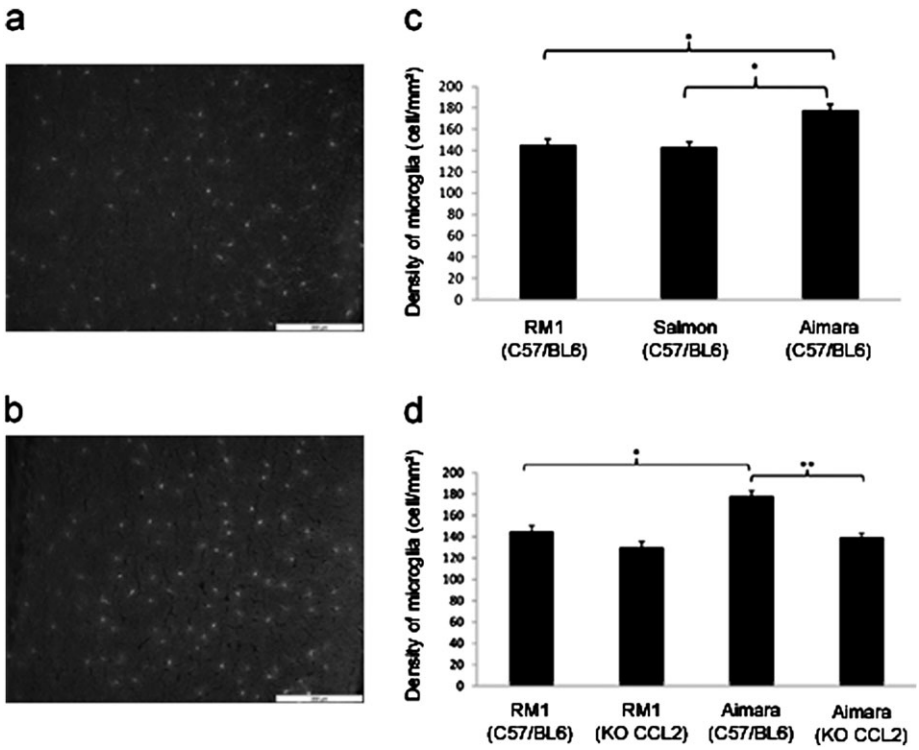

FIG. 2. Effect of MeHg-contaminated diet on microglial activation in the mouse cortex. (a and b) Microphotographs taken at the level of the mouse sensorimotor cortex stained with an anti-Iba-1 rabbit antibody and a second Alexa-488 fluorescent antibody in order to visualize microglial cells. (a) Control mice fed for 3 months with vegetal RM1 food. (b) Mice fed for 3 months with contaminated aimara fish. (c) Quantification of the increase in microglial number in aimara fed wild-type mice as compared with animals fed with RM1 or salmon diet, $n = 17$/group. (d) Number of microglial cells in wild-type (C57BL6) mice versus KO CCL2 under control RM1 and aimara diets, $n = 17$. Values are expressed as number of microglial cells/mm^2 and indicate means. Error bars indicate SEM. *$p < 0.05$ was considered as significant. **$p < 0.01$. Scale bars: 200 μm.

conditions, the basal neuronal cell death represented around 20%. Addition of MeHg in the incubation medium induced a twofold increase in neuronal cell death (40–50%). A dose-dependent effect with a *U*-shaped curve was observed with an increased neuroprotective effect against 500nM MeHg incubation for 2 days with low concentrations of CCL2 (1–10nM), with a peak at 10nM followed by a progressive and reversed effect at 50nM (Fig. 5c). A ten-nanomolar concentration of CCL2 was thus used in the following experiment.

CCL2 Blunts the Inhibition in GSH Levels Induced by MeHg

MeHg neurotoxicity has been correlated to the production of reactive oxygen species (ROS) inducing a decrease in energy balance, in particular in the production of GSH, an antioxidant agent (Ceccatelli *et al*., 2007; Stringari *et al*., 2008). We confirmed these data in our *in vitro* model showing that 500nM MeHg for 2 days produced a significant decrease in GSH concentration (Table 3). It can be noticed that CCL2 by itself at 10nM did not modify the amount of GSH but was able to counteract the decreased level of GSH observed after MeHg application (Table 3).

DISCUSSION

The first major finding of the present work is that the chemokine CCL2 has a neuroprotective effect against MeHg neurotoxicity. Previous reports had suggested that chemokines, known to play an essential role in the immune system, may be activated in neuroinflammatory processes such as multiple sclerosis, stroke, and HIV encephalitis presumably through leukocyte attraction and migration into the CNS (Ransohoff, 2009). It has been demonstrated that these chemokines may be produced by various glial cells in the CNS (Ransohoff, 2009). However, more recently, we and others observed that under normal conditions in which the blood brain barrier is intact, selective neurons in the brain were also able to synthesize CCL2 and to express CCR2, both of which play a modulatory role in neurotransmission (Banisadr *et al*., 2005a,b; Rostène *et al*., 2007). The present *in vitro* experiments confirm this observation because neurons from mice and rat cortex are able to synthesize CCL2. Furthermore, evidence has demonstrated a fast expression and a protective effect of several chemokines such as CCL2 in response to neuronal damage (Bruno *et al*., 2000; Eugenin *et al*., 2003; Schreiber *et al*., 2001).

