

Deletion of CB₂ Cannabinoid Receptor Induces Schizophrenia-Related Behaviors in Mice

Antonio Ortega-Alvaro¹, Auxiliadora Aracil-Fernández^{2,3}, María S García-Gutiérrez^{2,3}, Francisco Navarrete^{2,3} and Jorge Manzanares^{*,2,3}

¹Unidad de Neuropsicofarmacología Traslacional, Complejo Hospitalario Universitario de Albacete, Albacete, Spain; ²Instituto de Neurociencias, Universidad Miguel Hernández-CSIC, San Juan de Alicante, Alicante, Spain; ³Red Temática de Investigación Cooperativa en Salud (RETICS), Red de Trastornos Adictivos, Instituto de Salud Carlos III, MICINN and FEDER, Madrid, Spain

The possible role of the CB₂ receptor (CB₂r) in psychiatric disorders has been considered. Several animal models use knockout (KO) mice that display schizophrenia-like behaviors and this study evaluated the role of CB₂r in the regulation of such behaviors. Mice lacking the CB₂r (CB₂KO) were challenged in open field, light–dark box, elevated plus-maze, tail suspension, step down inhibitory avoidance, and pre-pulse inhibition tests (PPI). Furthermore, the effects of treatment with cocaine and risperidone were evaluated using the OF and the PPI test. Gene expression of dopamine D₂ (D₂r), adrenergic- α_{2C} (α_{2C} r), serotonergic 5-HT_{2A} and 5-HT_{2C} receptors (5-HT_{2Ar} and 5-HT_{2Cr}) were studied by RT-PCR in brain regions related to schizophrenia. Deletion of CB₂r decreased motor activity in the OF test, but enhanced response to acute cocaine and produced mood-related alterations, PPI deficit, and cognitive impairment. Chronic treatment with risperidone tended to impair PPI in WT mice, whereas it 'normalized' the PPI deficit in CB₂KO mice. CB₂KO mice presented increased D₂r and α_{2C} r gene expressions in the prefrontal cortex (PFC) and locus coeruleus (LC), decreased 5-HT_{2Cr} gene expression in the dorsal raphe (DR), and 5-HT_{2Ar} gene expression in the PFC. Chronic risperidone treatment in WT mice left α_{2C} r gene expression unchanged, decreased D₂r gene expression (15 μ g/kg), and decreased 5-HT_{2Cr} and 5-HT_{2Ar} in PFC and DR. In CB₂KO, the gene expression of D₂r in the PFC, of α_{2C} r in the LC, and of 5-HT_{2Cr} and 5-HT_{2Ar} in PFC was reduced; 5-HT_{2Cr} and 5-HT_{2Ar} gene expressions in DR were increased after treatment with risperidone. These results suggest that deletion of CB₂r has a relation with schizophrenia-like behaviors. Pharmacological manipulation of CB₂r may merit further study as a potential therapeutic target for the treatment of schizophrenia-related disorders.

Neuropsychopharmacology (2011) **36**, 1489–1504; doi:10.1038/npp.2011.34; published online 23 March 2011

Keywords: cannabinoid; CB₂ receptor; schizophrenia; risperidone; pre-pulse inhibition; gene expression

INTRODUCTION

In recent years, it has been postulated that the endocannabinoid system may be an important element involved in the development of schizophrenia. This assumption is supported by several observations: (1) cannabis use was reported in around 50% of schizophrenic patients (Barnett *et al*, 2007; Bersani *et al*, 2002); (2) cannabis use is associated with an increased risk of developing schizophrenia (Andreasson *et al*, 1987; Zammit *et al*, 2002); (3) a decrease in the age of onset of schizophrenia has been reported (Sugranyes *et al*, 2009); and (4) schizophrenia-like

symptoms may develop in non-schizophrenic cannabis users (Morgan and Curran, 2008). In addition, schizophrenic patients showed a worsening of both positive and negative symptoms and cognitive deficits after administration of Δ^9 -THC (D'Souza *et al*, 2005). Indeed, high levels of anandamide have been found in plasma and cerebrospinal fluid (CSF) in antipsychotic-naïve first-episode paranoid schizophrenics (Leweke *et al*, 1999; Yao *et al*, 2002), and increased CB₁ receptor (CB₁r) expression in the dorsolateral prefrontal cortex (PFC) of schizophrenic patients (Dean *et al*, 2001). It is interesting to note that drugs used to treat schizophrenia modify these abnormal parameters in the endogenous cannabinoid system. In fact, the increased levels of anandamide in the CSF (Giuffrida *et al*, 2004) and plasma (De Marchi *et al*, 2003) are normalized by antipsychotic treatment. On the other hand, antipsychotic treatment decrease CB₁r immunodensity in the PFC of subjects with schizophrenia as determined in post-mortem studies (Urigüen *et al*, 2009).

*Correspondence: Dr J Manzanares, Instituto de Neurociencias, Universidad Miguel Hernández-CSIC, Avda. Ramón y Cajal s/n, San Juan de Alicante, Alicante 03550, Spain, Tel: +34 96 591 9248, E-mail: jmanzanares@umh.es

Received 1 July 2010; revised 7 February 2011; accepted 12 February 2011

As for the anatomic location of cannabinoid receptors, CB₁r is mainly expressed in the CNS, particularly the basal ganglia, hippocampus, cerebellum, and cerebral cortex (Abood *et al*, 2010a; Herkenham *et al*, 1990, 1991). In contrast, CB₂ receptor (CB₂r) has been considered the 'peripheral' cannabinoid receptor owing to its presence in the spleen and lymphocytes (Abood *et al*, 2010b; Munro *et al*, 1993). However, considerable functional and anatomic evidence suggests that CB₂r are expressed in the nervous system. CB₂r were recently found in the brainstem of rat, mouse, and ferret (Van Sickle *et al*, 2005). Further studies in rats have identified CB₂r distributed extensively throughout different brain areas, including the spinal nucleus, hippocampus, olfactory nucleus, cerebral cortex, amygdala, striatum, thalamus, and cerebellum (Atwood and Mackie, 2010; Gong *et al*, 2006; Onaivi *et al*, 2006). In addition, CB₂r gene expression has been identified in the thalamus, periaqueductal grey matter, cervical and thoracic spinal cord, and different brain nuclei, including the caudate-putamen, nucleus accumbens, cingulate cortex, amygdala, hippocampus, ventromedial hypothalamic nucleus, arcuate nucleus, substantia nigra, and dorsal and medial raphe nuclei (Garcia-Gutierrez *et al*, 2010; Racz *et al*, 2008).

In addition, recent studies have sketched out the potential role of cannabinoid CB₂r in the neurobiology of psychiatric disorders (Ishiguro *et al*, 2010; Onaivi, 2009). Interestingly, a close relation between diminished CB₂r function (polymorphism Q63R) and increased susceptibility to schizophrenia in the presence of other risk factors has been reported (Ishiguro *et al*, 2010). This observation supports the notion of a relationship between the cannabinoid system and the development of schizophrenia. It is important to point out the role of the CB₂r in the control of fundamental neural cell processes, such as proliferation and survival (Fernandez-Ruiz *et al*, 2007). The proliferation of hippocampal neural progenitors may be modulated through CB₂r (Goncalves *et al*, 2008; Palazuelos *et al*, 2006) and has resulted defective in CB₂KO (knockout) mice (Buckley *et al*, 2000). Therefore, it can be hypothesized that deletion of the CB₂r gene could result in the development of neurochemical abnormalities that may underlie possible behavioral alterations in several experimental paradigms.

On the other hand, several reports have pointed out that the deletion of CB₁r produces a behavioral endophenotype consisting of a high degree of anxiety and increased vulnerability to depression-like behaviors (Martin *et al*, 2002; Urigüen *et al*, 2004) and decreased memory impairment (Bohme *et al*, 1999; Reibaud *et al*, 1999). To date, information on the impact of the elimination of the CB₁r on the development of schizophrenia/like behaviors has not been available.

The aim of this study was to determine the response of CB₂KO mice in different behavioral and cognitive experimental paradigms and gene expression alterations in brain areas related to schizophrenia. This behavioral and cognitive profile covered motor, anxiety, depression, short- and long-term memory, and attention deficit. Furthermore, the effects of treatment with risperidone were evaluated by using the pre-pulse inhibition test (PPI) in wild-type (WT) and CB₂KO mice. The gene expression studies were designed to detect changes in dopamine D₂ receptor (D₂r) in the PFC, adrenergic- α_{2C} receptor (α_{2C} r) in the PFC and locus coeruleus (LC), and serotonergic 5-HT_{2A} and 5-HT_{2C}

receptors (5-HT_{2A}r and 5-HT_{2C}r) gene expression in the PFC and dorsal raphe (DR) by real-time PCR of naive WT and CB₂KO mice treated with risperidone.

MATERIALS AND METHODS

Animals

Male CB₂KO mice on a C57BL/6J congenic background (kindly provided by Nancy E Buckley, Cal State Polytechnic University, Pomona, CA) were used. CB₂KO founders crossed with outbred CD1 (Charles River, L'Arbresle Cedex, France) background (Buckley *et al*, 2000). Homozygotes from CB₂KO ($n = 119$) and age-matched WT mice ($n = 108$) were used in all experiments. Mice were 2–3 months old and weighed 25–35 g at the beginning of the experiments. All animals were kept at controlled temperature ($23 \pm 2^\circ\text{C}$) and light conditions (light–dark cycle switching at 0800 hours and 2000 hours). All studies were conducted in compliance with Spanish Royal Decree 223/1998 of 14 March (BOE. 8 18), the Ministerial Order of 13 October 1989 (BOE 18), and European Council Directive of 24 November 1986 (86/609/EEC) regulating the care of experimental animals. The evaluation of behaviors in the light–dark box, elevated plus-maze, tail suspension, and memory tests were made manually under blind conditions.

Drugs

Cocaine hydrochloride was obtained from the Ministry of Health and Consumer Affairs (Ministerio de Sanidad y Consumo, AGEMED, Madrid, Spain) and was dissolved in sterile 0.9% physiological saline. Mice were administered a single intraperitoneal 15 mg/kg dose 10 min before motor activity assessment. The cocaine dose was selected based on previous experiments from our laboratory not showing stereotyped behavior (data not shown). The atypical antipsychotic risperidone (STADA, Barcelona, Spain) was dissolved in sterile 0.9% physiological saline and administered *per os* in a volume of 10 ml/kg. Risperidone was administered at doses of 15, 30, and 60 $\mu\text{g}/\text{kg}$, twice a day (0830 and 1800 hours). CB₂KO ($n = 36$) and WT ($n = 36$) animals treated with risperidone or saline were used for PPI and gene expression studies.

Motor Activity

Open field test. The open field consists of a transparent square cage $25 \times 25 \times 25 \text{ cm}^3$ with a white Plexiglas floor (Urigüen *et al*, 2004). Mice were individually placed in the center to initiate a 20-min test that was recorded with a video camera and analyzed with the SMART (Spontaneous Motor Activity Recording and Tracking) v.2.5.3 software system (Panlab, Barcelona, Spain). Traveled distance and mean speed were analyzed. At 10 min after cocaine administration, motor activity was measured for 20 min. Results obtained in this test were analyzed in the whole 20-min period and also divided into 5-min periods.

Anxiety-Like Behavior

Light–dark box test. This model (Crawley and Goodwin, 1980) consisted of two methacrylate boxes $20 \times 20 \times 15 \text{ cm}^3$, one transparent and one black and opaque, linked by an

opaque tunnel (4 cm). Light from a 60 W desk lamp located 25 cm above the light box provided room illumination. Mice were individually placed facing the black box and tested in 5-min sessions. The time spent in the lighted area and the number of transitions was recorded. A mouse that introduced three paws into the opposite side of the box was counted as a transition.

Elevated plus-maze test. This paradigm consisted of two open arms and two enclosed horizontal perpendicular arms 50 cm above the floor (Lister, 1987). The junction of four arms formed a central squared platform (5 × 5 cm²). The test began with the animal being placed in the center of the apparatus facing one of the enclosed arms and allowed to explore freely for 5 min. We counted as arm entries the introduction of four paws into the arm. The time spent in the open arms and the number of open-arm entries was recorded.

Depression-Like Behavior

Tail suspension test. Mice were individually suspended by the tail at the edge of a lever suspended above the table top (the distance to the table surface was 35 cm), and affixed with adhesive tape placed approximately 1–2 cm from the tip of the tail (Vaugeois *et al*, 1997). The duration of immobility was measured for 6 min. In this situation, mice develop escape-oriented behaviors interspersed with increasingly longer bouts of immobility.

Evaluation of Short- and Long-Term Memory

Step down inhibitory avoidance. The apparatus is a 31 × 19 × 15 cm³ acrylic box with a platform located next to a grid. Mice were placed on the platform and their latency to step down on the grid with all four paws was measured; a modified protocol was followed (Izquierdo *et al*, 1998). During the training session, immediately after stepping down on the grid, the animals received a 2.0-s, 0.4-mA scrambled foot shock. Retention tests were procedurally identical, except that no foot shock was given and the latency to step down in these conditions was taken as a measure of emotional memory. A ceiling of 180 s was imposed, that is, animals with a test latency of more than 180 s were counted as 180 s. Each animal was tested at 1 and 3 h after training (short-term memory) and at 24 h (long-term memory).

