### Identification of BiP as a CB₁ Receptor-Interacting Protein That Fine-Tunes Cannabinoid Signaling in the Mouse Brain

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Cannabinoids, the bioactive constituents of cannabis, exert a wide array of effects on the brain by engaging Type 1 cannabinoid receptor (CB₁R). Accruing evidence suggests that cannabinoid action relies on context-dependent factors, such as the biological characteristics of the target cell, suggesting that cell population-intrinsic molecular cues modulate CB₁R-dependent signaling. Here, by using a yeast two-hybrid-based high-throughput screening, we identified BiP as a potential CB₁R-interacting protein. We next found that CB₁R and BiP interact specifically in vitro, and mapped the interaction site within the CB₁R C-terminal (intracellular) domain and the BiP C-terminal (substrate-binding) domain. BiP selectively shaped agonist-evoked CB₁R signaling by blocking an “alternative” G_{αi} protein-dependent signaling module while leaving the “classical” G_{i/o} protein-dependent inhibition of the CAMP pathway unaffected. In situ proximity ligation assays conducted on brain samples from various genetic mouse models of conditional loss or gain of CB₁R expression allowed to map CB₁R-BiP complexes selectively on terminals of GABAergic neurons. Behavioral studies using cannabinoid-treated male BiP^{+/−} mice supported that CB₁R-BiP complexes modulate cannabinoid-evoked anxiety, one of the most frequent undesired effects of cannabis. Together, by identifying BiP as a CB₁R-interacting protein that controls receptor function in a signaling pathway- and neuron population-selective manner, our findings may help to understand the striking context-dependent actions of cannabis in the brain.

**Key words:** BiP; cannabinoid; cell signaling; G-protein-coupled receptor; neurotransmission; protein–protein interaction

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Introduction
Preparations of the hemp plant Cannabis sativa L. have been used by humankind for millennia. During the last decades, there has been a strong renaissance in the study of the molecular and pharmacological bases of cannabinoid action; and, in concert, many countries have approved the use of cannabinoid-based medicines and standardized preparations of medicinal cannabis (Hill, 2015; Abrams, 2018). Both the therapeutic and the adverse effects of cannabis are mostly attributed to a single molecule, Δ⁹-tetrahydrocannabinol (THC) (Mechoulam et al., 2014). This compound engages and activates two specific G-protein-coupled receptors (GPCRs), designated as cannabinoid CB1 receptor (CB1R) and cannabinoid CB2 receptor (CB2R) (Pertwee et al., 2010). CB1R is one of the most abundant GPCRs in the mammalian brain (Katona and Freund, 2008; Pertwee et al., 2010; Dudok et al., 2015). It mediates a large number of pharmacological effects of THC, and, on binding endocannabinoids (anandamide and 2-arachidonoylglycerol), participates in the physiological control of multiple processes, such as motor behavior, learning and memory, fear and anxiety, pain, food intake, and energy metabolism (Piomelli, 2003; Mechoulam et al., 2014).

The precise molecular mechanism of CB1R action remains unsolved. For example, CB1R couples to the inhibitory family of heterotrimeric G-proteins (G_i/o), but its expression and signaling efficacy differ remarkably between excitatory and inhibitory neurons (Steindel et al., 2013), which could explain, at least in part, the widely reported biphasic effects elicited by THC and other CB1R agonists (Bellochio et al., 2010; Rey et al., 2012; Mechoulam and Parker, 2013). Likewise, under different cellular settings, CB1R can signal through other G-protein families, such as G_q11 and G_s (Lauckner et al., 2005; Priestley et al., 2017). Furthermore, CB1R activation protects neurons from death in a wide array of pathologic conditions (Fernández-Ruiz, 2019), while it triggers apoptosis of brain cancer cells (Velasco et al., 2012). How these striking differences in signaling efficacy, G-protein coupling, and biological response occur is not understood. Together, these observations call a specific population-selective action of CB1R colligated to the physiopathological context of the target cell expressing the receptor. Understanding how CB1R evokes such varying responses is important to clarify the neurobiological role of the endocannabinoid system and, potentially, to improve the design of CB1R-targeted therapies.

Interaction with regulatory proteins represents one of the pivotal molecular processes by which GPCR-evoked signaling is affected. Diverse subsets of these interacting proteins assist GPCRs during biosynthesis, trafficking, activation, desensitization, and degradation (Maurice et al., 2016). Aside from the most ubiquitous GPCR-associated proteins (i.e., G-proteins, β-arrestins, and GPCR kinases), specific interacting partners have been identified for particular types of receptors (e.g., NHERF proteins for adrenergic receptors and others, and Homer proteins for metabotropic glutamate receptors and others) (Wheeler et al., 2007; Magalhaes et al., 2012). Regarding CB1R, several intracellular proteins (led by CRIP1a) (Howlett et al., 2010; Guggenhuber et al., 2016), as well as membrane-anchored GPCRs (e.g., serotonin 5-HT2A and adenosine A2A receptors) (Viñals et al., 2015; Moreno et al., 2018), have been proposed as receptor interactors. However, most studies on these putative protein complexes have been conducted in vitro, and only subtle effects have been unraveled so far in vivo.