TABLE 2
Superoxide Dismutase *sod 1*- and *sod2*-Encoding Gene Expression in Brains from Wild-Type or KO CCL2 Mice Fed with Fish-Containing Diets for 3 Months

	Wild-type mice (C57/BL6)			KO CCL2 mice		
Gene	Control RM1	Aimara	Ratio A/C	Control RM1	Aimara	Ratio A/C
Sod1	28.3 ± 7.9	*56.7 ± 4.5	*2.0	44 ± 8	44 ± 14	1.0
Sod2	14.6 ± 2.9	*37.4 ± 4.7	*2.6	°24 ± 2	§18.5 ± 3	0.76

Note. *Sod1* and *sod2* gene expression was measured by real-time PCR. Data are given as relative gene expression (mean ± SEM, $n = 5$). β-actin was the reference gene. Asterisks indicate a significant differential gene expression in brain of wild-type mice fed the aimara diet compared with those fed the control diet, as determined with the Mann-Whitney *U*-test, $^{*}p < 0.05$. The circle indicates a significant differential gene expression in brain of KO CCL2 mice fed the control diet compared with wild-type mice fed the same diet, as determined with the Mann-Whitney *U*-test, $^{\circ}p < 0.05$. The symbol § indicates a significant differential gene expression in brain of KO CCL2 mice fed the aimara diet compared with wild-type mice fed the same diet, as determined with the Mann-Whitney *U*-test, $^{\S}p < 0.05$. Ratio A/C: ratio of the mean relative expression observed in tissues from mice fed the aimara diet over that of the control diet.

Here, we observed that CCL2 is able to protect neurons against MeHg-induced neuronal cell death. To support the physiological neuroprotective role of CCL2 in MeHg neurotoxicity, we carried out a series of *in vivo* and *in vitro* experiments. An original aspect of the present work is the experimental *in vivo* paradigm used to study the effects of MeHg intoxication. We have transferred and mimicked in wild-type and transgenic mice the quantity of MeHg and the mode of contamination observed in the Wayana Amerindians living in French Guiana (Bourdineaud *et al.*, 2008, 2011). These Amerindian populations are contaminated after consumption of such carnivorous fish as aimara due to climatic and environmental conditions such as illicit gold mining. More than 85% of Wayana Amerindians present a hair Hg concentration (12 μg/g) exceeding the safety limit set up by the World Health Organization (10 μg/g). We previously found that the aimara fish diet used in the present study, which represents 0.1% of fish flesh in food corresponding to 5 ng/g of Hg, was able to produce a 10-fold increase in Hg concentration in the brain as also reported here, resulting in altered mitochondrial protein concentrations and ATP synthesis (Bourdineaud *et al.*, 2008, 2011). Others have mainly used high micromolar concentrations of MeHg either in the drinking water (Stringari *et al.*, 2008) or by gavage (Huang *et al.*, 2008), which do not represent the main contamination observed in humans with food via fish consumption. Indeed, the toxic methylated form of Hg, MeHg, represents the major form of Hg in fish (Maury-Brachet *et al.*, 2005).

The main adverse health effects of MeHg observed in humans are by far neurological disorders affecting behavior and motricity