Sensorimotor Gating

Acoustic pre-pulse inhibition. Pre-pulse inhibition refers to the reduction in amplitude of the startle reflex that occurs when a brief, sub-threshold stimulus immediately precedes a startle stimulus (Hoffman and Ison, 1980). Startle responses were measured using the CIBERTEC REST 141 system (Madrid, Spain). The testing chamber consisted of a plastic adjustable cover mounted on a platform. Movement of the mice within the cover was detected by a piezoelectric accelerometer attached below the platform. A loudspeaker mounted 15 cm above the cover provided background white noise and both acoustic pulses and pre-pulses. The entire apparatus was housed in a ventilated enclosure.

Presentation of acoustic pulse and pre-pulse stimuli was controlled by the MONRS software and interface system, which also digitized, rectified, and recorded the responses from the accelerometer. Mean startle amplitude was determined by averaging ten 100 ms readings taken from the beginning of the pulse stimulus onset. Test sessions consisted of no stimulus, pulse-only, and pre-pulse trials. Each 'pre-pulse' trial consisted of a 20-ms 68, 71, or 77 dB non-startling pre-pulse followed 100 ms later by a 40-ms startling pulse of 120 dB. In contrast, 'pulse-only' trials consisted of the 120-dB stimulus only, and 'no-stimulus' trials contained background noise only. To allow acclimatizing, 3 days before the performance of the test sessions, mice were placed each day in the apparatus for 5 min without background noise. Test sessions began with a 5-min acclimatization period using a background noise of 65 dB. The test sessions consisted of a series of 11 pulse-only trials for habituation purposes, followed by 10 trials of each pre-pulse intensity plus pulse, and 10 no-stimulus trials, all presented in a pseudorandom order with a 7–23 s inter-trial variable interval. The percentage of pre-pulse inhibition was defined as ((startle amplitude on pulse alone trials – startle amplitude on pre-pulse trials) × 100)/startle amplitude on pulse alone trials.

Experimental design. Pre-pulse inhibition experiments were carried out in two steps. Firstly, the PPI response was determined under baseline conditions ($n = 36$). After confirming a significant difference in the PPI response, the effect of chronic oral risperidone treatment (twice a day for 12 days) was tested in both CB₂KO ($n = 36$) and WT ($n = 36$) mice. Animals were randomly assigned to each treatment group (saline, risperidone 15, 30, and 60 μg/kg) in each genotype. PPI response was evaluated after 4, 8, and 12 days of treatment. Each PPI test session was conducted between 1200 and 1500 hours. At 1 h after the last test session, animals were killed and brains were removed for gene expression studies. The number of animals used for statistical analyses ($n = 32$ per genotype) was slightly lower than the initial number of treated animals owing to software failure ($n = 4$), escape from PPI restraint ($n = 3$), and accidental death after oral administration ($n = 1$).

Gene Expression Analyses

Gene expression studies focused on the main targets of the mechanism of action of risperidone, which is characterized by potent blockade of 5-HT_{2A}r coupled with the relatively weaker antagonism of the dopamine D₂r. In addition, this drug displays high affinity for serotonin 5-HT_{2C}r and adrenergic α_{2C}r (Schotte *et al*, 1995).

Real-time PCR. Mice were killed and brains were removed from the skull and frozen over dry ice. Coronal brain sections (500 μm) beginning at plates 19–20 (Paxinos and Franklin, 2001) were obtained in a cryostat (–10°C). The PFC, LC, and DR were microdissected according to a modification of the Palkovits method (Palkovits, 1983) as described previously (Garcia-Gutierrez *et al*, 2010). Total RNA was isolated from brain tissue micropunches using Trizol reagent (Invitrogen, Madrid, Spain) and subsequently retrotranscribed to cDNA. Quantitative analysis of

the relative abundance of 5-HT_{2A}R, 5-HT_{2C}R, D₂R, and α _{2C}R gene expressions was performed on the ABI PRISM 7700 Sequence Detector System (Applied Biosystems, Foster City, CA). All reagents were obtained from Applied Biosystems and the manufacturer protocols were followed. The reference gene used was 18S rRNA, detected using Taqman ribosomal RNA control reagents. All primer–probe combinations were optimized and validated for relative quantification of gene expression. Briefly, data for each target gene were normalized to the endogenous reference gene, and the fold change in target gene mRNA abundance was determined using the $2^{-\Delta\Delta Ct}$ method (Schmittgen *et al*, 2000). This quantification method involves comparing the Ct values of the samples of interest with a control or calibrator, such as a non-treated sample or RNA from normal tissue. The Ct values of both the calibrator and the samples of interest are normalized to an appropriate endogenous housekeeping gene (18S rRNA). CB₂KO ($n = 10$) and WT ($n = 8$) intact animals were used to study receptor gene expression under baseline conditions. Not all the samples analyzed resulted in useful data owing to failed reactions during RT-PCR processing. From the initial CB₂KO ($n = 36$) and WT ($n = 36$) mice treated with risperidone, eight samples were used per treatment group.

Statistical Analyses

In the open field, light–dark box, elevated plus-maze and tail suspension tests, amplitude of acoustic startle response baseline determination, and gene expression studies under baseline conditions, statistical analysis was performed using the Student's *t*-test for comparing two groups. One-way

analysis of variance (ANOVA) with repeated measures was carried out for both 5-min periods in the open field and step down inhibitory avoidance tests, and pre-pulse inhibition first determination. When appropriate, *post hoc* individual differences between groups were determined using the Student–Newman–Keuls test. Two-way ANOVA was carried out to evaluate the dose–response effects of risperidone treatment on gene expression. When appropriate, *post hoc* individual differences between groups were determined using the Student–Newman–Keuls test. Two-way ANOVA with repeated measures was used to analyze the temporal course and dose–response effects of risperidone treatment on the amplitude of the acoustic startle response. Two-way ANOVA with two repeated measures was used to analyze the temporal course and dose–response effects of risperidone treatment on %PPI. Differences were considered significant if the probability of error was less than 5%. SigmaStat v3.11 and SPSS v17 software was used for all statistical analyses.

RESULTS

Assessment of Motor Activity: Open Field Test

Analyses of 20-min periods: CB₂KO mice ($n = 14$) presented significantly shorter traveled distances compared with their respective controls ($n = 10$) (Student's *t*-test, $t = 2.482$, $p = 0.021$, 22 d.f.) (Figure 1a). Interestingly, the administration of cocaine (15 mg/kg, intraperitoneal) significantly increased the traveled distance in CB₂KO mice ($n = 14$) compared with WT mice ($n = 10$) (Student's *t*-test, $t = -5.410$, $p < 0.001$, 22 d.f.) (Figure 1c).

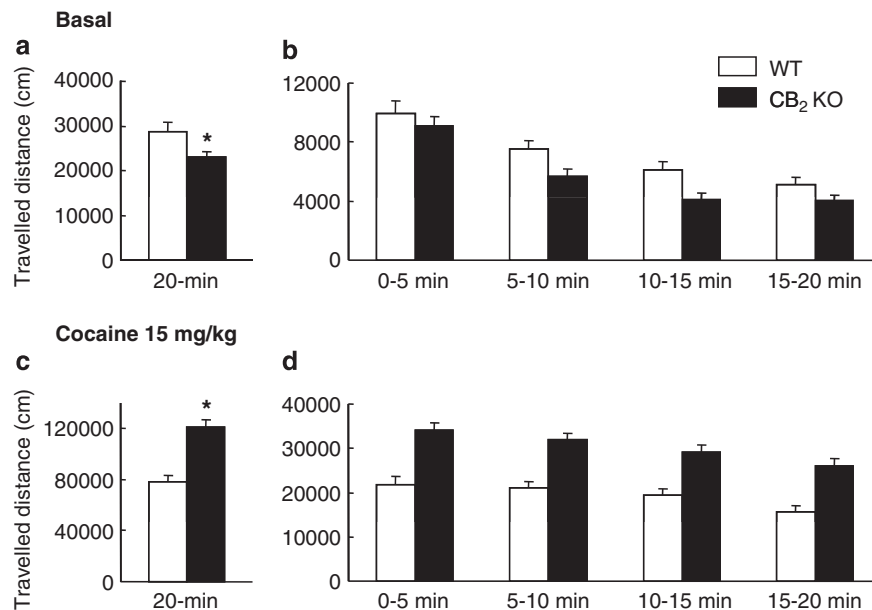


Figure 1 Evaluation of spontaneous motor activity in wild-type (WT) and CB₂KO (knockout) mice. Effect of cocaine on motor activity in both genotypes. The assessment of motor activity was determined measuring the traveled distance (cm) in the open field test during 20 min. In (a), the columns represent the means and the vertical lines represent the $1 \pm$ standard error of mean (SEM) of the traveled distance (cm) by CB₂KO compared with WT mice, under baseline conditions. In (c), WT and CB₂KO mice received a single cocaine dose (15 mg/kg) and 10 min after the traveled distance was measured during 20 min. Columns represent the means and the vertical lines represent the $1 \pm$ SEM of the traveled distance (cm) in mice treated with cocaine (15 mg/kg). In (b) and (d), the columns represent the means and the vertical lines represent the $1 \pm$ SEM of the traveled distance (cm) by CB₂KO compared with WT mice analyzed in 5-min periods. *Values from CB₂KO mice that differ significantly from values in WT mice (Student's *t*-test, $p < 0.05$).

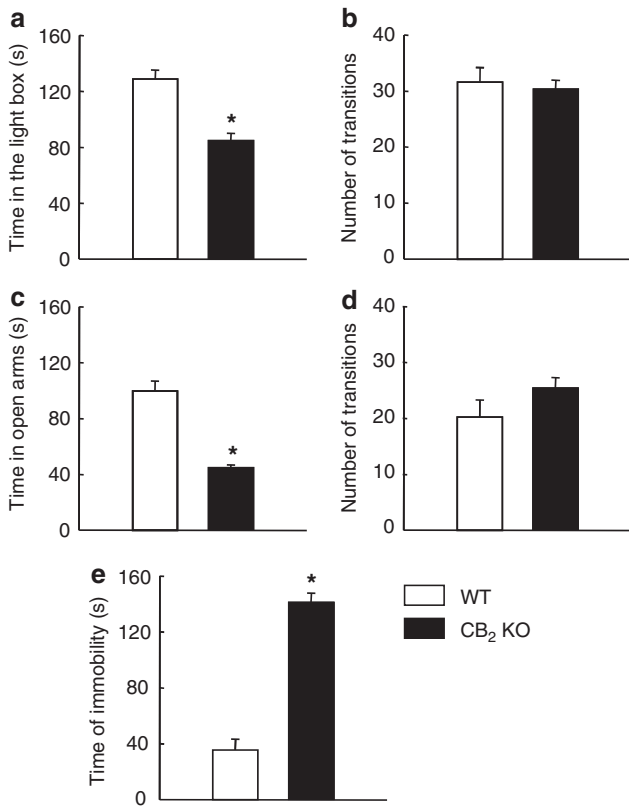


Figure 2 Evaluation of anxiogenic- and depressive-like behaviors in wild-type (WT) and CB₂KO (knockout) mice. The assessment of anxiogenic-like behaviors in WT and CB₂KO mice was carried out by using the light–dark box and the elevated plus maze. Columns represent the means and vertical lines represent the $1 \pm$ standard error of mean (SEM) of the time spent in the light side of the light–dark box and the time spent in the open arms of the elevated plus maze (s), (a) and (c) respectively. Columns represent the means and vertical lines represent the $1 \pm$ SEM of the number of transitions in the light–dark box and in the open arms, (b) and (d) respectively. In (e), the assessment of depressive-like behaviors in WT and CB₂KO mice in tail suspension. Columns represent the means and vertical lines represent the $1 \pm$ SEM of the time of immobility (s). *Values from CB₂KO that differ significantly from WT values (Student's *t*-test, $p < 0.05$).

Analyses of 5-min periods: Under baseline conditions, CB₂KO mice ($n = 14$) presented significantly shorter traveled distances compared with their corresponding control ($n = 10$) in the open field test. One-way ANOVA with repeated measures showed the significant main effects of genotype ($F_{(1,22)} = 6.150$, $p = 0.021$) and time course ($F_{(1,22)} = 124.922$, $p < 0.001$), but not significant effect of the genotype \times time-course interaction ($F_{(1,22)} = 0.097$, $p = 0.759$) (Figure 1b). The administration of cocaine (15 mg/kg, intraperitoneal) significantly increased the traveled distance in CB₂KO ($n = 14$) compared with WT mice ($n = 10$). One-way ANOVA with repeated measures showed significant main effects of genotype ($F_{(1,22)} = 29.271$, $p < 0.001$) and time course ($F_{(1,22)} = 36.851$, $p < 0.001$), but no significant effect of the genotype \times time-course interaction ($F_{(1,22)} = 0.773$, $p = 0.389$) (Figure 1d).