Here, we hypothesized that unidentified neuron population-specific CB1R-interacting proteins modulate cannabinoid signaling in the brain. By using a yeast two-hybrid (Y2H)-based approach, complemented with a wide array of molecular, genetic, pharmacological, and behavioral procedures, we identified the protein BiP as a new modulator of biased signaling of CB1R, and defined the molecular features, signal-transduction consequences, neuroanatomical mapping, and behavioral outcomes of the CB1R-BiP interaction.

Materials and Methods
Gene constructs. Y2H vectors were generated by PCR and subsequent restriction cloning by using pGBT9 and pGAD as vectors (ClonTech, TaKaraBio). Short amino-acid stretches (CB1R mutants) were ligated by using long annealing oligonucleotides with protruding overhangs. The cDNA encoding full-length BiP was provided by Valerie Petegnief (Institute for Biomedical Research of Barcelona), and expression vectors encoding nontagged (pcDNA3.1 +/− ); Thermo Fisher Scientific), GFP-tagged (pEGFP-C2 backbone; ClonTech), and recombinant bacterial-expression [pBH4 backbone (Merino-Gracia et al., 2016b)] versions were built as well by PCR and restriction cloning. BiP-ΔIR comprised BiP amino acids 1-308. 2XFLAG-tagged versions were obtained by using IVA cloning (García-Nafria et al., 2016) with pcDNA3.1+ plasmids as templates. pcDNA3.1-ΔHA-CB1R, pcDNA3.1-ΔCB1R-myc, CB1R-ΔRluc, CB1R-R-GFP, pcDNA3.1-ΔAIR constructs had been generated previously in our laboratory. Single phosphomimetic mutants of CB1R–carboxy-terminal domain (CTD), as well as the CB1R-S452D-Rluc construct, were obtained through QuickChange mutagenesis with the aforementioned plasmids as templates. pcDNA3.1-ΔCB1R was provided by Cristina Sánchez (Complutense University of Madrid) and used to construct the corresponding Y2H vector. pCEFL-GFP and pCEFL-GFP-GRK2 plasmids were given by J. Silvio Gutkind (University of California San Diego). All constructs were validated by Sanger sequencing before use.

Y2H. Screening of the library was performed following the manufacturer’s instructions (MatchMaker system, TaKaRaBio). Plasmids of positive transformants were isolated and subsequently sequenced by standard procedures. Directed Y2H experiments were conducted as previously reported (Merino-Gracia et al., 2016a). Yeasts were transformed with plasmids containing the GAL4 binding domain and the GAL4 activation domain following a lithium acetate-based method. Double transformants were placed on Leu/Trp/His-deficient plates in the presence of 12 mM 3-amino triazole (triple dropout plates) as well as only Leu/Trp-
achieved by adding YM-254890 (Focus Biomolecules; 1 μM final concentration) or vehicle (DMSO, 0.1% v/v final concentration) 30 min before WIN-55212-2 (100 nM final concentration) or vehicle (DMSO, 0.1% v/v final concentration). All incubations were conducted in triplicate. Cells were subsequently washed with ice-cold PBS, snap-frozen in liquid nitrogen, and harvested at ~80°C for Western blot analyses.

In situ proximity ligation assay (PLA). BIP-CB1R complexes were detected by using the Duolink In Situ PLA Detection Kit (Sigma-Aldrich) following the manufacturer’s instructions. Synaptosomal preparations were incubated with a rabbit-anti-CB1R antibody (1:500, Frontier-Institute, #CB1-R-Ab530) and a mouse anti-GRP78/BiP antibody (1:500, Santa Cruz Biotechnology, #sc-376768). Negative controls were performed with just one primary antibody. Ligation and amplification procedures were performed with In Situ Detection Reagent Red (Sigma-Aldrich), and coverslips were mounted in DAPI-containing medium. Samples were analyzed with a Leica SP2/SP8 confocal microscope (Leica Microsystems). For each FOV, a stack of two channels (one per staining) and 9-13 Z stacks with a step size of 0.3 μm were acquired with a 63× oil-immersion objective and processed with ImageJ software (National Institutes of Health). Representative images for each condition were prepared for figure presentation by applying color adjustments uniformly with Adobe Photoshop version CS6.