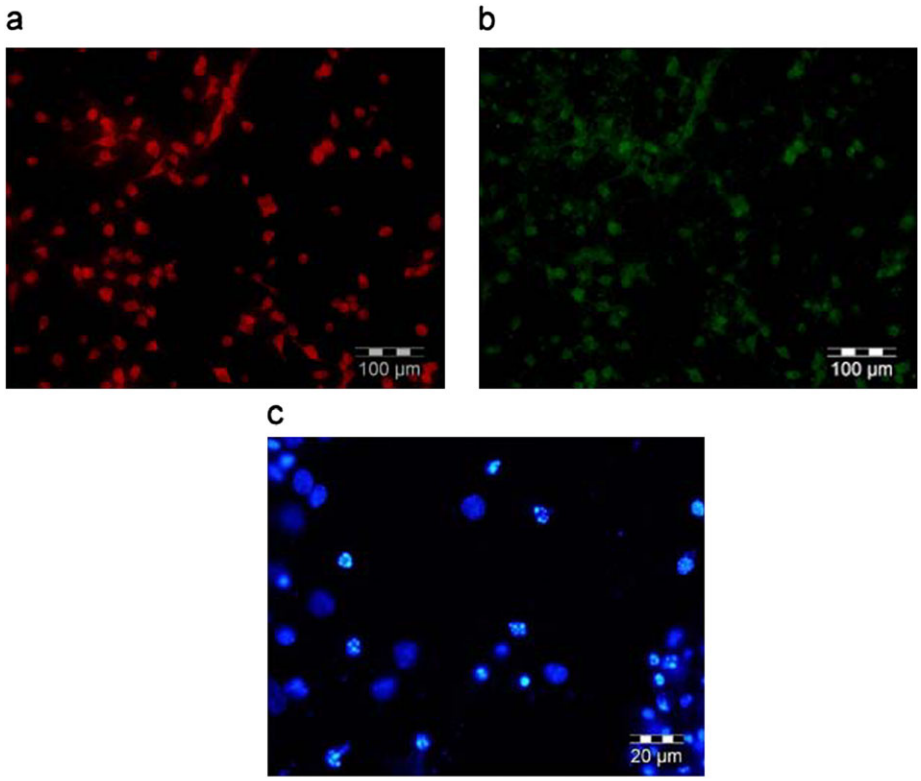

FIG. 3. Immunocytochemistry of the cells grown in primary cultures. (a) Cortical neuronal cells stained with a human anti-HuD antibody selective for neuronal phenotype. (b) Cortical neuronal cells stained with a rabbit anti-CCL2 antibody. (c) Apoptotic neuronal cortical cells presenting a DNA condensation with DAPI staining.

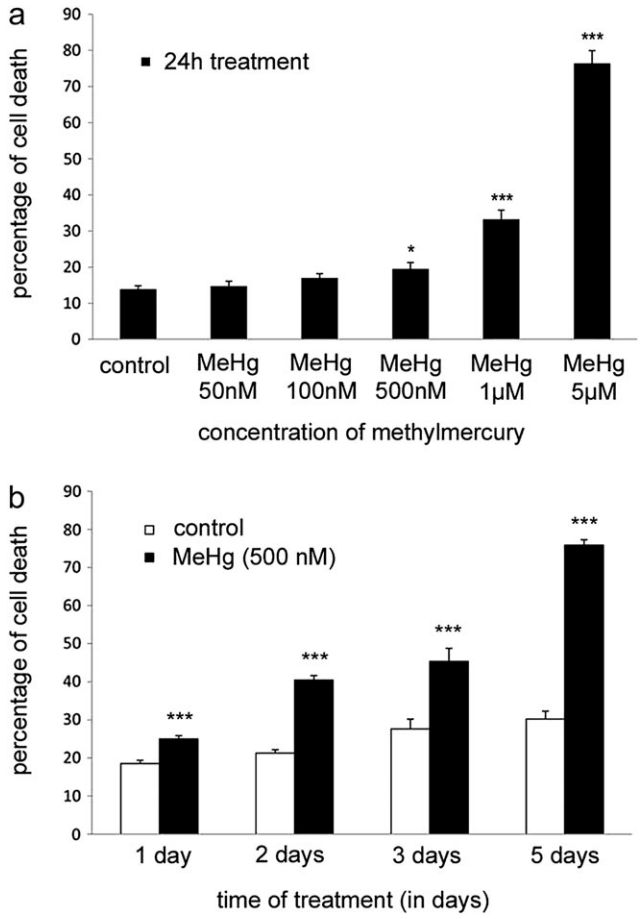

FIG. 4. Dose- and time-dependent neurotoxic effect of MeHg *in vitro*. (a) Dose-dependent effect of MeHg on cortical neuronal cell death following 1-day MeHg exposure. (b) Time-dependent effect of 500nM MeHg on cortical neuronal cell death. Open bars represent cell death observed in control cultures without MeHg. Experiments were carried out in triplicate. $n = 12$/point for (a); $n = 36$/point for (b). Values indicate means. Error bars indicate SEM. $p < 0.05$ was considered as significant. $^{*}p < 0.05$; $^{***}p < 0.001$.