Assessment of Anxiety-Like Behaviors

CB₂KO mice ($n = 12$) spent significantly less time in the light box compared with WT mice ($n = 14$) (Student's *t*-test,

$t = 4.367$, $p < 0.001$, 24 d.f.) (Figure 2a). No differences were observed between the two genotypes in the number of transitions (Student's *t*-test, $t = 0.341$, $p = 0.736$, 24 d.f.) (Figure 2b).

In the elevated plus-maze test, the percentage of time spent in the open arms significantly decreased in CB₂KO ($n = 12$) compared with WT mice ($n = 14$) (Student's *t*-test, $t = 5.440$, $p < 0.001$, 24 d.f.) (Figure 2c). No differences were observed in the number of transitions between compartments (Student's *t*-test, $t = -1.024$, $p = 0.316$, 24 d.f.) (Figure 2d).

Assessment of Depressive-Like Behaviors: Tail Suspension Test

Exposure to the tail suspension induced a higher immobility time in CB₂KO mice ($n = 8$) than in WT littermates ($n = 10$) (Student's *t*-test, $t = -10.047$, $p < 0.001$, 16 d.f.), revealing increased despair behavior in the mice that lacked CB₂r (Figure 2e).

Assessment of Memory Impairment: Step Down Inhibitory Avoidance

No difference was observed in the pre-training session between CB₂KO ($n = 11$) and WT ($n = 8$) mice. Interestingly, the evaluation of representative parameters of short-term memory revealed that CB₂KO presented a shorter latency time at 1 and 3 h after scrambled foot shock. Moreover, CB₂KO mice had a lower latency time at 24 h (long-term memory) (one-way ANOVA with repeated measures followed by Student–Newman–Keuls test, genotype $F_{(1,17)} = 7.446$, $p = 0.014$; time $F_{(1,17)} = 6.297$, $p = 0.023$; genotype \times time $F_{(1,17)} = 8.069$, $p = 0.011$) (Figure 3).

Assessment of Sensorimotor Gating: Pre-pulse Inhibition

CB₂KO mice ($n = 36$) did not show differences in the acoustic startle response amplitude compared with WT mice ($n = 36$) (Student's *t*-test, $t = 0.265$, $p = 0.792$, 70 d.f.) (Figure 4a). On the other hand, PPI was significantly decreased in CB₂KO compared with WT mice. One-way ANOVA with repeated measures revealed the significant main effects of genotype ($F_{(1,70)} = 16.762$, $p < 0.001$) and pre-pulse intensity ($F_{(1,70)} = 230.285$, $p < 0.001$), whereas the genotype \times pre-pulse intensity interaction was not significant ($F_{(1,70)} = 0.155$, $p = 0.695$) (Figure 4b). Therefore, the reduction of PPI observed in CB₂KO mice was independent of the pre-pulse intensity tested.

Time Course and Dose Response of the Effects of Treatment with Risperidone on Acoustic Startle Response Amplitude

Risperidone treatment had a statistically significant effect, whereas genotype factor ($n = 32$) did not alter the acoustic startle response amplitude (Figure 5, Table 1). The time of treatment induced significant changes in startle amplitude.

Time Course and Dose Response of the Effects of Treatment with Risperidone on %PPI

The complexity of this experimental design did not allow the main factors of variation, genotype, and risperidone

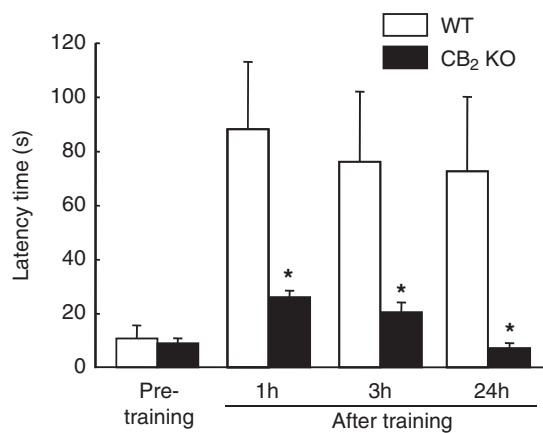


Figure 3 Evaluation of short- and long-term memory in wild-type (WT) and CB₂KO (knockout) mice. The memory assessment of WT and CB₂KO mice was evaluated using the step down inhibitory avoidance task. Columns represent the means and vertical lines represent the $1 \pm$ standard error of mean (SEM) of latency time before descent from the platform at four time points (pre-training, 1, 3, and 24 h). *Values from CB₂KO mice that differ significantly from values in WT mice (Student–Newman–Keuls test, $p < 0.05$).

treatment to reach statistical significance (Figure 6, Table 2). However, the two factors of repetition, pre-pulse intensity and time of treatment, have emerged as relevant factors of variation. In the case of pre-pulse intensity, more intense pre-pulse induced a higher %PPI value. In addition, the significant interaction between these two factors and genotype indicates that the evolution of %PPI differed in WT and CB₂KO mice. Thus, WT mice treated with saline showed a tendency toward lower %PPI (10–15%) over the course of treatment. In contrast, CB₂KO mice treated with saline showed a tendency toward higher %PPI (5–15%) in the same period. Although CB₂KO mice had a lower %PPI in the baseline determination, this slight increase could indicate that these mice maintain capacity to improve pre-attention. The differences between genotypes in the temporal course of %PPI were also observed in risperidone-treated animals. Thus, risperidone treatment enhanced the reduction of %PPI observed in saline-treated WT mice. The lowest and medium doses resulted in a 12–17% decrease, and the highest dose in a 16–21% decrease. Consequently, risperidone treatment tended to reduce pre-pulse inhibition. On the other hand, risperidone treatment increased %PPI in CB₂KO mice. The percentage PPI increased by 25–36% (15 μ g/kg), 25–30% (30 μ g/kg), and 32–34% (60 μ g/kg). In CB₂KO mice, risperidone treatment tended to improve PPI response (Figure 6, Table 2).

Evaluation of D₂R, α_{2C} R, 5-HT_{2C}R, and 5-HT_{2A}R Gene Expressions

Dopamine D₂R gene expression was studied in the PFC under baseline conditions and after 12 days of treatment with risperidone (15, 30, and 60 μ g/kg, *per os*) or saline in WT and CB₂KO mice. D₂R gene expression was significantly increased in the PFC of CB₂KO mice compared with WT mice (Student's *t*-test, $t = -2.933$, $p = 0.013$, 12 d.f.) ($n = 6-8$)

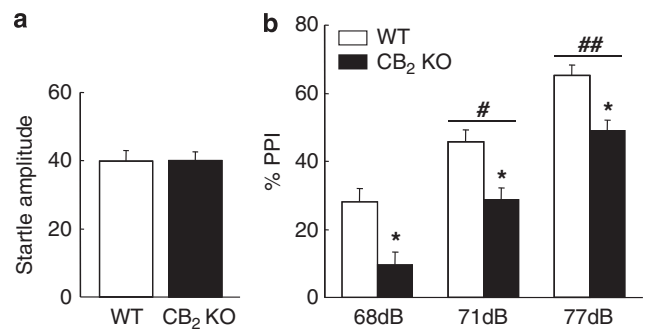


Figure 4 Amplitude and pre-pulse inhibition of the acoustic startle response in wild-type (WT) and CB₂KO (knockout) mice. Startle amplitude was measured using 120-dB pulse trials in WT and CB₂KO mice. In (a), the columns represent the means and the vertical lines represent the $1 \pm$ SEM of the startle amplitude. Pre-pulse inhibition of the acoustic startle response was measured using 68, 71, and 77-dB pre-pulse stimuli in WT and CB₂KO mice. In (b), the columns represent the means and the vertical lines represent the $1 \pm$ SEM of % pre-pulse inhibition. *Values from CB₂KO mice that differ significantly from the values in WT mice (one-way analysis of variance (ANOVA) with repeated measures, genotype, $p < 0.001$). #Values obtained at 71 dB that differ significantly from those obtained at 68 dB; and ##values obtained at 77 dB that differ significantly from those obtained at 68 and 71 dB (one-way ANOVA with repeated measures, intensity, $p < 0.001$).

(Figure 7a). After 12 days, risperidone treatment modified D₂R gene expression in the PFC (two-way ANOVA, genotype: $F_{(1,63)} = 5.397$, $p = 0.024$; risperidone treatment: $F_{(3,63)} = 6.805$, $p < 0.001$; genotype \times treatment interaction: $F_{(3,63)} = 6.856$, $p < 0.001$). In WT mice ($n = 8$ per group), only the 15 μ g/kg risperidone dose significantly reduced D₂R gene expression in the PFC (Student–Newman–Keuls test, $p < 0.05$) (Figure 7b). In CB₂KO mice ($n = 8$ per group), treatment with all risperidone doses (15, 30, and 60 μ g/kg, *per os*) significantly reduced D₂R gene expression in the PFC (Student–Newman–Keuls test, $p < 0.05$) (Figure 7b). Saline treatment did not modify the observed differences (under baseline conditions) in D₂R gene expression between CB₂KO and WT mice (Student–Newman–Keuls test, $p < 0.05$) (Figure 7b). D₂R gene expression at doses of 30 and 60 μ g/kg of risperidone was significantly reduced in CB₂KO compared with risperidone-treated WT mice (Student–Newman–Keuls test, $p < 0.05$) (Figure 7b).

Secondly, α_{2C} R gene expression was analyzed in the PFC and the LC under baseline conditions and after 12 days of treatment with risperidone (15, 30, and 60 μ g/kg, *per os*) or saline in WT and CB₂KO mice. The α_{2C} R gene expression was significantly increased in the PFC (Student's *t*-test, $t = -4.262$, $p = 0.003$, 9 d.f.) ($n = 5-6$) (Figure 8a) and LC (Student's *t*-test, $t = -2.420$, $p = 0.039$, 10 d.f.) ($n = 6$) (Figure 8c) of CB₂KO compared with WT mice under baseline conditions. In the PFC, risperidone or saline treatment did not modify the α_{2C} R gene expression found under baseline conditions (two-way ANOVA, genotype: $F_{(1,63)} = 960.581$, $p < 0.001$; risperidone treatment: $F_{(3,63)} = 0.426$, $p = 0.735$; genotype \times treatment interaction: $F_{(3,63)} = 1.447$, $p = 0.239$) (Figure 8b). In the LC, risperidone treatment reduced α_{2C} R gene expression only in CB₂KO mice ($n = 8$ per group), whereas it failed to alter α_{2C} R gene expression in WT mice ($n = 8$ per group) (two-way ANOVA, genotype: $F_{(1,63)} = 114.593$, $p < 0.001$; risperidone

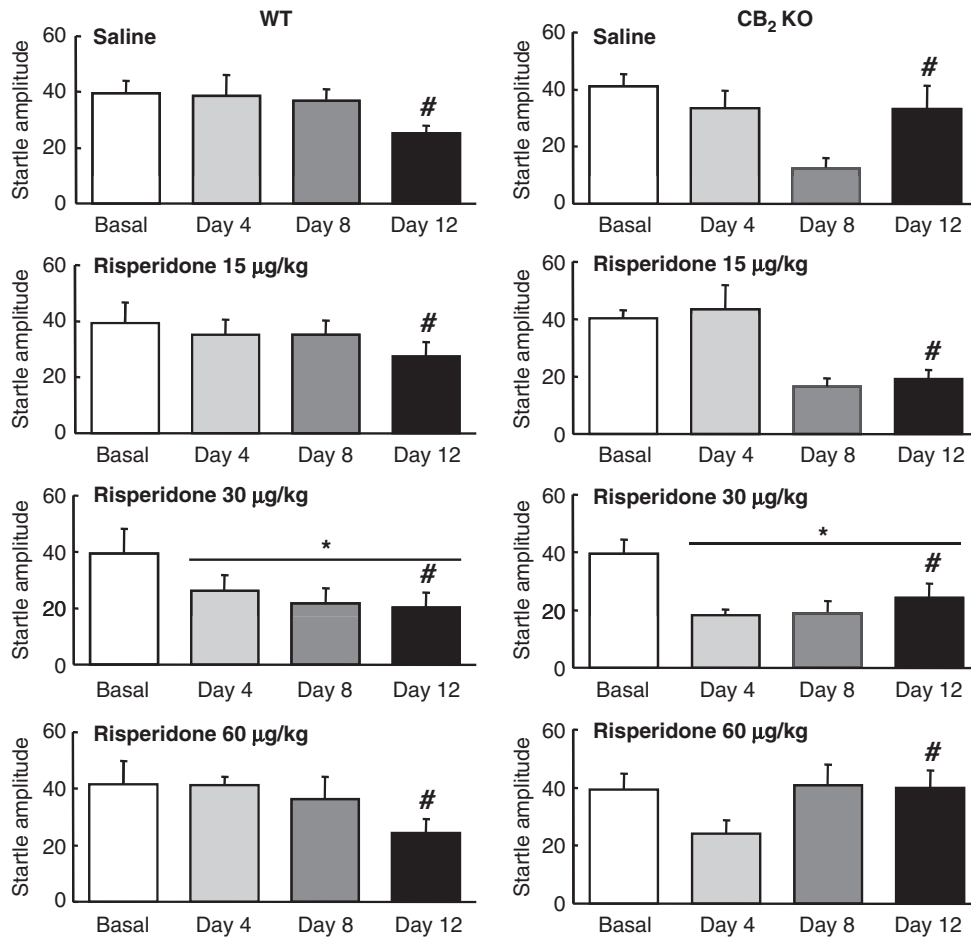


Figure 5 Effects of risperidone on the amplitude of the acoustic startle response in wild-type (WT) and CB₂KO (knockout) mice. The effect of oral chronic treatment with risperidone on the amplitude of the acoustic startle response was measured using 120 dB pulse trials in WT and CB₂KO mice. Determinations were performed before (baseline), and after 4, 8, and 12 days of treatment. Each panel corresponds with different groups of treatment with saline or risperidone (15, 30, and 60 µg/kg, *per os*). Columns represent the means and vertical lines represent the $1 \pm$ standard error of mean (SEM) of % startle amplitude. *Values from risperidone-treated CB₂KO and WT mice that differ significantly from values in saline-treated CB₂KO and WT mice (two-way analysis of variance (ANOVA) with repeated measures, treatment, $p < 0.05$). #Values from day 12 that differ significantly from baseline (two-way ANOVA with repeated measures, time, $p < 0.001$).