For PLA imaging in brain sections, mice were deeply anesthetized and immediately perfused transcardially with PBS followed by 4% PFA/PB. Brains were removed and postfixed overnight in the same solution, cryoprotected by immersion in 10%, 20%, 30% gradient sucrose (24 h each), cryosectioned at 30 μm and thaw-mounted on sticky slides coated with methylbutane. Serial coronal or sagittal cryostat sections (30-μm-thick) through the whole brain were collected in cryoprotective solution and stored at −20°C until PLA experiments were performed. Immediately before the assay, mouse brain sections were mounted on glass slides, washed in PBS, permeabilized with PBS containing 0.01% Triton X-100 for 10 min, and successively washed with PBS. Interactions were detected with Duolink In Situ PLA Detection and In Situ Detection Reagent Red Kits. A mixture of the primary antibodies [mouse anti-GRP78/BiP antibody (1:100, Santa Cruz Biotechnology, #sc-376768) and rabbit anti-CB1R antibody (1:100, Thermo Fisher Scientific, #PA1-745)] was used. Samples were analyzed in a Leica SP2 confocal microscope (Leica Microsystems) equipped with an apochromatic 63× oil-immersion objective (1.4 numerical aperture), and a 405 nm and a 561 nm laser lines. For each FOV, a stack of two channels (one per staining) and 9-13 Z stacks with a step size of 1 μm were acquired. Images were opened and processed with ImageJ software (National Institutes of Health). Quantification of cells containing one or more red dots versus total cells (blue nuclei) was determined by using the Fiji package (https://image.janelia.org/software/fiji). Nuclear stains were used in combination with the respective primary antibodies. For PLA imaging, brain sections were used.

**Biology.**

**Bioluminescence resonance energy transfer (BRET).** HEK-293T cells growing in 6-well plates were transiently cotransfected with a constant amount of cDNA encoding the receptor fused to Rluc protein and with increasingly amounts of GFP-Bip-IR. To quantify protein-GFP expression, cells (20 μg total protein) were distributed in 96-well microplates (black plates with a transparent bottom) and the fluorescence was read in a Fluostar Optima fluorimeter (BMG Labtech) equipped with a high-energy xenon flash lamp using a 10 nm bandwidth excitation filter at 410 nm for protein-GFP reading. Protein-fluorescence expression was determined as fluorescence of the sample minus the fluorescence of cells expressing only the BRET donor. For BRET measurements, cells (20 μg of protein) were distributed in 96-well microplates (Corning 3600, White plates; Sigma) and BRET signal was collected 1 min after addition of 5 μM DeepBlue C (Invitrogen) on the imaging plate in a LB 940 microplate reader (Berthold Technologies) that allows the integration of the signals detected in the short-wavelength filter at 410 nm and the long-
wavelength filter at 510 nm. To quantify receptor-Rluc expression, luminescence readings were also performed after 10 min of adding 5 μM DeepBlueC (Invitrogen). The net BRET is defined as [(long-wavelength emission)/(short-wavelength emission)] – CF where CF corresponds to [(long-wavelength emission)/(short-wavelength emission)] for the Rluc construct expressed alone in the same experiment. BRET is expressed as milliBRET units (mBU; net BRET × 1000). In BRET curves, BRET was expressed as a function of the ratio between fluorescence and luminescence (GFP/Rluc). To calculate maximal BRET from saturation curves, data were fitted using a nonlinear regression equation and assuming a single phase with GraphPad Prism software version 8.0.1. Each representative curve shown is the mean of three independent replicates.

Western blot and coimmunoprecipitation. Samples for Western blotting were prepared on ice-cold lysis buffer (50 mM Tris-Cl, 1 mM EDTA, 1 mM EGTA, 0.1% Triton X-100, 50 mM NaCl, 10 mM Na-glycerophosphate, 5 mM Na-pyrophosphate, 1 mM Na-orthovanadate, pH 7.5). Cell lysates were clarified by centrifugation at 12,000 × g for 15 min (4°C), and total protein was quantified using the Bradford assay. Then, 2.5 μg aliquots of total protein, boiled for 5 min at 95°C and prepared in 5× Laemmli sample buffer, were resolved by using SDS-PAGE and transferred to PVDF membranes. Membranes were blocked with 5% defatted milk (w/v) or 5% BSA (w/v) in TBS-Tween-20 (0.1%) for 1 h and incubated overnight with the following antibodies and dilutions: anti-phospho-ERK1/2 (1:1000, CST, #9101), anti-ERK1/2 (1:1000, CST, #4696), anti-phospho-p70S6K (1:1000, CST, #9206), anti-phospho-CREB (1:1000, CST, #9198), anti-Bip (1:1000, Sigma-Aldrich, #G9819), anti-GFP (1:1000, Thermo Fisher Scientific), anti-phospho-c-Jun (1:1000, CST, #9258), anti-calnexin (1:1000, Santa Cruz Biotechnology, #SC-6465). All antibodies were then washed 3 times with TBS-Tween-20 (0.1%), and HRP-labeled secondary antibodies, selected according to the species of origin of the primary antibodies (Sigma-Aldrich, #NA-931-1 and #NA-934V), were added for 1 h at a 1:5000 dilution in TBS-Tween-20 (0.1%) at room temperature. Finally, protein bands were detected by incubation with an enhanced chemiluminescence reagent (Bio-Rad), and densitometric analysis of the relative expression of the protein of interest versus the corresponding loading control was performed with ImageJ software. Western blot images were cropped for clarity. Electrophoretic migration of molecular weight markers is depicted on the left-hand side of each blot.