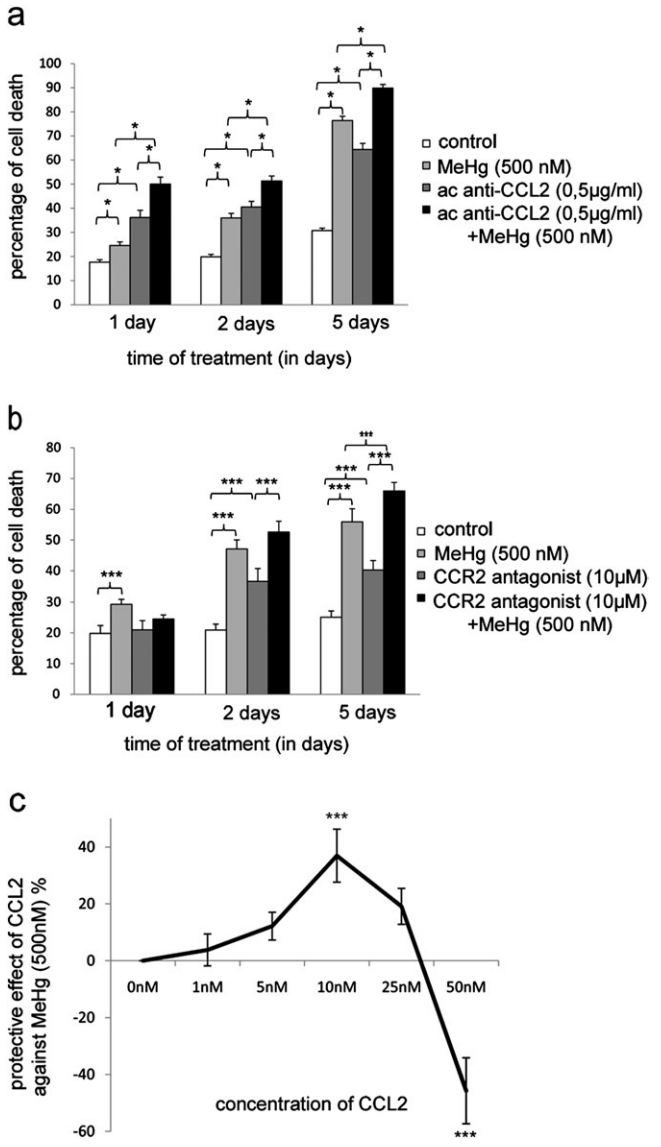

FIG. 5. Role of CCL2 in the effects of MeHg. (a) Blockade of CCL2 in the incubation medium by a blocking anti-CCL2 antibody induced an increase in neuronal cell death alone and following MeHg incubation ($n = 18$/point). (b) Blockade of the CCL2 receptor, CCR2, similarly induced an increase in apoptotic neuronal cell death alone and following MeHg incubation. (c) Administration of increasing concentrations of CCL2 in the incubation medium during 2 days produced a dose-dependent protective effect on MeHg-induced neuronal cell death with a peak at 10nM CCL2 (47.63 ± 2.45% vs. 32.57 ± 1.01% cell death for MeHg and MeHg + CCL2, respectively, $p < 0.001$ vs. MeHg), whereas a high concentration (50nM) induced apoptosis (41.53 ± 2.68% vs. 61.57 ± 2.63% cell death for MeHg and MeHg + CCL2, respectively, $p < 0.001$ vs. MeHg; $n = 18$/point). Experiments were carried out in triplicate. Values indicate means. Error bars indicate SEM. An ANOVA test was used for comparison. $p < 0.05$ was considered as significant. $^{*}p < 0.05$; $^{**}p < 0.01$; and $^{***}p < 0.001$.

(Auger *et al.*, 2005; Eto, 2000). We previously reported that feeding wild-type mice with such a low dose of MeHg-contaminated aimara food induced an increase in anxiety levels (Bourdineaud *et al.*, 2008) without affecting locomotor activity (data not shown). We report here that such diet induces a decrease in cortical CCL2 level (Table 1). The decrease in CCL2 is more pronounced in the sensorimotor and visual cortex than in the frontal cortex. It was reported by Eto (2000) in human brain with Minamata disease that the effect of MeHg was not uniformly observed in all brain regions, mainly affecting structures in which neurons are known to be more vulnerable to toxic insults as in the cortex. Variations in Hg content may thus explain the differences observed in the various cortical regions in the effect of MeHg on the decrease in CCL2 levels.

This decrease in CCL2 content, probably resulting from both neurons and glial cells (Banisadr *et al.*, 2005a; Lawrence *et al.*, 2006), may be linked to less neuronal protection. Indeed, we made an interesting observation showing that KO CCL2 mice fed with the control food RM1 present a significant reduction in neuronal cell density in the cortex in comparison with

TABLE 3
Inhibition by CCL2 of MeHg-Induced GSH Depletion in Cortical Neurons in Culture

	Control	MeHg (500nM)	MeHg (500nM) + CCL2 (10nM)	CCL2 (10nM)
Concentration of GSH (nmol/mg protein)	26.98 ± 1.56	20.09 ± 1.82*	27 ± 2.1**	26.25 ± 1.84

Note. MeHg (500nM) induced a decrease in GSH levels. This effect was counteracted by 10nM CCL2, which by itself had no effect on GSH ($n = 12$). Values indicate means ± SEM. A two-way ANOVA was used for comparison (Harvey, 1966; Winer, 1971).