Table I Results of Two-way ANOVA with Repeated Measures Performed on Startle Amplitude Data

Factors	d.f.	F	p-value
<i>Between subject</i>			
Genotype	1, 59	1.447	0.234
Treatment	3, 59	3.380	<0.05
<i>Within subject</i>			
Time	1, 59	33.348	<0.001
Time x genotype	1, 59	0.319	0.574
Time x treatment	3, 59	1.477	0.230

treatment: $F_{(3,63)} = 5.204$, $p = 0.003$; genotype \times treatment interaction: $F_{(3,63)} = 5.077$, $p = 0.004$ (Figure 8d). Treatment with all the doses studied of risperidone in CB₂KO significantly reduced $\alpha_{2C}r$ gene expression in the LC (Student–Newman–Keuls test, $p < 0.05$) (Figure 8d).

Although treatment with all the doses of risperidone studied reduced gene expression level in CB₂KO, these levels were significantly higher than those observed in WT mice (Student–Newman–Keuls, $p < 0.05$) (Figure 8d).

Thirdly, 5-HT_{2C}r gene expression was examined in the PFC and DR under baseline conditions and after 12 days of risperidone treatment (15, 30, and 60 µg/kg, *per os*) or saline in WT and CB₂KO mice. Under baseline conditions, no difference was observed between the two genotypes in the PFC (Student’s *t*-test, $t = -0.025$, $p = 0.981$, 10 d.f.) ($n = 6$) (Figure 9a). However, risperidone treatment reduced 5-HT_{2C}r gene expression in the PFC in both genotypes (two-way ANOVA, genotype: $F_{(1,63)} = 237.027$, $p < 0.001$; risperidone treatment: $F_{(3,63)} = 36.346$, $p < 0.001$; genotype \times treatment interaction: $F_{(3,63)} = 37.532$, $p < 0.001$). In WT mice ($n = 8$ per group), oral risperidone treatment (15, 30, and 60 µg/kg, *per os*) significantly reduced 5-HT_{2C}r gene expression in the PFC (Student–Newman–Keuls test, $p < 0.05$) (Figure 9b). In CB₂KO mice ($n = 8$ per group), only risperidone at the dose of 60 µg/kg (*per os*) significantly reduced 5-HT_{2C}r gene expression in the PFC

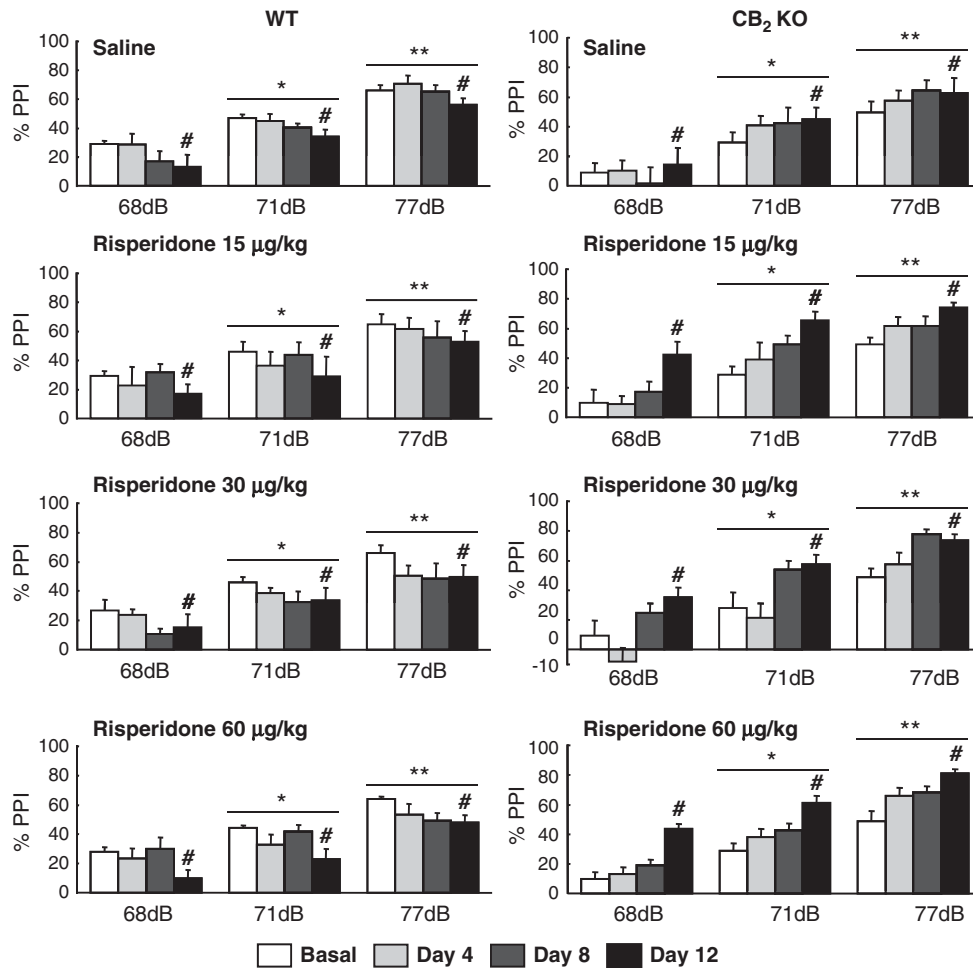


Figure 6 Effects of risperidone on pre-pulse inhibition test (PPI) of the acoustic startle response in wild-type (WT) and CB₂KO (knockout) mice. The effect of oral chronic treatment with risperidone on pre-pulse inhibition of the acoustic startle response was measured using 68, 71, and 77 dB pre-pulse stimuli in WT and CB₂KO mice. Determinations were performed before (baseline), and after 4, 8, and 12 days of treatment. Each panel corresponds to different groups of treatment with saline or risperidone (15, 30, and 60 µg/kg, *per os*). Columns represent the means and vertical lines represent the $1 \pm$ standard error of mean (SEM) of % pre-pulse inhibition. *Values obtained at 71 dB that differ significantly from those obtained at 68 dB; **values obtained at 77 dB that differ significantly from those obtained at 68 and 71 dB (two-way analysis of variance (ANOVA) with two repeated measures, intensity, $p < 0.001$). #Values from day 12 that differ significantly from baseline (two-way ANOVA with two repeated measures, time, $p < 0.05$).

compared with the saline group (Student–Newman–Keuls test, $p < 0.05$) (Figure 9b). The reduction observed in the risperidone-treated WT mice was significant compared with risperidone-treated CB₂KO mice at all doses (Student–Newman–Keuls test, $p < 0.05$) (Figure 9b). On the other hand, under baseline conditions, CB₂KO presented significantly reduced 5-HT_{2C}r gene expression in the DR compared with WT mice (Student's *t*-test, $t = 2.919$, $p = 0.011$, 14 d.f.) ($n = 7-9$) (Figure 9c). The effect of risperidone treatment on 5-HT_{2C}r gene expression in the DR was different in WT and CB₂KO mice (two-way ANOVA, genotype: $F_{(1,63)} = 4.901$, $p = 0.031$; risperidone treatment: $F_{(3,63)} = 4.164$, $p = 0.010$; genotype \times treatment interaction: $F_{(3,63)} = 14.026$, $p < 0.001$). In WT mice ($n = 8$ per group), 30 and 60 µg/kg risperidone doses significantly reduced 5-HT_{2C}r gene expression in the DR (Student–Newman–Keuls test, $p < 0.05$) (Figure 9d). In contrast, in CB₂KO mice ($n = 8$ per group) the 60 µg/kg risperidone dose significantly increased 5-HT_{2C}r gene expression in the DR (Student–Newman–Keuls test, $p < 0.05$) (Figure 9d). Significant differences between CB₂KO and WT mice were observed in saline-treated and 30

and 60 µg/kg risperidone-treated mice (Student–Newman–Keuls test, $p < 0.05$) (Figure 9d).

Finally, 5-HT_{2A}r gene expression was examined in the PFC and DR under baseline conditions and after 12 days of risperidone (15, 30, and 60 µg/kg, *per os*) or saline treatment in WT and CB₂KO mice. Under baseline conditions, gene expression of 5-HT_{2A}r was significantly reduced in the PFC of CB₂KO compared with WT mice (Student's *t*-test, $t = 2.502$, $p = 0.024$, 15 d.f.) ($n = 7-10$) (Figure 10a). Risperidone treatment had not significant effect of on 5-HT_{2A}r gene expression in the PFC (two-way ANOVA, genotype: $F_{(1,63)} = 13.838$, $p < 0.001$; risperidone treatment: $F_{(3,63)} = 2.756$, $p = 0.051$; genotype \times treatment interaction: $F_{(3,63)} = 0.274$, $p = 0.844$). The differences observed in CB₂KO and WT mice treated with risperidone ($n = 8$ per group) were due to the genotype factor (Figure 10b). In the DR under baseline conditions, no significant difference was observed in 5-HT_{2A}r gene expression between CB₂KO and WT mice (Student's *t*-test, $t = 1.533$, $p = 0.164$, 8 d.f.) ($n = 5$) (Figure 10c). However, risperidone treatment induced different effects on 5-HT_{2A}r gene expression in the DR of

WT and CB₂KO mice (two-way ANOVA, genotype: $F_{(1,63)} = 36.216$, $p < 0.001$; risperidone treatment: $F_{(3,63)} = 4.012$, $p = 0.012$; genotype \times treatment interaction: $F_{(3,63)} = 23.454$, $p < 0.001$). In WT mice ($n = 8$ per group), treatment with risperidone doses of 30 and 60 $\mu\text{g}/\text{kg}$ significantly reduced 5-HT_{2A}R gene expression in the DR (Student–Newman–Keuls test, $p < 0.05$) (Figure 10d). In CB₂KO mice ($n = 8$ per group), the 60 $\mu\text{g}/\text{kg}$ risperidone dose significantly increased 5-HT_{2A}R gene expression in the DR (Student–Newman–Keuls test, $p < 0.05$) (Figure 10d). Significant differences between CB₂KO and WT were observed in mice treated with 30 and 60 $\mu\text{g}/\text{kg}$ risperidone (Student–Newman–Keuls test, $p < 0.05$) (Figure 10d).

DISCUSSION

The results of this study provide new information about a possible role of the CB₂R in the regulation of schizophrenia-like behaviors. This claim is supported by several observations: (1) CB₂KO mice exhibited decreased spontaneous

motor activity and increased sensitivity to the motor stimulant effects of acute cocaine administration in the open field test; (2) deletion of *CB₂r* gene produced an anxiogenic-like response in the light–dark box and elevated plus-maze tests, and a depressogenic-like response in the tail suspension test; (3) CB₂KO mice showed disrupted short- and long-term memory consolidation in the step down inhibitory avoidance paradigm; (4) the PPI of the acoustic startle response was significantly lower in CB₂KO mice compared with WT mice; (5) PPI was markedly enhanced after chronic oral treatment with the antipsychotic drug risperidone in CB₂KO mice, but was not affected in WT mice; (6) deletion of CB₂r's increased D₂r and α_{2C} r gene expression in the PFC and LC and decreased 5-HT_{2C}r gene expression in the DR and 5-HT_{2A}r gene expression in the PFC of CB₂KO compared with WT mice; (7) oral risperidone treatment of WT mice did not affect α_{2C} r gene expression, decreased D₂r (15 $\mu\text{g}/\text{kg}$) in the PFC, and decreased 5-HT_{2C}r and 5-HT_{2A}r in the PFC and DR; and (8) treatment with risperidone in CB₂KO mice reduced gene expressions of D₂r in the PFC, α_{2C} r in the LC, and 5-HT_{2C}r and 5-HT_{2A}r in the PFC; risperidone treatment increased 5-HT_{2C}r and 5-HT_{2A}r gene expression in the DR.