For coimmunoprecipitation experiments, 48 h after transfection, cells were lysed on ice-cold GST buffer (50 mM Tris-Cl, 10% glycerol v/v, 100 mM NaCl, 2 mM MgCl₂, 1% v/v NP-40, pH 7.4), supplemented with protease inhibitors. Cell lysates were clarified by centrifugation at 12,000 × g for 15 min (4°C), and total protein was quantified with Coomassie protein concentration of 1 mg/ml. Beads were subsequently washed 3 times with TBS-Tween-20 (0.1%), and HRP-labeled secondary antibodies, selected according to the species of origin of the primary antibodies (Sigma-Aldrich, #NA-931-1 and #NA-934V), were added for 1 h at a 1:5000 dilution in TBS-Tween-20 (0.1%) at room temperature. Finally, protein bands were detected by incubation with an enhanced chemiluminescence reagent (Bio-Rad), and densitometric analysis of the relative expression of the protein of interest versus the corresponding loading control was performed with ImageJ software. Western blot images were cropped for clarity. Electrophoretic migration of molecular weight markers is depicted on the left-hand side of each blot.

Dynamic mass redistribution (DMR). The cell-signaling signal was determined using an EnisPe Multimode Plate Reader (PerkinElmer) by a label-free technology. Cellular mass movements induced on receptor activation were detected by illuminating the underside of the biosensor with polychromatic light and measured as changes in wavelength of the reflected monochromatic light that is a sensitive function of the index of refraction. The magnitude of this wavelength shift ( absorbance) is directly proportional to the amount of DMR. Briefly, 24 h before the assay, cells were seeded at a density of 10,000 cells per well in 384-well sensor microplates with 30 μl growth medium and cultured for 24 h (37°C, 5% CO₂) to obtain 70%-80% confluent monolayers. Previous to the assay, cells were washed twice with assay buffer (HBSS with 20 mM HEPES, pH 7.15) and incubated for 2 h in 30 μl per well of assay buffer with 0.1% DMSO in the reader at 24°C. Hereafter, the sensor plate was scanned, and a baseline optical signature was recorded before adding 10 μl of the test compound dissolved in assay buffer containing 0.1% DMSO. Then, DMR responses were monitored along time, and kinetic data were analyzed using EnisPe Workstation Software version 4.10. Each representative curve shown is the mean of three independent replicates.

Phosphoprotein array. Cells transfected with CB1R-GFP and BIP-IR (or control) plasmids were treated with WIN-55212-2 (100 mM final concentration) or vehicle (DMSO, 0.1% v/v final concentration) as described above for 5 and 15 min. Samples from two independent experiments were processed separately by using 350 μg of total protein per experimental condition, following the instructions of the Proteome Profiler Human Phospho-Kinase Array Kit (R&D Systems, Bio-techne, #ARY003C). Densitometric analysis of the relative phosphorylation levels versus the corresponding housekeeping controls and between WIN-55212-2/vehicle treatments was performed with ImageJ software and the Protein Array Analyzer toolset.

Cellular and subcellular fraction preparations. Membrane preparations for G-protein-coupling assays were obtained from HEK-293T-cell pellets or adult mouse hippocampus tissue specimens. Frozen samples were thawed at 4°C and homogenized with a glass/Teflon grinder (IKA labortechnik), 10 strokes at maximum speed, in 30 volumes of homogenization buffer (250 mM sucrose, 50 mM Tris-Cl, 1 mM EDTA, 1 mM EGTA, 1 mM MgCl₂, 1 mM DTT, pH 7.4). The homogenates were centrifuged at 1100 × g for 10 min at 4°C. The pellets were discarded, and the supernatants were recentrifuged at 40,000 × g for 10 min at 4°C. The resultant pellets were resuspended in 20 volumes of ice-cold centrifugation buffer (50 mM Tris-Cl, 1 mM EDTA, 3 mM MgCl₂, 1 mM DTT, pH 7.4) with a glass stick and recentrifuged at 40,000 × g for 10 min at 4°C. The pellets obtained were then resuspended in 5 volumes of centrifugation buffer. Protein content was determined by the Bradford method. Finally, aliquots of 0.5, 1.0, and 2.0 mg protein were centrifuged at 21,000 × g for 15 min at 4°C. The supernatant layer was carefully discarded, and the pellets were stored at −80°C until assayed.