*$p < 0.05$ versus control. **$p < 0.05$ versus MeHg.

wild-type animals under similar diet conditions, suggesting that the presence of CCL2 is required for normal neuronal survival even in the absence of MeHg. The lack of statistical interaction between the diet and the presence or not of CCL2 suggests that CCL2 is not directly involved in the mechanism by which MeHg induced neuronal cell death. In other words, by decreasing CCL2 or in the absence of CCL2, neurons become more susceptible to the neurotoxic effect of MeHg. Indeed, as shown in Figure 1b, KO CCL2 mice show a significant higher decrease in neuronal cell density in the parietal/sensorimotor cortex in response to MeHg.

MeHg has been shown to produce neuronal cell death *in vitro* on cerebellar granular cells (Daré *et al*., 2000; Sakaue *et al*., 2005), hippocampal cells (Falluel-Morel *et al*., 2007), and cultured neural progenitor cells (Ceccatelli *et al*., 2007; Tamm *et al*., 2006; Xu *et al*., 2010). It was reported that under various conditions MeHg caused both necrosis and apoptosis (Ceccatelli *et al*., 2010). We recently showed that MeHg can induce *in vitro* cortical neuronal cell death via a caspase-dependent apoptosis and suppression of the Rho-family protein Rac1, resulting in axonal degeneration preceding the apoptotic process (Fujimura *et al*., 2009). The present *in vitro* results carried out on pure neuronal cultures, though not analyzing the morphological apoptotic process itself, are in agreement with these data because the neurotoxic effects of MeHg are obtained with similar nanomolar concentrations of MeHg (Fujimura *et al*., 2009). Our results not only show a dose-dependent effect of MeHg on neuronal cell death, but also show a time-dependent effect. A dose of MeHg that does not induce cell death at 1 day of culture can become as deleterious as a much higher concentration after 2–5 days of treatment. Such effect can be seen in the human contamination by MeHg with food intake, in particular fish consumption, with a body accumulation of MeHg becoming deleterious with time (Bourdineaud *et al*., 2008, 2011).

We have used different approaches to demonstrate that the lack of CCL2 potentiates the neurotoxic effect of MeHg. We first observed an increase in neuronal cell death, which is stronger in the presence of MeHg when CCL2 is blocked with either an antibody against the chemokine resulting in an undetectable level of free CCL2 in the incubation medium or with a nonpeptide antagonist known to block the binding of CCL2 to its receptor CCR2. This suggests that CCL2 via CCR2 may be protective against basal or MeHg-induced neuronal cell death. Such neuroprotective effect of CCL2 has been already reported *in vitro* on *N*-methyl-D-aspartate-induced apoptosis (Bruno *et al*., 2000; Eugenin *et al*., 2003). In regard to the data shown in Figures 5a and 5b, we cannot exclude the possibility that MeHg may induce cell death on a population of neurons that are different from a population of neurons undergoing cell death in response to blockade of CCL2 neurotransmission. Second, the *U*-shaped curve on the protective effect of CCL2 observed with increasing concentrations of CCL2 (Fig. 5c) suggests opposing functions depending on the chemokine concentration. Such a process, named "hormesis," relates to adaptative responses to compensate disruption in homeostasis by overshooting homeostatic feedback controls and was recently suggested to play a role in the effects of MeHg (Helmcke and Aschner, 2010).

It has been shown that neurons respond to MeHg with ROS production, representing a key mechanism by which MeHg causes cell damage (Aschner *et al*., 2007; Yee and Choi, 1996). The brain is highly vulnerable to oxidative stress due to its high rate of metabolism, a low level of oxidative defense mechanisms and a high production of ROS resulting in neuronal cell death (Aschner *et al*., 2007). Several reports demonstrated that GSH, which has important functions as an antioxidant and on detoxification of xenobiotics, is a potential molecular target for MeHg neurotoxicity (Ceccatelli *et al*., 2007, 2010; Kaur *et al*., 2006; Stringari *et al*., 2008). The beneficial effect of GSH is attributed to its capacity to form conjugates with MeHg, facilitating cell efflux of these organometallic molecules (Stringari *et al*., 2008).

Interestingly, the presence of CCL2 is able to counteract the depletion in GSH induced by MeHg, suggesting a possible mechanism by which low concentrations of CCL2 protects neuronal cells to the neurotoxic effect of MeHg. Indeed, maintenance of adequate GSH levels was shown to protect against MeHg-induced oxidative stress in primary neuronal cell cultures (Ceccatelli *et al*., 2010). Though the connection between CCL2 signaling via CCR2 involving various kinases and GSH is not well documented, it has been reported in relation to the present work that intracellular GSH redox status modulates the expression of CCL2 through redox-sensitive transcription factors in a rat model of lung disease (Desai *et al*., 1999).

The present results showing an upregulation of *sod* genes following MeHg exposure further demonstrate the implication of the oxidative stress in the deleterious effect of MeHg. The fact that the aimara-fed KO CCL2 mice do not present such upregulation of sod genes confirms the protective effect of the chemokine. Furthermore, the observation that KO CCL2 mice fed with the control RM1 diet displays *sod* gene expression 60% higher than that in wild-type brain is indicative that the oxidative level increased in the absence of CCL2. Finally, the twofold

decrease in the expression level of the *sod2* gene as compared with wild-type brain in KO CCL2 mice fed with the aimara-containing diet demonstrates that CCL2 production is needed to stimulate the *sod* gene expression in response to MeHg.