It is known that schizophrenia is associated with brain abnormalities induced during CNS development (Rapoport et al, 2005; Ross et al, 2006). A number of findings suggest a pro-neurogenic role of CB₂R in the control of fundamental neural cell processes (Galve-Roperh et al, 2008; Harkany et al, 2007; Katona and Freund, 2008). Therefore, it can be hypothesized that the lack of CB₂R might impair neural development, thus inducing relevant alterations in several brain areas. In this context, it can be postulated that these alterations could be the substrate underlying the behavioral modifications observed in CB₂KO mice. However, the existence of developmental compensatory mechanisms related to the lack of this receptor cannot be excluded. In addition, it is well known that the systemic administration of receptor antagonists does not mimic the situation of a KO mouse for the same receptor. The blockade of the CB₂R has been involved in the prevention of alcohol preference development (Ishiguro et al, 2006), the inhibition of food consumption, and the enhancement of spontaneous activity and stereotyped behavior in C57BL/6 and DBA/2 mice (Onaivi et al, 2008). In contrast, pre-pulse inhibition or

Table 2 Results of Two-way ANOVA with Two Repeated Measures Performed on PPI Data

Factors	d.f.	F	p-value
<i>Between subject</i>			
Genotype	1, 59	0.160	0.690
Treatment	3, 59	0.417	0.741
<i>Within subject</i>			
Pre-pulse intensity	1, 59	925.419	<0.001
Pre-pulse intensity \times genotype	1, 59	16.421	<0.001
Pre-pulse intensity \times treatment	3, 59	2.163	0.102
Time	1, 59	5.264	<0.05
Time \times genotype	1, 59	55.211	<0.001
Time \times treatment	3, 59	0.986	0.406
Pre-pulse intensity \times time	1, 59	0.022	0.884
Pre-pulse intensity \times time \times genotype	1, 59	0.041	0.840
Pre-pulse intensity \times time \times treatment	3, 59	1.113	0.351

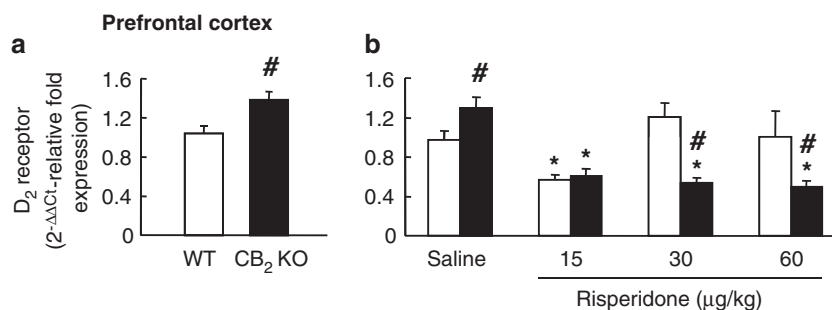


Figure 7 Evaluation of dopamine D₂ receptor (D₂r) gene expression in the prefrontal cortex. In (a), columns represent the means and vertical lines represent the $1 \pm$ standard error of mean (SEM) of $2^{-\Delta\Delta C_t}$ of relative D₂r gene expression in WT and CB₂KO mice under baseline conditions. In (b), WT and CB₂KO mice received risperidone (15, 30, or 60 $\mu\text{g}/\text{kg}/\text{day}$; 12 days; *per os*; 0.3 ml per mice) or saline. Columns represent the means and vertical lines represent the $1 \pm$ SEM of $2^{-\Delta\Delta C_t}$ of relative D₂r gene expression on day 12. #Values from CB₂KO mice that differ significantly from values in WT mice (Student–Newman–Keuls, $p < 0.05$). *Values from WT and CB₂KO mice treated with risperidone that differ significantly from values in saline-treated mice (Student–Newman–Keuls, $p < 0.05$).

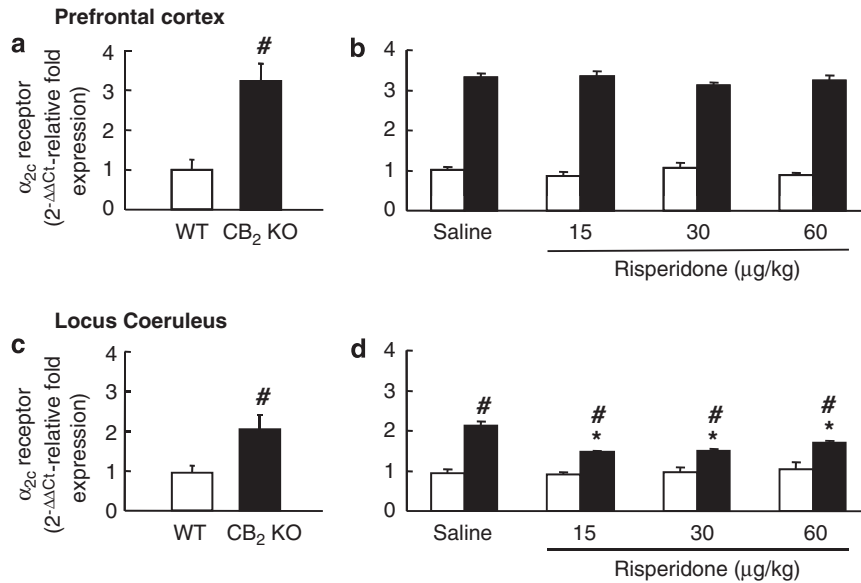


Figure 8 Evaluation of adrenergic α_{2C} receptor ($\alpha_{2C}r$) gene expression in the prefrontal cortex (PFC) and locus coeruleus (LC). In (a) and (c), columns represent the means and vertical lines represent the \pm standard error of mean (SEM) of $2^{-\Delta\Delta C_t}$ of relative $\alpha_{2C}r$ gene expression in the PFC and LC, respectively, of wild-type (WT) and CB₂KO (knockout) mice under baseline conditions. In (b) and (d), WT and CB₂KO mice received risperidone (15, 30, or 60 μ g/kg/day; 12 days; per os; 0.3 ml per mice) or saline. Columns represent the means and vertical lines represent the \pm SEM of $2^{-\Delta\Delta C_t}$ of relative $\alpha_{2C}r$ adrenergic gene expression in the PFC and LC on day 12. #Values from CB₂KO mice that differ significantly from values in WT mice (Student's *t*-test, $p < 0.05$). *Values from CB₂KO mice treated with risperidone that differ significantly from values in saline-treated CB₂KO mice (Student–Newman–Keuls, $p < 0.05$).

locomotor activity was not affected in mice (Ishiguro *et al*, 2010). Indeed, transient inactivation of the receptor by CB₂r antagonist use in WT mice does not induce the behavioral abnormalities observed in CB₂KO mice.

In recent years, a considerable number of susceptibility genes for schizophrenia have been described (Desbonnet *et al*, 2009). The generation of mice with targeted mutation of these genes was focused on the development of genetic models of the putative regulation of the pathophysiological mechanisms (Gray *et al*, 2009; Halene *et al*, 2009; Han *et al*, 2009; Perry *et al*, 2009; Powell *et al*, 2008; Rojas *et al*, 2007; Sakae *et al*, 2008; Tanda *et al*, 2009; Wiedholz *et al*, 2008) and genetic models of risk for schizophrenia (Bégou *et al*, 2008; Dyck *et al*, 2009; Karl *et al*, 2007; Kvafo *et al*, 2008; Willi *et al*, 2010). Schizophrenia includes abnormalities in coordination and movement including extrapyramidal paradigms (tending toward higher motor activity) and catatonia (usually lower motor activity) (Peralta *et al*, 2010). Schizophrenia manifests a spectrum of different levels of motor activity observable as endophenotypes of this disease. Mice with mutations in the genes of susceptibility to schizophrenia exhibited increased (Gray *et al*, 2009; Powell *et al*, 2008; Sakae *et al*, 2008; Wiedholz *et al*, 2008), decreased (Hattori *et al*, 2008), or failure to alter (Wolinsky *et al*, 2007) motor activity. The results found in this study revealed that deletion of the *CB2r* gene significantly reduced spontaneous motor activity in the open field and increased sensitivity to the motor stimulant effects of acute cocaine administration. Similarly, PKCI/HINT1 KO mice presented diminished spontaneous motor activity with increased sensitivity to the motor action of amphetamine (Barbier *et al*, 2007). In contrast, mice that were genetically modified at the NMDA or dopamine receptors presented increased spontaneous motor activity

and reduced reactivity to dizocilpine, phencyclidine, amphetamine, or cocaine (Gainetdinov *et al*, 1999; Mohn *et al*, 1999). The limitations of this paradigm seem to be related to the lack of specificity and predictive value of the effects on negative or cognitive symptoms. In addition, it has been reported that individuals with bipolar disorder and schizophrenia have distinctive profiles of exploratory behavior (Perry *et al*, 2009). Patients with bipolar mania present high motor activity and increased object interaction, whereas patients with schizophrenia exhibit normal object interaction (Perry *et al*, 2009). As patients with bipolar disorder present reduced PPI (Giakoumaki *et al*, 2007) and increased motor activity (Perry *et al*, 2009), it is possible that mutant mice with motor hyperactivity and reduced PPI are more closely related to animal models of bipolar disorder than to schizophrenia.

The response of CB₂KO mice has been studied in animal models of anxiety and depression. It is important to note that schizophrenic patients report depression and anxiety as the most frequent early signs and symptoms occurring before the first psychotic episode (Iyer *et al*, 2008). Thus, the characterization of clinically important phenomena observed before the onset of psychosis could be important in the diagnostic process. CB₂KO mice display increased anxiogenic-like response in the light–dark box and elevated plus-maze tests. Similarly, mutant mice like the heterozygous YWHAE and homozygous sandy show moderately enhanced anxiety-like behavior in the elevated plus-maze test (Hattori *et al*, 2008; Ikeda *et al*, 2008), whereas other mice with deletion of schizophrenia-related genes did not show any variation in anxiety-like behaviors in the light–dark box and elevated plus-maze tests compared with WT mice (Barbier and Wang, 2009; Hsu *et al*, 2007; Wolinsky *et al*, 2007). On the other hand, mice with

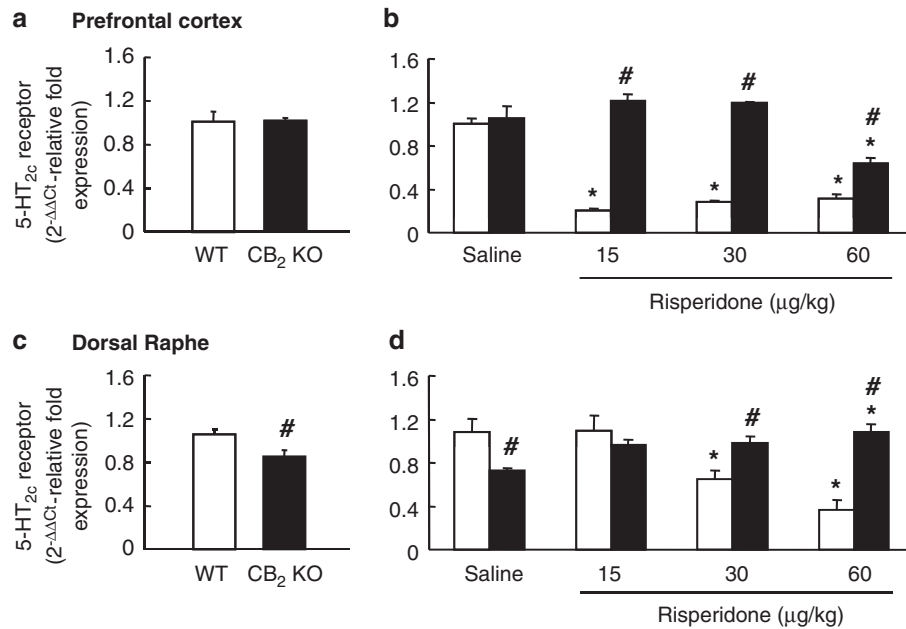


Figure 9 Evaluation of serotonergic 5-HT_{2C} receptor (5-HT_{2CR}) gene expression in the prefrontal cortex (PFC) and dorsal raphe (DR). In (a) and (c), columns represent the means and vertical lines represent the $1 \pm$ standard error of mean (SEM) of $2^{-\Delta\Delta C_t}$ of 5-HT_{2CR} gene expression in the PFC and DR, respectively, of wild-type (WT) and CB₂KO (knockout) mice. In (b) and (d), WT and CB₂KO mice received risperidone (15, 30, or 60 μ g/kg/day; 12 days; *per os*; 0.3 ml per mice) or saline. Columns represent the means and vertical lines represent the $1 \pm$ SEM of $2^{-\Delta\Delta C_t}$ of 5-HT_{2CR} gene expression in the PFC and DR on day 12. #Values from CB₂KO mice that differ significantly from values in WT mice (Student's *t*-test, $p < 0.05$). *Values from WT and CB₂KO mice treated with risperidone that differ significantly from the values in the saline-treated mice (Student–Newman–Keuls, $p < 0.05$).