Total, cytosolic, and ER fractions from hippocampus, cortex, and striatum of the adult mouse brain were obtained by lysing the corresponding regions through sonication in 2 ml of ice-cold MTE buffer (270 mM D-mannitol, 10 mM Tris-Cl, 0.1 mM EDTA, pH 7.4). Tissue extracts were centrifuged (1400 × g, 10 min, 4°C), and the supernatant (total cell lysate) was recentrifuged (15,000 × g, 10 min, 4°C) to separate the pelletated mitochondrial crude fraction. Isolation of ER from cytosol was achieved by loading the sample in a sucrose gradient (2 × 1.5 M sucrose) with choice of 5% (v/v) chilling solution, pH 4.0, 4°C. The ER fraction appears as a band at the 1.5/1.3 M sucrose interface, while the cytosolic fraction remains at the top of the tube. Both fractions were collected, in the case of the ER with the aid of a syringe with a 20G needle, and the ER fraction was further purified by an additional ultracentrifugation step (126,000 × g, 45 min, 4°C). The ER-containing pellet was resuspended in 100 μl of PBS and immediately frozen. Likewise, aliquots of total cell lysate and cytosolic fractions were collected throughout the process and immediately frozen. Samples were kept at −80°C for Western blot analysis.

Striatal, hippocampal, and cortical synaptosomes were isolated from adult CB1R-KO mice and CB1R-WT control littermates, plated on poly-L-lysine-covered coverslips, fixed in 4% PFA, and characterized as described previously (Martin et al., 2010). PLA assays were conducted as described above.

Antibody-capture [35S]GTPγS scintillation proximity assay. Specific activation of different subtypes of Gα protein subunits (Gαq, Gα12, Gα13, Gα11, Gαi3, Gα12, and Gα13) was determined by using a homogeneous protocol of [35S]GTPγS scintillation proximity assay coupled to the use of the following antibodies: mouse monoclonal anti-Gαq (1:20, Santa Cruz Biotechnology, #S5535), rabbit polyclonal anti-Gα12 (1:20; Santa Cruz Biotechnology, #sc-7726), rabbit polyclonal anti-Gα13 (1:30, Antibodies on-line, #ABIN6258933), mouse...
monoclonal anti-Gaα (1:40, Santa Cruz Biotechnology, #sc-393874), mouse monoclonal anti-Gaα1 (1:20, Santa Cruz Biotechnology, #sc-383), rabbit polyclonal anti-Gaα (1:20, Santa Cruz Biotechnology, #sc-515689), and rabbit polyclonal anti-Gaα1/2 (1:20 Santa Cruz Biotechnology, sc-28588). [35S]GTPγS binding was measured in 96-well isoplates (PerkinElmer Life Sciences) and a final volume of 20 μL containing 1 mM EGTA, 3 mM MgCl2, 100 mM NaCl, 0.2 mM DTT, 50 mM Tris-HCl, pH 7.4, 0.4 nM [35S]GTPγS, 10 μg of protein per well, and different concentrations of GDP (between 50 and 100 μM) depending on the Gaα subunit subtype tested. At the end of the 2 h incubation period (at 30°C), 20 μL of 0.1% Igepal plus 0.1% SDS was added to each well, and plates were incubated at 23°C for 30 min with gentle agitation. The specific antibody for the Gaα subunit of interest was then added to each well before an additional 90 min incubation period at room temperature. Polyvinylthene SPA beads coated with protein A (PerkinElmer) were then added (0.75 mg of beads per well), and plates were incubated for 3 h at room temperature with gentle agitation. Finally, plates were centrifuged (5 min at 1000 × g), and the bound radioactivity was detected on a MicroBeta TriLux scintillation counter (PerkinElmer). To determine their effect on [35S]GTPγS binding to the different Gaα subunit subtypes in the different experimental conditions, a single submaximal concentration (10 μM) of WIN-55212-2 was used, either alone or in the presence of the CB1R antagonist O-2050 (10 μM) as control. Nonspecific binding was defined as the remaining [35S]GTPγS binding in the presence of 10 μM unlabeled GTPγS. For each Gaα protein, specific [35S]GTPγS binding values were transformed to percentages of basal [35S]GTPγS binding values (those obtained in the presence of vehicle).