The decrease in brain CCL2 content observed *in vivo* in the aimara fed mice also reveals another possible mechanism for MeHg neurotoxicity. The CCL2 molecule has four cysteines in its primary structure, which represent a target for MeHg that binds in the same manner to GSH and free cysteines (de Melo Reis *et al*., 2007). According to the respective brain concentrations of CCL2 and of Hg, the chemokine can be partially neutralized by MeHg.

Finally, we observed that MeHg exposure not only induces neuronal cell death but also increases the number of microglial cells in the sensoricortex of wild-type mice. This increase in microglial cell number is not observed in KO CCL2 mice. It may be due to the known effect of CCL2 on microglial migration, which is hampered in the absence of CCL2 (Meucci, 2010). Although it was not the aim of the present work, future experiments would be of interest to study the impact of microglia in brain responses to MeHg neurotoxicity. Indeed, it was recently shown *in vitro* that microglia may be affected by MeHg (Garg and Chang, 2006; Ni *et al*., 2011). It has been extensively described that microglia as well as astrocytes can synthesize and release CCL2 (Lawrence *et al*., 2006; Meucci, 2010). The present *in vivo* and *in vitro* results suggest that the activation of glial cells such as microglia following MeHg contamination may prevent neuronal apoptosis by releasing CCL2 and other protective molecules as shown *in vitro* in Supplementary figure 1. However, when the glial protection is no longer active with time under long-term MeHg toxicity, primarily due to a decrease in detoxification process (Bourdineaud *et al*., 2008) or to the decrease in the neuroprotective effect of CCL2 (decrease in CCL2 content, absence of CCL2, and/or too much CCL2 released; Fig. 5c), the neurotoxic effect of MeHg can be observed, as shown in the present study following 3 months of low contamination with MeHg.

Taken together, these original data bring new ideas and orientations on the possible implication of the chemokines such as CCL2 in the physiopathology of brain diseases due to heavy metal intoxication. The MeHg pollution in the Minamata Bay in Japan (Eto, 2000) brought light to industrial MeHg contamination and the human health concern on the impact of adverse effects of MeHg contamination through daily fish, seafood, or marine mammal consumption (Myers *et al*., 2007). Therefore, the present work is highly relevant to better understanding the basic neurobiological mechanisms involved in brain MeHg intoxication inducing neurological deficits.

SUPPLEMENTARY DATA

Supplementary data are available online at http://toxsci.oxfordjournals.org/.

FUNDING

French National Research Agency "Santé-environnement et santé-travail" program, ANR no. SEST 2005-034; University P and M. Curie Paris VI for France–Japan exchanges.

ACKNOWLEDGMENTS

We thank P. Casanova for help with the *in vivo* experiments with mice contaminated with MeHg, J. Shibato, Y. Masuo (Japan) and P. Gonzalez (France) for help and advice for the *in vitro* experiments and A. Reaux-LeGoazigo for advice on statistical analysis. The CCR2 antagonist was provided by Pfizer. Author contributions: Experiments were carried out by D.G., R.-D.G., M.F., A.Y., R.M.-B., and M.L. J.P.B. was supervising the program entitled "Mercury impacts on aquatic ecosystems and human populations health" funded by the French National Research Agency. C.C. provided some CCL2 KO mice and advice. R.R. participated to the *in vitro* experiments and contributed to the English corrections of the manuscript. S.M.P. contributed to the writing and advice of the manuscript.

REFERENCES

Aschner, M., Syversen, T., Souza, D. O., Rocha, J. B., and Farina, M. (2007). Involvement of glutamate and reactive oxygen species in methylmercury neurotoxicity. *Braz. J. Med. Biol. Res.* **40,** 285–291.

Auger, N., Kofman, O., Kosatsky, T., and Armstrong, B. (2005). Low-level methylmercury exposure as a risk factor for neurologic abnormalities in adults. *Neurotoxicology* **26,** 149–157.

Banisadr, G., Gosselin, R. D., Mechighel, P., Kitabgi, P., Rostène, W., and Parsadaniantz, S. M. (2005a). Highly regionalized neuronal expression of monocyte chemoattractant protein-1 (MCP-1/CCL2) in rat brain: Evidence for its colocalization with neurotransmitters and neuropeptides. *J. Comp. Neurol.* **489,** 275–292.

Banisadr, G., Gosselin, R. D., Mechighel, P., Rostène, W., Kitabgi, P., and Mélik-Parsadaniantz, S. (2005b). Constitutive neuronal expression of CCR2 chemokine receptor and its colocalization with neurotransmitters in normal rat brain: Functional effect of MCP-1/CCL2 on calcium mobilization in primary cultured neurons. *J. Comp. Neurol.* **492,** 178–192.