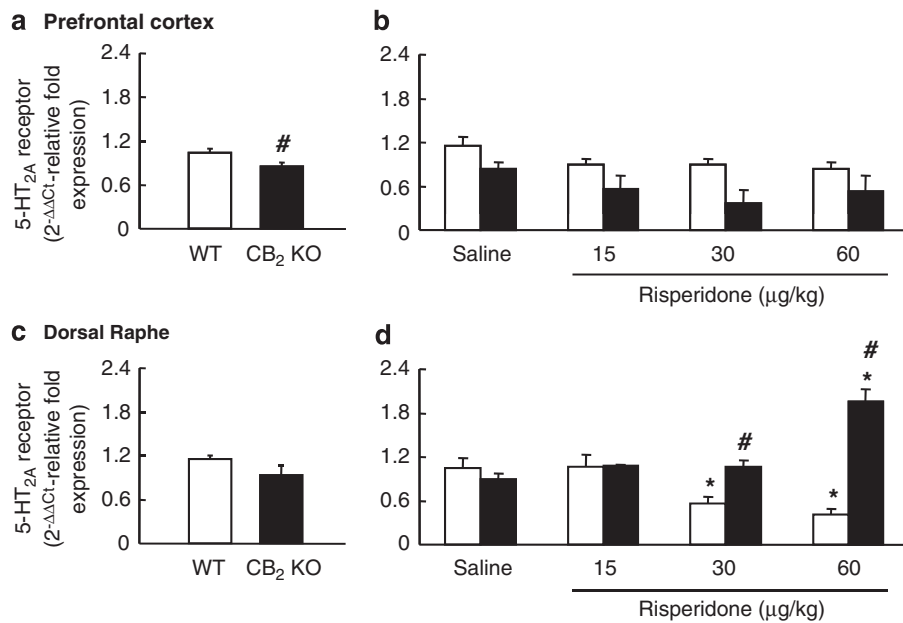


Figure 10 Evaluation of serotonergic 5-HT_{2A} receptor (5-HT_{2AR}) gene expression in the prefrontal cortex (PFC) and dorsal raphe (DR). In (a) and (c), columns represent the means and vertical lines represent the $1 \pm$ standard error of mean (SEM) of $2^{-\Delta\Delta C_t}$ of relative 5-HT_{2AR} gene expression in the PFC and DR, respectively, of wild-type (WT) and CB₂KO (knockout) mice. In (b) and (d), WT and CB₂KO mice received risperidone (15, 30, or 60 μ g/kg/day; 12 days; *per os*; 0.3 ml per mice) or saline. Columns represent the means and vertical lines represent the $1 \pm$ SEM of $2^{-\Delta\Delta C_t}$ of relative 5-HT_{2AR} gene expression in the PFC and DR on day 12. #Values of CB₂KO mice that differ significantly from the values in WT mice (Student's *t*-test, $p < 0.05$). *Values from WT and CB₂KO mice treated with risperidone that differ significantly from the values in saline-treated mice (Student–Newman–Keuls, $p < 0.05$).

overexpression of CB₂r presented reduced anxiety-like behaviors using the same experimental paradigm (García-Gutiérrez and Manzanara, 2011). Deletion of the CB₂r gene induced depressive-like responses in the tail

suspension test. Similarly, Homer1-KO mice and STOP-null mice show increased depressive-like behavior in the Porsolt test (Delotterie et al, 2010; Szumlinski et al, 2005). However, other animal models based on schizophrenia susceptibility

gene mutations showed an antidepressant-like response (Barbier and Wang, 2009; Perona *et al*, 2008; Sakae *et al*, 2008; Tanda *et al*, 2009; Yamasaki *et al*, 2008). In contrast, overexpression of CB₂r resulted in decreased depressive-like behaviors in acute models (tail suspension and novelty-suppressed feeding test) and in exposure to chronic mild stress, suggesting that pharmacological manipulation of this receptor may be an interesting therapeutic target in depression-related behaviors (Garcia-Gutierrez *et al*, 2010).

Cognitive dysfunction is one of the three main clusters of symptoms in schizophrenia and rodent models involving susceptibility genes related to schizophrenia manifesting as significant deficits in working memory and spatial learning (Gainetdinov *et al*, 1999; Ikeda *et al*, 2008; Yamasaki *et al*, 2008). Using the step down inhibitory avoidance task, CB₂KO mice showed disrupted short- and long-term memory consolidation of the task. Other genetically modified mice, proposed as animal models of behavioral and biochemical alterations implicated in schizophrenia, show deficits in short-term working and spatial memory (Bégou *et al*, 2008; Gray *et al*, 2009) and deficits in retention of emotional or spatial memory (Rojas *et al*, 2007; Tanda *et al*, 2009). However, not all these mutant mice present memory impairment; for instance, trace amine 1 receptor KO mice show no difference on a working memory task compared with WT mice (Wolinsky *et al*, 2007).

Impaired sensorimotor gating has been proposed as a common feature of the cognitive dysfunction observed in schizophrenia (Braff *et al*, 2001). The presence of PPI deficit has thus been considered an important behavioral trait in rodent models of schizophrenia. For instance, a clear attention deficit has been observed in mice with mutations in dopamine or glutamate receptors (Ralph *et al*, 2001; Wiedholz *et al*, 2008; Yamashita *et al*, 2006). In this study, baseline PPI was significantly lower in CB₂KO mice than WT mice; however, there is little information about the role of CB₂r in the regulation of PPI in mice. Previous studies have reported that blockade of the CB₂r fails to alter the response to PPI, but increases the attention deficit induced by MK-801 (Ishiguro *et al*, 2010). Disruption of PPI in rats is at least partly due to activation of D₂r (Swerdlow *et al*, 1991), suggesting that increased activity at these receptors might also be a substrate for PPI deficits in schizophrenia. In this sense, patients with schizophrenia present significant differences in the acoustic startle reflex, habituation to startle stimuli, and several PPI levels compared with healthy controls (Moriwaki *et al*, 2009), and antipsychotic treatment with olanzapine, aripiprazole, and risperidone improve PPI, but do not modify the acoustic startle reflex or habituation (Kishi *et al*, 2010; Wynn *et al*, 2007). Another study using a longitudinal within-subjects design reported improved results after switching from the conventional antipsychotic zuclopenthixol to long-acting injectable risperidone (Martinez-Gras *et al*, 2009). On the other hand, the administration of antipsychotics increases PPI or reverses the PPI disruptions induced by psychostimulants in animal studies (Egashira *et al*, 2005; Gray *et al*, 2009; Nagai *et al*, 2006; Powell *et al*, 2008; Swerdlow *et al*, 1991; Thomsen *et al*, 2010). Acute administration of clozapine, risperidone, quetiapine, and haloperidol (Egashira *et al*, 2005; Powell *et al*, 2008; Thomsen *et al*, 2010), and chronic

administration of clozapine (Gray *et al*, 2009) reverse the PPI deficit observed in different genetically manipulated mice. In addition, the administration of haloperidol, clozapine, and risperidone reverses drug-induced PPI deficits (Nagai *et al*, 2006; Swerdlow *et al*, 1991). The results of this study are consistent with these reports as chronic oral treatment with the atypical antipsychotic risperidone (at doses commonly used in the treatment of schizophrenia in patients) markedly attenuated the PPI deficits observed in CB₂KO mice. In contrast, risperidone tended to disrupt PPI progressively over the course of treatment in WT mice. In particular, the dose of 60 µg/kg markedly decreased PPI after 12 days of treatment (21% at 71 dB). On the other hand, risperidone reduced startle amplitude in both genotypes, being more evident in the CB₂KO mice.

The exploration of neurochemical changes in CB₂KO mice potentially related with the schizophrenia-like behaviors observed revealed alterations in the expression of dopaminergic, adrenergic, and serotonergic receptor genes. It is important to note that variations in the amount of gene transcript do not necessarily mean that concomitant changes in protein occur. These functional modifications could underlie the attention deficit, at least in part, as treatment with risperidone improved the PPI response and tended to 'normalize' some of the genes that are altered in CB₂KO mice. In contrast, treatment with risperidone failed to improve the PPI response in WT mice, but slightly impaired PPI response at the highest dose and longest duration of treatment. In addition, the effects of risperidone induced different alterations in receptor gene expression compared with CB₂KO mice.

The genes and the brain regions studied were selected based on two criteria: (1) previously reported alterations in gene expression associated with schizophrenia-like behaviors in genetically modified mice (Willi *et al*, 2010) and (2) a relation between the main receptor targets and the mechanism of action of risperidone. D₂r, 5-HT_{2AR}, 5-HT_{2CR}, and α_{2CR} satisfied these criteria (Abi-Dargham and Laruelle, 2005; McCormick *et al*, 2010; Meltzer and Huang, 2008).

Deletion of the CB₂r increased D₂r gene expression in the PFC. This situation could be related with increased dopaminergic tone, thus favoring deficient sensorimotor gating as occurs in DAT KO mice that present a chronic hyperdopaminergic state and deficient sensorimotor gating in the PPI (Ralph *et al*, 2001). The increased gene expression of this dopamine receptor was significantly reduced after treatment with risperidone, suggesting that the effectiveness of this drug on the PPI deficit could be at least partly related to this reduction in gene expression and its ability to block the receptor. The reduced effect of risperidone treatment on D₂r gene expression in the PFC of WT mice could be related with the lack of improvement in %PPI observed in these mice.

CB₂KO mice presented significantly reduced 5-HT_{2CR} gene expression in the DR nucleus. This reduction could be related with a decrease in the inhibitory control of DR serotonergic neurons played by 5-HT_{2CR} (Quéree *et al*, 2009), which may result in increased serotonin release in the PFC. Furthermore, deletion of the CB₂r significantly reduced 5-HT_{2AR} gene expression in PFC. Taking into account that PFC activity is modulated by serotonin through 5-HT_{2AR} (Puig *et al*, 2010), it can be hypothesized

that decreased gene expression of 5-HT_{2A}R could be a compensatory mechanism induced by persistently increased serotonin release by the DR terminals in the PFC. In CB₂KO mice, the effects of risperidone tend to restore 5-HT_{2C}R gene expression in the DR to the levels observed in WT mice, whereas risperidone treatment tends to reduce gene expression of this serotonergic receptor in the PFC. Typical and atypical antipsychotics show a similar effect of reducing 5-HT_{2C}R gene expression in the cortex (Buckland *et al*, 1997; Huang *et al*, 2006). Therefore, if decreased gene expression of 5-HT_{2A}R in the PFC reflects a possible compensatory mechanism in response to increased serotonin release from DR terminals, it can be hypothesized that risperidone treatment contributes to this mechanism by reducing 5-HT_{2A}R gene expression in the PFC even more at the same time that it increases 5-HT_{2A}R gene expression in the DR. Similarly, clozapine reduces 5-HT_{2A}R gene expression in the frontal cortex (Burnet *et al*, 1996). In WT mice risperidone treatment reduces 5-HT_{2A}R and 5-HT_{2C}R gene expression in the PFC and DR. In the PFC, CB₂KO 5-HT_{2A}R and 5-HT_{2C}R were reduced, whereas they were increased in the DR. In addition, risperidone treatment in these CB₂KO mice markedly improves the PPI deficit. In summary, CB₂KO mice present alterations in the serotonergic pathway from the DR to the PFC that could be responsible, at least in part, for the observed PPI deficit. It seems that the effect of risperidone treatment on this serotonergic pathway could be related to its beneficial effect on PPI.

The α_{2C} R plays an important role in cognitive processing in the PFC. The activation of the α_{2C} R by an α_2 agonist impairs performance of a spatial delayed alternation task, as seen in α_{2A} KO mice (Franowicz *et al*, 2002). In this sense, we found increased α_{2C} R gene expression in both the PFC and LC of CB₂KO mice. This alteration could thus be related with the observed PPI deficit. However, results obtained in studies made in two types of α_{2C} mutant mice do not support this explanation. Overexpression of α_{2C} R results in enhanced PPI response (Sallinen *et al*, 1998). On the other hand, α_{2C} KO mice show reduced PPI response (Sallinen *et al*, 1998). Despite this discrepancy, it may be speculated that increased expression of the α_{2C} receptor contributes somewhat to the PPI deficit in CB₂KO mice. This contribution could be related to the effects of increased α_{2C} R expression in the LC. Noradrenaline release in the PFC by LC terminals could be reduced. As risperidone treatment in CB₂KO mice reduced α_{2C} R expression in the LC, this effect could restore noradrenaline release in the PFC, thus contributing to PPI improvement. In WT mice, risperidone did not significantly modify α_{2C} R gene expression.

In summary, deletion of the cannabinoid CB₂R gene produced behavioral alterations that are commonly expressed in preclinical animal models of schizophrenia, namely altered locomotor activity, anxiety-like and depressive-like behaviors, and cognitive deficits including impaired sensorimotor gating. Gene expression studies in the PFC, DR, and LC revealed alterations in different dopaminergic, serotonergic, and noradrenergic receptors. Chronic treatment with the atypical antipsychotic risperidone reduced the PPI deficit, an effect that could be associated with modifications in the biochemical alterations observed in CB₂KO mice. These results suggest that CB₂R deletion was related to the observed schizophrenia-like

behaviors. Pharmacological manipulation of CB₂R may be further explored as a potential therapeutic target for the treatment of schizophrenia-related disorders.