**Determination of CAMP concentration.** Homogeneous time-resolved fluorescence energy transfer assays were performed using the Lance Ultra CAMP kit (PerkinElmer). HEK-293T cells (1000 per well), growing in medium containing 50 μM zardverine, were incubated in triplicate for 15 min in white ProxiPlate 384-well microplates (PerkinElmer) at 25°C with vehicle or WIN-55212-2 (100 μM final concentration) before adding vehicle or forskolin (0.5 μM final concentration) and incubating for 15 additional minutes. Fluorescence at 665 nm was analyzed on a PHERAstar Flagship microplate reader equipped with a homogeneous time-resolved fluorescence optical module (BMG Lab Technologies).

**Animals.** All the experimental procedures used were performed in accordance with the guidelines and approval of the Animal Welfare Committees of Universidad Complutense de Madrid and Comunidad de Madrid, as well as of Universitat de Barcelona and Generalitat de Catalunya, and in accordance with the directives of the Spanish Government and the European Commission. BIP+/− (herein referred to as BIP-HET) mice were purchased from The Jackson Laboratory (019549). We also used CB1R−/− mice (herein referred to as CB1R-foxed) and CB1R+/− mice (herein referred to as CB1R-RKO) mice, conditional CB1R−/− mice (herein referred to as Glu-CB1R-KO) mice, and conditional CB1R−/− mice (herein referred to as GABA-CB1R-RKO) mice (Monory et al., 2006). As well as Stop-CB1R, Stop-CB1R (herein referred to as CB1R-RS) mice, and conditional Stop-CB1R−/− mice (herein referred to as Glu-CB1R-RS), mice, to allow CB1R gene-expression rescue from a CB1R-null background (Ruehl et al., 2013; De Salas-Quiroga et al., 2015). Animal housing, handling, and assignment to the different experimental groups were conducted as described previously (Ruiz-Calvo et al., 2018). Adequate measures were taken to minimize pain and discomfort of the animals.

**ISH histochemistry.** For ISH histochemistry, 14-μm-thick coronal whole-brain tissue sections were obtained from adult C57BL/6 mice (Janvier Laboratories), cut on a microtome-cryostat (Microim HM450 OM), thaw-mounted on 3-aminopropyltriethoxysilane-coated slides (Sigma-Aldrich), and kept at −20°C until further processing. The oligonucleotides complementary to the mRNA encoding BIP, CB1R, and GABAergic or glutamatergic markers are listed in Table 1. Oligonucleotides for each mRNA were labeled at their 3′-end by using [α-32P]dATP (3000 Ci/mmol, Hartmann Analytic). Labeled probes were purified on ProbeQuant G-50 Micro Columns (GE Healthcare). ISH histochemistry procedures were performed as described previously (Sanabria and Mengol, 2011). For autoradiography, hybridized sections were exposed to Biomax MR (Kodak) films for 1-10 d at −70°C with intensifying screens. Double in situ-hybridized sections were processed as described previously (Reyes-Irisarri et al., 2007). They were exposed in the dark for 4-6 weeks at 4°C. Images from autoradiograms were obtained by using a Wild M420 macroscopic (Leica Microsystems) equipped with a digital camera (DXY1200 F, Nikon) and ACT-1 Nikon software. Microphotography was performed with an Olympus BX51 Stereologic Microscope (Olympus) equipped with a digital camera (DP71, Olympus) or with a Carl Zeiss Axioptan microscope equipped with an Olympus XC50 digital camera. Figures were assembled using Adobe Photoshop (Adobe Systems). Only contrast and brightness were uniformly adjusted to optimize images.

**Behavioral tests.** Adult male mice (3- to 4-month-old) were injected intraperitoneally with vehicle (2% v/v DMSO in 1:18 v/v Tween-80/saline solution) or 10 mg/kg THC (THC Pharm). The cannabinoid tetra- rad was assessed, starting 30 min after injection, following standard guidelines (Metna-Laurent et al., 2017). First, the open-field test was conducted for 10 min in an arena of 70 × 70 cm. To evaluate anxiety-like behaviors, the number of entries of the animal into the central part of the arena (25 × 25 cm) relative to total ambulation was assessed, one entry being counted when the animal had placed at least both forelimbs in the square. Next, angesias was assessed as the latency to paw licking in the hotplate paradigm at a constant temperature of 52°C. Then, for the catalepsy test, the animal was placed with both forelimbs leaning on a bar situated at a height of 3.5 cm. Immobility was considered maximal when the animal exceeded 60 s of immobility, and null when the immobility time was lower than 5 s. In all cases, three attempts were performed, and the maximal immobility time was selected as the representative value. Finally, body temperature was measured with a rectal thermometer and compared with the basal, pre-injection value.