Bourdineaud, J. P., Bellance, N., Bénard, G., Brèthes, D., Fujimura, M., Gonzalez, P., Marighetto, A., Maury-Brachet, R., Mormède, C., Pédron, V., *et al*. (2008). Feeding mice with diets containing mercury-contaminated fish flesh from French Guiana: A model for the mercurial intoxication of the Wayana Amerindians. *Environ. Health* **7,** 53–66.

Bourdineaud, J. P., Fujimura, M., Laclau, M., Sawada, M., and Yasutake, A. (2011). Deleterious effects in mice of fish-associated methylmercury contained in a diet mimicking the Western populations' average fish consumption. *Environ. Int.* **37,** 303–313.

Brodmerkel, C. M., Huber, R., Covington, M., Diamond, S., Hall, L., Collins, R., Leffet, L., Gallagher, K., Feldman, P., Collier, P., *et al*. (2005). Discovery and pharmacological characterization of a novel rodent-active CCR2 antagonist, INCB3344. *J. Immunol.* **175,** 5370–5378.

Bruno, V., Copani, A., Besong, G., Scoto, G., and Nicoletti, F. (2000). Neuroprotective activity of chemokines against N-methyl-D-aspartate or beta-amyloid-induced toxicity in culture. *Eur. J. Pharmacol.* **399,** 117–121.

Ceccatelli, S., Daré, E., and Moors, M. (2010). Methylmercury-induced neurotoxicity and apoptosis. *Chem. Biol. Interact.* **188,** 301–308.

Ceccatelli, S., Tamm, C., Zhang, Q., and Chen, M. (2007). Mechanisms and modulation of neural cell damage induced by oxidative stress. *Physiol. Behav.* **92,** 87–92.

Daré, E., Götz, M. E., Zhivotovsky, B., Manzo, L., and Ceccatelli, S. (2000). Antioxidants J811 and 17beta-estradiol protect cerebellar granule cells from methylmercury-induced apoptotic cell death. *J. Neurosci. Res.* **62,** 557–565.

Desai, A., Huang, X., and Warren, J. S. (1999). Intracellular glutathione redox status modulates MCP-1 expression in pulmonary granulomatous vasculitis. *Lab. Invest.* **79,** 837–847.

Eto, K. (2000). Minamata disease. *Neuropathology* **20**(Suppl), S14–S19.

Eugenin, E. A., D'Aversa, T. G., Lopez, L., Calderon, T. M., and Berman, J. W. (2003). MCP-1 (CCL2) protects human neurons and astrocytes from NMDA or HIV-tat-induced apoptosis. *J. Neurochem.* **85,** 1299–1311.

Falluel-Morel, A., Sokolowski, K., Sisti, H. M., Zhou, X., Shors, T. J., and Dicicco-Bloom, E. (2007). Developmental mercury exposure elicits acute hippocampal cell death, reductions in neurogenesis, and severe learning deficits during puberty. *J. Neurochem.* **103,** 1968–1981.

Franklin, K., and Paxinos, G. (1997). *The Mouse Brain in Stereotaxic Coordinates*. Academic Press, San Diego, CA.

Fujimura, M., Usuki, F., Sawada, M., Rostène, W., Godefroy, D., and Takashima, A. (2009). Methylmercury exposure downregulates the expression of Racl and leads to neuritic degeneration and ultimately apoptosis in cerebrocortical neurons. *Neurotoxicology* **30,** 16–22.

Garg, T. K., and Chang, J. Y. (2006). Methylmercury causes oxidative stress and cytotoxicity in microglia: Attenuation by 15-deoxy-delta 12, 14-prostaglandin J2. *J. Neuroimmunol.* **171,** 17–28.

Harvey, W. R. (1966). *Least-Square Analysis of Data with Unequal Subclass Numbers*. U.S. Agricultural Research Service, ARS20.

Helmcke, K. J., and Aschner, M. (2010). Hormetic effect of methylmercury on Caenorhabditis elegans. *Toxicol. Appl. Pharmacol.* **248,** 156–164.

Huang, C. F., Hsu, C. J., Liu, S. H., and Lin-Shiau, S. Y. (2008). Neurotoxicological mechanism of methylmercury induced by low-dose and long-term exposure in mice: Oxidative stress and down-regulated Na+/K(+)-ATPase involved. *Toxicol. Lett.* **176,** 188–197.

Hwang, G. W., Lee, J. Y., Ryoke, K., Matsuyama, F., Kim, J. M., Takahashi, T., and Naganuma, A. (2011). Gene expression profiling using DNA microarray analysis of the cerebellum of mice treated with methylmercury. *J. Toxicol. Sci.* **36,** 389–391.