ACKNOWLEDGEMENTS

This research was supported by grants from the Ministry of Science and Innovation (SAF 2008-01106) and Ministry of Health (RETICS RD06/0001/1004 and PNSD 2007/061) to JM. AOA is a postdoctoral fellow of 'Fundación para la Investigación Sanitaria en Castilla La Mancha' (FISCAM). MSGG and FN are predoctoral fellows from the Spanish Ministry of Science and Innovation, respectively. AAF is a predoctoral fellow from RETICS. We thank Patricia Rodríguez (FISCAM), Raquel Poveda (FISCAM), and Analía Rico (RETICS) for excellent technical assistance. We thank Dr. José Sánchez from 'Servicio de Medicina Preventiva' of 'Hospital General Universitario de Alicante' for statistical advice.

DISCLOSURE

The authors declare no conflict of interest.

REFERENCES

- Abi-Dargham A, Laruelle M (2005). Mechanisms of action of second generation antipsychotic drugs in schizophrenia: insights from brain imaging studies. *Eur Psychiatry* **20**: 15–27.
- Abood M, Barth F, Bonner TI, Cabral G, Casellas P, Cravatt BF *et al* (2010a). Cannabinoid receptors: CB1. Last modified on 2010-06-2. <http://www.iuphar-db.org/DATABASE/ObjectDisplayForward?objectId=56>. (accessed on 19-08-2010. IUPHAR database (IUPHAR-DB)).
- Abood M, Barth F, Bonner TI, Cabral G, Casellas P, Cravatt BF *et al* (2010b). Cannabinoid receptors: CB2. Last modified on 2010-06-29. <http://www.iuphar-db.org/DATABASE/ObjectDisplayForward?objectId=57>. (accessed on 19-08-2010. IUPHAR database (IUPHAR-DB)).
- Andreasson S, Allebeck P, Engstrom A, Rydberg U (1987). Cannabis and schizophrenia. A longitudinal study of Swedish conscripts. *Lancet* **2**: 1483–1486.
- Atwood BK, Mackie K (2010). CB2: a cannabinoid receptor with an identity crisis. *Br J Pharmacol* **160**: 467–479.
- Barbier E, Wang J (2009). Anti-depressant and anxiolytic like behaviors in PKCI/HINT1 knockout mice associated with elevated plasma corticosterone level. *BMC Neuroscience* **10**: 132.
- Barbier E, Zapata A, Oh E, Liu Q, Zhu F, Undie A *et al* (2007). Supersensitivity to amphetamine in protein kinase-C interacting protein/HINT1 knockout mice. *Neuropsychopharmacology* **32**: 1774–1782.
- Barnett JH, Werners U, Secher SM, Hill KE, Brazil R, Masson K *et al* (2007). Substance use in a population-based clinic sample of people with first-episode psychosis. *Br J Psychiatry* **190**: 515–520.
- Bégou M, Volle J, Bertrand JB, Brun P, Job D, Schweitzer A *et al* (2008). The stop null mice model for schizophrenia displays cognitive and social deficits partly alleviated by neuroleptics. *Neuroscience* **157**: 29–39.
- Bersani G, Orlandi V, Kotzalidis GD, Pancheri P (2002). Cannabis and schizophrenia: impact on onset, course, psychopathology and outcomes. *Eur Arch Psychiatry Clin Neurosci* **252**: 86–92.
- Bohme GA, Laville M, Ledent C, Parmentier M, Imperato A (1999). Enhanced long-term potentiation in mice lacking cannabinoid CB1 receptors. *Neuroscience* **95**: 5–7.

- Braff D, Geyer M, Swerdlow N (2001). Human studies of prepulse inhibition of startle: normal subjects, patient groups, and pharmacological studies. *Psychopharmacology* **156**: 234–258.
- Buckland PR, D'Souza U, Maher NA, McGuffin P (1997). The effects of antipsychotic drugs on the mRNA levels of serotonin 5HT_{2A} and 5HT_{2C} receptors. *Mol Brain Res* **48**: 45–52.
- Buckley NE, McCoy KL, Mezey E, Bonner T, Zimmer A, Felder CC *et al* (2000). Immunomodulation by cannabinoids is absent in mice deficient for the cannabinoid CB₂ receptor. *Eur J Pharmacol* **396**: 141–149.
- Burnet PWJ, Chen CPLH, McGowan S, Franklin M, Harrison PJ (1996). The effects of clozapine and haloperidol on serotonin-1A, -2A and -2C receptor gene expression and serotonin metabolism in the rat forebrain. *Neuroscience* **73**: 531–540.
- Crawley J, Goodwin FK (1980). Preliminary report of a simple animal behavior model for the anxiolytic effects of benzodiazepines. *Pharmacol Biochem Behav* **13**: 167–170.
- D'Souza DC, Abi-Saab WM, Madonick S, Forselius-Bielen K, Doersch A, Braley G *et al* (2005). Delta-9-tetrahydrocannabinol effects in schizophrenia: implications for cognition, psychosis, and addiction. *Biol Psychiatry* **57**: 594–608.
- De Marchi N, De Petrocellis L, Orlando P, Daniele F, Fezza F, Di Marzo V (2003). Endocannabinoid signalling in the blood of patients with schizophrenia. *Lipids Health Dis* **2**: 5.
- Dean B, Sundram S, Bradbury R, Scarr E, Copolov D (2001). Studies on [³H]CP-55940 binding in the human central nervous system: regional specific changes in density of cannabinoid-1 receptors associated with schizophrenia and cannabis use. *Neuroscience* **103**: 9–15.
- Delotterie D, Ruiz G, Brocard J, Schweitzer A, Roucard C, Roche Y *et al* (2010). Chronic administration of atypical antipsychotics improves behavioral and synaptic defects of STOP null mice. *Psychopharmacology* **208**: 131–141.
- Desbonnet L, Waddington JL, O'Tuathaigh CMP (2009). Mutant models for genes associated with schizophrenia. *Biochem Soc Trans* **037**: 308–312.
- Dyck BA, Skoblenick KJ, Castellano JM, Ki K, Thomas N, Mishra RK (2009). Behavioral abnormalities in synapsin II knockout mice implicate a causal factor in schizophrenia. *Synapse* **63**: 662–672.
- Egashira N, Tanoue A, Higashihara F, Fuchigami H, Sano K, Mishima K *et al* (2005). Disruption of the prepulse inhibition of the startle reflex in vasopressin V1b receptor knockout mice: reversal by antipsychotic drugs. *Neuropsychopharmacology* **30**: 1996–2005.
- Fernandez-Ruiz J, Romero J, Velasco G, Tolon RM, Ramos JA, Guzman M (2007). Cannabinoid CB₂ receptor: a new target for controlling neural cell survival? *Trends Pharmacol Sci* **28**: 39–45.
- Franowicz JS, Kessler LE, Borja CMD, Kobilka BK, Limbird LE, Arnsten AFT (2002). Mutation of the alpha 2A-adrenoceptor impairs working memory performance and annuls cognitive enhancement by guanfacine. *J Neurosci* **22**: 8771–8777.
- Gainetdinov RR, Wetsel WC, Jones SR, Levin ED, Jaber M, Caron MG (1999). Role of serotonin in the paradoxical calming effect of psychostimulants on hyperactivity. *Science* **283**: 397–401.
- Galve-Roperh I, Aguado T, Palazuelos J, Guzman M (2008). Mechanisms of control of neuron survival by the endocannabinoid system. *Curr Pharm Des* **14**: 2279–2288.
- García-Gutiérrez MS, Manzanares J (2011). Overexpression of CB₂ cannabinoid receptor gene decreased vulnerability to anxiety and impaired anxiolytic action of alprazolam in mice. *J Psychopharmacol* **25**: 111–120.
- García-Gutiérrez MS, Perez-Ortiz JM, Gutierrez-Adan A, Manzanares J (2010). Depression-resistant endophenotype in mice overexpressing cannabinoid CB₂ receptors. *Br J Pharmacol* **160**: 1773–1784.
- Giakoumaki SG, Roussos P, Rogdaki M, Karli C, Bitsios P, Frangou S (2007). Evidence of disrupted prepulse inhibition in unaffected siblings of bipolar disorder patients. *Biol Psychiatry* **62**: 1418–1422.
- Giuffrida A, Leweke FM, Gerth CW, Schreiber D, Koethe D, Faulhaber J *et al* (2004). Cerebrospinal anandamide levels are elevated in acute schizophrenia and are inversely correlated with psychotic symptoms. *Neuropsychopharmacology* **29**: 2108–2114.
- Goncalves MB, Suetterlin P, Yip P, Molina-Holgado F, Walker DJ, Oudin MJ *et al* (2008). A diacylglycerol lipase-CB₂ cannabinoid pathway regulates adult subventricular zone neurogenesis in an age-dependent manner. *Mol Cell Neurosci* **38**: 526–536.
- Gong JP, Onaivi ES, Ishiguro H, Liu QR, Tagliaferro PA, Brusco A *et al* (2006). Cannabinoid CB₂ receptors: immunohistochemical localization in rat brain. *Brain Res* **1071**: 10–23.
- Gray L, Van den Buuse M, Scarr E, Dean B, Hannan AJ (2009). Clozapine reverses schizophrenia-related behaviours in the metabotropic glutamate receptor 5 knockout mouse: association with N-methyl-D-aspartic acid receptor up-regulation. *Int J Neuropsychopharmacol* **12**: 45–60.
- Halene TB, Ehrlichman RS, Liang Y, Christian EP, Jonak GJ, Gur TL *et al* (2009). Assessment of NMDA receptor NR1 subunit hypofunction in mice as a model for schizophrenia. *Genes Brain Behav* **8**: 661–675.
- Han L, Picker JD, Schaevitz LR, Tsai G, Feng J, Jiang Z *et al* (2009). Phenotypic characterization of mice heterozygous for a null mutation of glutamate carboxypeptidase II. *Synapse* **63**: 625–635.
- Harkany T, Guzman M, Galve-Roperh I, Berghuis P, Devi LA, Mackie K (2007). The emerging functions of endocannabinoid signaling during CNS development. *Trends Pharmacol Sci* **28**: 83–92.
- Hattori S, Murotani T, Matsuzaki S, Ishizuka T, Kumamoto N, Takeda M *et al* (2008). Behavioral abnormalities and dopamine reductions in *sdv* mutant mice with a deletion in *Dtnbp1*, a susceptibility gene for schizophrenia. *Biochem Biophys Res Commun* **373**: 298–302.
- Herkenham M, Lynn AB, Johnson MR, Melvin LS, de Costa BR, Rice KC (1991). Characterization and localization of cannabinoid receptors in rat brain: a quantitative *in vitro* autoradiographic study. *J Neurosci* **11**: 563–583.
- Herkenham M, Lynn AB, Little MD, Johnson MR, Melvin LS, de Costa BR *et al* (1990). Cannabinoid receptor localization in brain. *Proc Natl Acad Sci USA* **87**: 1932–1936.
- Hoffman HS, Ison JR (1980). Reflex modification in the domain of startle: I. Some empirical findings and their implications for how the nervous system processes sensory input. *Psychol Rev* **87**: 175–189.
- Hsu R, Woodroffe A, Lai W-S, Cook MN, Mukai J, Dunning JP *et al* (2007). Nogo receptor 1 (RTN4R) as a candidate gene for schizophrenia: analysis using human and mouse genetic approaches. *PLoS ONE* **2**: e1234.
- Huang X-F, Han M, Huang X, Zavitsanou K, Deng C (2006). Olanzapine differentially affects 5-HT_{2A} and 2C receptor mRNA expression in the rat brain. *Behav Brain Res* **171**: 355–362.
- Ikeda M, Hikita T, Taya S, Uraguchi-Asaki J, Toyo-oka K, Wynshaw-Boris A *et al* (2008). Identification of YWHAЕ, a gene encoding 14-3-3epsilon, as a possible susceptibility gene for schizophrenia. *Hum Mol Genet* **17**: 3212–3222.
- Ishiguro H, Horiuchi Y, Ishikawa M, Koga M, Imai K, Suzuki Y *et al* (2010). Brain cannabinoid CB₂ receptor in schizophrenia. *Biol Psychiatry* **67**: 974–982.
- Ishiguro H, Iwasaki S, Teasensfitz L, Higuchi S, Horiuchi Y, Saito T *et al* (2006). Involvement of cannabinoid CB₂ receptor in alcohol preference in mice and alcoholism in humans. *Pharmacogenomics J* **7**: 380–385.
- Iyer S, Boekestyn L, Cassidy C, King S, Joobar R, Malla A (2008). Signs and symptoms in the pre-psychotic phase: description and implications for diagnostic trajectories. *Psychol Med* **38**: 1147–1156.
- Izquierdo I, Medina JH, Izquierdo LA, Barros DM, de Souza MM, Mello e Souza T (1998). Short- and long-term memory are differentially regulated by monoaminergic systems in the rat brain. *Neurobiol Learn Mem* **69**: 219–224.
- Karl T, Duffy L, Scimone A, Harvey RP, Schofield PR (2007). Altered motor activity, exploration and anxiety in heterozygous