The elevated plus maze test was evaluated 4 h after acute intraperitoneal injection of vehicle or THC (10 mg/kg). The maze consisted of a cross-shaped plastic device with two opposite open arms (30-cm-long, 5-cm-wide) and two opposite closed arms (30-cm-long, 5-cm-wide, 16-cm-tall walls), connected by a central structure (5 × 5 cm), and elevated 50 cm from the floor. Each mouse was placed in the center of the maze, facing one of the open arms, and the exploratory behavior of the animal was video-recorded for 5 min. The number and duration of entries were measured separately for the open arms and the closed arms. One arm

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**Table 1. Oligonucleotides used for ISH histochemistry**

| Oligonucleotide designation | mRNA | Accession number | bp limits | Oligonucleotide sequence |
|----------------------------|-------|------------------|-----------|-------------------------|
| mcB1/1                      | CB1R  | U22948.1         | 186-230   | GATGCGAGGCAGCTGACGAGCCCTAGGATCAGTGCCTTGATCAGGTT |
| mcB1/2                      | CB1R  | U22948.1         | 556-600   | ATACGACAGCTGCACACCCCTAGGACGAGGGCGCAGGAGTCCTT |
| mcB1/3                      | CB1R  | U22948.1         | 1556-1601 | CAGAGCTGGGACAGCGGACGCCAGAGCAGCAAGGAGTCCTT |
| mGRP78/1                    | 78 kDa glutamate-regulated protein (BIP) | D78645.1 | 121-165 | TTCTTGGTCTCTGCTGGTCGGCGCGCGGCCAGGACGGAGGAC |
| mGRP78/2                    | 78 kDa glutamate-regulated protein (BIP) | D78645.1 | 1262-1306 | ACCACCGCTGAGCAGAGGGACGCTGACGAGCCCTAGGATCAG |
| mGRP78/3                    | 78 kDa glutamate-regulated protein (BIP) | D78645.1 | 1996-2040 | ATAGCTTCCGAGCTTGTCGGCGCGCGGCCAGGAGTCCTT |
| rmA6D6/1                    | Glutamic acid decarboxylase 65 | NM_008078.2 | 421-465 | CTGTTGCGATGCGCGCGGCTCGTTGTCAGGATCAGGACAGCA |
| rmA6D6/2                    | Glutamic acid decarboxylase 65 | NM_008078.2 | 776-820 | GCGTAAATGTCCACGAGCTTGGTCAGGATCAGGACAGCA |
| rGAD/5                      | Glutamic acid decarboxylase 67 | M76177.1 | 1601-1654 | ATAGAGATTGATCGCAGCAGCGGTGTCAGGATCAGGACAGCA |
| rVGluT1/1                   | Vesicular GluT1 transporter | NM_053589.1 | 127-171 | CAGGCGGCGCCGACGAGCTTGTCAGGATCAGGACAGCA |
| rVGluT1/2                   | Vesicular GluT1 transporter | NM_053589.1 | 1756-1800 | GTCGCCAGAGCGGCGCGCGGCCAGGACAGGATCAGGACAGCA |
Figure 1. BiP interacts with CB1R in vitro. 

A, Scheme of the Y2H experiment using CB1R-CTD (amino acids 408-472) as bait and a human cDNA library (>10⁶ clones) as prey. One cDNA clone (stained in blue) contained BiP/GRP78/Hspa5 amino acids 497-654 (BiP-IR). Diagram represents the main structural domains of BiP/GRP78/Hspa5 is shown.

B, Scheme of the Y2H experiment using fragments of CB1R-CTD or CB2R-CTD as bait and BiP-IR as prey.

C, Fluorescence polarization-based protein–protein binding experiments using 5-IAF-labeled CB1R-CTD and increasing amounts of unlabeled BiP-IR (top) or BiP (bottom). A representative experiment, including the gels of the purified proteins, is shown (n = 3).

D, Coimmunoprecipitation experiments in HEK-293T cells expressing fragments of GFP-CB1R-CTD and 3xFLAG-BiP-IR. Immunoprecipitation (IP) was conducted with anti-GFP antibody. WCL, Whole-cell lysate. A representative experiment is shown (n = 3).

E, Coimmunoprecipitation experiments in HEK-293T cells expressing HA-CB1R and 3xFLAG-BiP or 3xFLAG-BiP-IR. IP was conducted with anti-HA antibody (left) or anti-FLAG antibody (right). Asterisk indicates immunoglobulin heavy and light chains. A representative experiment is shown (n = 3).

F, Coimmunoprecipitation experiments in HEK-293T cells expressing GFP-CB1R-CTD WT or an S452D point mutant form, along with 3xFLAG-BiP-IR. IP was conducted with anti-GFP antibody. A representative experiment is shown (n = 3).