Kaur, P., Aschner, M., and Syversen, T. (2006). Glutathione modulation influences methyl mercury induced neurotoxicity in primary cell cultures of neurons and astrocytes. *Neurotoxicology* **27,** 492–500.

Lawrence, D. M. P., Seth, P., Durham, L., Diaz, F., Boursiquot, R., Ransohoff, R. M., and Major, E. O. (2006). Astrocyte differentiation selectively upregulates CCL2/monocyte chemoattractant protein-1 in cultured human brain-derived progenitor cells. *Glia* **53,** 81–91.

Lu, B., Rutledge, B. J., Gu, L., Fiorillo, J., Lukacs, N. W., Kunkel, S. L., North, R., Gerard, C., and Rollins, B. J. (1998). Abnormalities in monocyte recruitment and cytokine expression in monocyte chemoattractant protein 1-deficient mice. *J. Exp. Med.* **187,** 601–608.

Maury-Brachet, R., Durieu, G., Dominique, Y., and Boudou, A. (2005). Mercury distribution in fish organs and food regimes: Significant relationships from twelve species collected in French Guiana (Amazonian basin). *Sci. Total Environ.* **368,** 262–270.

de Melo Reis, R. A., Herculano, A. M., da Silva, M. C., dos Santos, R. M., and do Nascimento, J. L. (2007). In vitro toxicity induced by methylmercury on sympathetic neurons is reverted by L-cysteine or glutathione. *Neurosci. Res.* **58,** 278–284.

Meucci, O. (2010). *Chemokine Receptors Function and NeuroAIDS*. Springer, New York, NY.

Myers, G. J., Davidson, P. W., and Strain, J. J. (2007). Nutrient and methyl mercury exposure from consuming fish. *J. Nutr.* **137,** 2805–2808.

Ni, M., Li, X., Yin, Z., Sidoryk-Węgrzynowicz, M., Jiang, H., Farina, M., Rocha, J. B., Syversen, T., and Aschner, M. (2011). Comparative study on the response of rat primary astrocytes and microglia to methylmercury toxicity. *Glia* **59,** 810–820.

Ransohoff, R. M. (2009). Chemokines and chemokine receptors: Standing at the crossroads of immunobiology and neurobiology. *Immunity* **31,** 711–721.

Rostène, W., Kitabgi, P., and Parsadaniantz, S. M. (2007). Chemokines: A new class of neuromodulator? *Nat. Rev. Neurosci.* **8,** 895–903.

Rush, T., Hjelmhaug, J., and Lobner, D. (2009). Effects of chelators on mercury, iron, and lead neurotoxicity in cortical culture. *Neurotoxicology* **30,** 47–51.

Sakaue, M., Okazaki, M., and Hara, S. (2005). Very low levels of methylmercury induce cell death of cultured rat cerebellar neurons via calpain activation. *Toxicology* **213,** 97–106.

Schreiber, R. C., Krivacic, K., Kirby, B., Vaccariello, S. A., Wei, T., Ransohoff, R. M., and Zigmond, R. E. (2001). Monocyte chemoattractant protein (MCP)-1 is rapidly expressed by sympathetic ganglion neurons following axonal injury. *Neuroreport* **12,** 601–606.

Stringari, J., Nunes, A. K., Franco, J. L., Bohrer, D., Garcia, S. C., Dafre, A. L., Milatovic, D., Souza, D. O., Rocha, J. B., Aschner, M., *et al.* (2008). Prenatal methylmercury exposure hampers glutathione antioxidant system ontogenesis and causes long-lasting oxidative stress in the mouse brain. *Toxicol. Appl. Pharmacol.* **227,** 147–154.

Szabo, A., Dalmau, J., Manley, G., Rosenfeld, M., Wong, E., Henson, J., Posner, J. B., and Furneaux, H. M. (1991). HuD, a paraneoplastic encephalomyelitis antigen, contains RNA-binding domains and is homologous to Elav and Sex-lethal. *Cell* **67,** 325–333.

Tamm, C., Duckworth, J., Hermanson, O., and Ceccatelli, S. (2006). High susceptibility of neural stem cells to methylmercury toxicity: Effects on cell survival and neuronal differentiation. *J. Neurochem.* **97,** 69–78.

Tietze, F. (1969). Enzymic method for quantitative determination of nanogram amounts of total and oxidized glutathione: Applications to mammalian blood and other tissues. *Anal. Biochem.* **27,** 502–522.

Winer, B. J. (1971). *Statistical Principles in Experimental Design*. McGraw Hill, New York, NY.

Xu, M., Yan, C., Tian, Y., Yuan, X., and Shen, X. (2010). Effects of low level of methylmercury on proliferation of cortical progenitor cells. *Brain Res.* **1359,** 272–280.

Yee, S., and Choi, B. H. (1996). Oxidative stress in neurotoxic effects of methylmercury poisoning. *Neurotoxicology* **17,** 17–26.