- neuregulin 1 mutant mice: implications for understanding schizophrenia. *Genes Brain Behav* 6: 677–687.
- Katona I, Freund TF (2008). Endocannabinoid signaling as a synaptic circuit breaker in neurological disease. *Nat Med* 14: 923–930.
- Kishi T, Moriwaki M, Kitajima T, Kawashima K, Okochi T, Fukuo Y et al (2010). Effect of aripiprazole, risperidone, and olanzapine on the acoustic startle response in Japanese chronic schizophrenia. *Psychopharmacology* 209: 185–190.
- Kvajo M, McKellar H, Arguello PA, Drew LJ, Moore H, MacDermott AB et al (2008). A mutation in mouse *Disc1* that models a schizophrenia risk allele leads to specific alterations in neuronal architecture and cognition. *Proc Natl Acad Sci USA* 105: 7076–7081.
- Leweke FM, Giuffrida A, Wurster U, Emrich HM, Piomelli D (1999). Elevated endogenous cannabinoids in schizophrenia. *NeuroReport* 10: 1665–1669.
- Lister RG (1987). The use of a plus-maze to measure anxiety in the mouse. *Psychopharmacology* 92: 180–185.
- Martin M, Ledent C, Parmentier M, Maldonado R, Valverde O (2002). Involvement of CB1 cannabinoid receptors in emotional behaviour. *Psychopharmacology* 159: 379–387.
- Martinez-Gras I, Rubio G, del Manzano BA, Rodriguez-Jimenez R, Garcia-Sanchez F, Bagny A et al (2009). The relationship between prepulse inhibition and general psychopathology in patients with schizophrenia treated with long-acting risperidone. *Schizophr Res* 115: 215–221.
- McCormick PN, Kapur S, Graff-Guerrero A, Raymond R, Nobrega JN, Wilson AA (2010). The antipsychotics olanzapine, risperidone, clozapine, and haloperidol are D2-selective *ex vivo* but not *in vitro*. *Neuropsychopharmacology* 35: 1826–1835.
- Meltzer HY, Huang M (2008). *In vivo* actions of atypical antipsychotic drug on serotonergic and dopaminergic systems. In: Di Giovanni G, Di Matteo V, Esposito E (eds). *Progress in Brain Research*, Vol 172, Elsevier: Amsterdam. pp 177–197.
- Mohn AR, Gainetdinov RR, Caron MG, Koller BH (1999). Mice with reduced NMDA receptor expression display behaviors related to schizophrenia. *Cell* 98: 427–436.
- Morgan CJ, Curran HV (2008). Effects of cannabidiol on schizophrenia-like symptoms in people who use cannabis. *Br J Psychiatry* 192: 306–307.
- Moriwaki M, Kishi T, Takahashi H, Hashimoto R, Kawashima K, Okochi T et al (2009). Prepulse inhibition of the startle response with chronic schizophrenia: a replication study. *Neurosci Res* 65: 259–262.
- Munro S, Thomas KL, Abu-Shaar M (1993). Molecular characterization of a peripheral receptor for cannabinoids. *Nature* 365: 61–65.
- Nagai H, Egashira N, Sano K, Ogata A, Mizuki A, Mishima K et al (2006). Antipsychotics improve [Delta]9-tetrahydrocannabinol-induced impairment of the prepulse inhibition of the startle reflex in mice. *Pharmacol Biochem Behav* 84: 330–336.
- Onaivi ES (2009). Cannabinoid receptors in brain: pharmacogenetics, neuropharmacology, neurotoxicology, and potential therapeutic applications. In: Hari Shanker S (ed.). *International Review of Neurobiology* Vol 88, Academic Press: New York. pp 335–369.
- Onaivi ES, Carpio O, Ishiguro H, Schanz N, Uhl GR, Benno R (2008). Behavioral effects of CB2 cannabinoid receptor activation and its influence on food and alcohol consumption. *Ann N Y Acad Sci* 1139: 426–433.
- Onaivi ES, Ishiguro H, Gong JP, Patel S, Perchuk A, Meozzi PA et al (2006). Discovery of the presence and functional expression of cannabinoid CB2 receptors in brain. *Ann N Y Acad Sci* 1074: 514–536.
- Palazuelos J, Aguado T, Egia A, Mechoulam R, Guzman M, Galve-Roperh I (2006). Non-psychoactive CB2 cannabinoid agonists stimulate neural progenitor proliferation. *FASEB J* 20: 2405–2407.
- Palkovits M (1983). Punch sampling biopsy technique. *Methods Enzymol* 103: 368–376.
- Paxinos G, Franklin KBJ (2001). *The Mouse Brain in Stereotaxic Coordinates*. Academic Press, Harcourt Science and Technology Company: New York.
- Peralta V, Campos MS, García de Jalón E, Cuesta MJ (2010). Motor behavior abnormalities in drug-naïve patients with schizophrenia spectrum disorders. *Mov Disord* 25: 1068–1076.
- Perona MT, Waters S, Hall FS, Sora I, Lesch KP, Murphy DL et al (2008). Animal models of depression in dopamine, serotonin, and norepinephrine transporter knockout mice: prominent effects of dopamine transporter deletions. *Behav Pharmacol* 19: 566–574.
- Perry W, Minassian A, Paulus MP, Young JW, Kincaid MJ, Ferguson EJ et al (2009). A reverse-translational study of dysfunctional exploration in psychiatric disorders: from mice to men. *Arch Gen Psychiatry* 66: 1072–1080.
- Powell SB, Young JW, Ong JC, Caron MG, Geyer MA (2008). Atypical antipsychotics clozapine and quetiapine attenuate prepulse inhibition deficits in dopamine transporter knockout mice. *Behav Pharmacol* 19: 562–565.
- Puig MV, Watakabe A, Ushimaru M, Yamamori T, Kawaguchi Y (2010). Serotonin modulates fast-spiking interneuron and synchronous activity in the rat prefrontal cortex through 5-HT1A and 5-HT2A receptors. *J Neurosci* 30: 2211–2222.
- Quéree P, Peters S, Sharp T (2009). Further pharmacological characterization of 5-HT2C receptor agonist-induced inhibition of 5-HT neuronal activity in the dorsal raphe nucleus 'in vivo'. *Br J Pharmacol* 158: 1477–1485.
- Racz I, Nadal X, Alferink J, Banos JE, Rehnelt J, Martin M et al (2008). Crucial role of CB2 cannabinoid receptor in the regulation of central immune responses during neuropathic pain. *J Neurosci* 28: 12125–12135.
- Ralph RJ, Paulus MP, Fumagalli F, Caron MG, Geyer MA (2001). Prepulse inhibition deficits and perseverative motor patterns in dopamine transporter knock-out mice: Differential effects of D1 and D2 receptor antagonists. *J Neurosci* 21: 305–313.
- Rapoport JL, Addington AM, Frangou S, Psych MR (2005). The neurodevelopmental model of schizophrenia: update 2005. *Mol Psychiatry* 10: 434–449.
- Reibaud M, Obinu MC, Ledent C, Parmentier M, Böhme GA, Imperato A (1999). Enhancement of memory in cannabinoid CB1 receptor knock-out mice. *Eur J Pharmacol* 379: R1–R2.
- Rojas P, Joodmardi E, Hong Y, Perlmann T, Ogren SO (2007). Adult mice with reduced *Nurr1* expression: an animal model for schizophrenia. *Mol Psychiatry* 12: 756–766.
- Ross CA, Margolis RL, Reading SA, Pletnikov M, Coyle JT (2006). Neurobiology of schizophrenia. *Neuron* 52: 139–153.
- Sakae N, Yamasaki N, Kitaichi K, Fukuda T, Yamada M, Yoshikawa H et al (2008). Mice lacking the schizophrenia-associated protein FEZ1 manifest hyperactivity and enhanced responsiveness to psychostimulants. *Hum Mol Genet* 17: 3191–3203.
- Sallinen J, Haapalinna A, Viitamaa T, Kobilka BK, Scheinin M (1998). Adrenergic alpha 2C-receptors modulate the acoustic startle reflex, prepulse inhibition, and aggression in mice. *J Neurosci* 18: 3035–3042.
- Schmittgen TD, Zakrajsek BA, Mills AG, Gorn V, Singer MJ, Reed MW (2000). Quantitative reverse transcription-polymerase chain reaction to study mRNA decay: comparison of endpoint and real-time methods. *Anal Biochem* 285: 194–204.
- Schotte A, Bonaventure P, Janssen PFM, Leysen JE (1995). *In vitro* receptor binding and *in vivo* receptor occupancy in rat and guinea pig brain: Risperidone compared with antipsychotics hitherto used. *Jpn J Pharmacol* 69: 399–412.
- Sugranyes G, Flamarique I, Parellada E, Baeza I, Goti J, Fernandez-Egea E et al (2009). Cannabis use and age of diagnosis of schizophrenia. *Eur Psychiatry* 24: 282–286.
- Swerdlow NR, Keith VA, Braff DL, Geyer MA (1991). Effects of spiperone, raclopride, SCH 23390 and clozapine on apomor-

- phine inhibition of sensorimotor gating of the startle response in the rat. *J Pharmacol Exp Ther* **256**: 530–536.
- Szumliński KK, Lominac KD, Kleschen MJ, Oleson EB, Dehoff MH, Schwartz MK *et al* (2005). Behavioral and neurochemical phenotyping of Homer1 mutant mice: possible relevance to schizophrenia. *Genes Brain Behav* **4**: 273–288.
- Tanda K, Nishi A, Matsuo N, Nakanishi K, Yamasaki N, Sugimoto T *et al* (2009). Abnormal social behavior, hyperactivity, impaired remote spatial memory, and increased D1-mediated dopaminergic signaling in neuronal nitric oxide synthase knockout mice. *Mol Brain* **2**: 19.
- Thomsen M, Wess J, Fulton B, Fink-Jensen A, Caine S (2010). Modulation of prepulse inhibition through both M1 and M4 muscarinic receptors in mice. *Psychopharmacology* **208**: 401–416.
- Urigüen L, García-Fuster M, Callado L, Morentin B, La Harpe R, Casadó V *et al* (2009). Immunodensity and mRNA expression of A2A adenosine, D2 dopamine, and CB1 cannabinoid receptors in postmortem frontal cortex of subjects with schizophrenia: effect of antipsychotic treatment. *Psychopharmacology* **206**: 313–324.
- Urigüen L, Pérez-Rial S, Ledent C, Palomo T, Manzanares J (2004). Impaired action of anxiolytic drugs in mice deficient in cannabinoid CB1 receptors. *Neuropharmacology* **46**: 966–973.
- Van Sickle MD, Duncan M, Kingsley PJ, Mouihate A, Urbani P, Mackie K *et al* (2005). Identification and functional characterization of brainstem cannabinoid CB2 receptors. *Science* **310**: 329–332.
- Vaugeois JM, Passera G, Zuccaro F, Costentin J (1997). Individual differences in response to imipramine in the mouse tail suspension test. *Psychopharmacology* **134**: 387–391.
- Wiedholz LM, Owens WA, Horton RE, Feyder M, Karlsson RM, Hefner K *et al* (2008). Mice lacking the AMPA GluR1 receptor exhibit striatal hyperdopaminergia and ‘schizophrenia-related’ behaviors. *Mol Psychiatry* **13**: 631–640.
- Willi R, Weinmann O, Winter C, Klein J, Sohr R, Schnell L *et al* (2010). Constitutive genetic deletion of the growth regulator Nogo-A induces schizophrenia-related endophenotypes. *J Neurosci* **30**: 556–567.
- Wolinsky TD, Swanson CJ, Smith KE, Zhong H, Borowsky B, Seeman P *et al* (2007). The Trace Amine 1 receptor knockout mouse: an animal model with relevance to schizophrenia. *Genes Brain Behav* **6**: 628–639.
- Wynn JK, Green MF, Sprock J, Light GA, Widmark C, Reist C *et al* (2007). Effects of olanzapine, risperidone and haloperidol on prepulse inhibition in schizophrenia patients: a double-blind, randomized controlled trial. *Schizophr Res* **95**: 134–142.
- Yamasaki N, Maekawa M, Kobayashi K, Kajii Y, Maeda J, Soma M *et al* (2008). Alpha-CaMKII deficiency causes immature dentate gyrus, a novel candidate endophenotype of psychiatric disorders. *Mol Brain* **1**: 6.
- Yamashita M, Fukushima S, Shen H-w, Hall FS, Uhl GR, Numachi Y *et al* (2006). Norepinephrine transporter blockade can normalize the prepulse inhibition deficits found in dopamine transporter knockout mice. *Neuropsychopharmacology* **31**: 2132–2139.
- Yao JK, van Kammen DP, Reddy RD, Keshavan MS, Schmid PC, Berdyshev EV *et al* (2002). Elevated endocannabinoids in plasma from patients with schizophrenia. *Biol Psychiatry* **51**: S64–S65.
- Zammit S, Allebeck P, Andreasson S, Lundberg I, Lewis G (2002). Self reported cannabis use as a risk factor for schizophrenia in Swedish conscripts of 1969: historical cohort study. *BMJ* **325**: 1199.