G, BRET experiments in HEK-293T cells expressing GFP-BiP-IR/CB1R-Luc. A representative experiment is shown (n = 3).
entry was registered when the animal had placed both forepaws in the arm.

In all cases, animals were assigned randomly to the different treatment groups, and all experiments were performed in a blinded manner for genotype and pharmacological treatment. All tests were video-recorded for subsequent blinded analysis using Smart3.0 version 3.00.6 Software (Panlab).

Experimental design and statistical analyses. Unless otherwise specified, data are presented as mean ± SEM. Statistical comparisons were conducted by one-way or two-way ANOVA with Tukey’s post hoc test, or by Student’s t test, as indicated in each case. All datasets were tested for normality (Kolmogorov–Smirnov’s test) and homoscedasticity (Levene’s test) before analysis. For clarity, only p values < 0.05 were considered statistically significant. The sample size for each experiment was estimated on the basis of previous studies conducted by our laboratories using similar protein-interaction, cell-culture, brain-sample, and motor-behavior approaches. Subsequent power analysis was conducted for each parameter by using IBM SPSS software. The number of biological replicates (e.g., number of mice, number of cell cultures) is provided in the corresponding figure legends. The number of technical replicates (e.g., number of Y2H assays, number of incubations within each cell culture, number of sections microscopically analyzed per mouse brain, number of behavioral trials per mouse) is provided in the corresponding figure legends or in the corresponding Materials and Methods subsections. All the experiments conducted with animals are presented as dot plots. Graphs and statistics were generated by GraphPad Prism version 8.0.1.

Results

Bip interacts with CB1R in vitro

To identify new CB1R-interacting intracellular proteins, we challenged the receptor’s CTD (amino acids 408-472) to a cDNA library containing >10^6 different clones by means of a Y2H system. One particular cDNA clone, comprising amino acids 497-654 of the protein BiP (hereafter “BiP-interacting region” [BiP-IR]), provided an unequivocally positive outcome (Fig. 1A). BiP, also known as GRP78 or Hspa5, belongs to the highly conserved Hsp70 family of molecular chaperones. These proteins consist of two different domains: an N-terminal nucleotide-binding domain with ATPase activity, and a C-terminal substrate-binding domain (SBD). The SBD, in turn, is composed of a β-sandwich domain (SBDβ) and an α-helical lid (SBDα), which are interlinked by a hydrophobic stretch (Wieteska et al., 2017). It is generally believed that ATP-assisted, BiP-mediated protein refolding proceeds when hydrophobic peptides bind to a conserved groove in the SBDβ domain of BiP. Conversely, here, we found that CB1R-CTD interacts essentially with the lid domain in the absence of the groove. Specifically, according to the reported structures (Yang et al., 2015, 2017), BiP-IR would span the entire SBDα and two strands of the SBDβ (Fig. 1A, bottom diagram).

We next aimed to validate the molecular specificity of the interaction between CB1R-CTD and BiP-IR. First, by using directed Y2H assays, we delimited the BiP-IR-binding site to a restricted 23 amino-acid stretch (residues 449-472) at the edge of CB1R-CTD (Fig. 1B). Second, we found that the CTD of CB1R, the GPCR with the highest sequence homology to CB1R, did not bind BiP-IR (Fig. 1B). Third, as the phosphorylation state of specific S and T residues in the CTD of a GPCR can determine its interaction with intracellular proteins, we challenged BiP-IR to every possible single phosphomimetic mutant (S/T → D) within CB1R-CTD as bait, and BiP-IR as prey. Only one clone abrogated the interaction (CB1R-CTD-S452D).

| Bait plasmid | Prey plasmid | Interaction |
|-------------|-------------|-------------|
| pGBT9 CB1R-CTD-S410D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S414D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S425D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S431D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S441D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S447D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S452D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S462D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-S464D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-T418D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-T453D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-T465D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-T467D | pACT2 BiP-IR | + (n = 3) |
| pGBT9 CB1R-CTD-T468D | pACT2 BiP-IR | + (n = 3) |

| Scheme of the Y2H experiment using every possible single phosphomimetic mutant (S/T → D) within CB1R-CTD as bait, and BiP-IR as prey. Only one clone abrogated the interaction (CB1R-CTD-S452D). |

We subsequently conducted experiments in HEK-293T cells. First, coimmunoprecipitation studies showed that (1) CB1R-CTD, and specifically its 449-460 amino-acid stretch, was sufficient to bind BiP-IR (Fig. 1D); (2) full-length CB1R also interacted with both BiP and BiP-IR (Fig. 1D); and (3) BiP-IR exhibited little association with the S452D point mutant of CB1R-CTD (Fig. 1F). Second, BRET experiments conducted with an Rluc-tagged version of CB1R also supported the protein–protein interaction (Fig. 1G, top), and adding non–GFPI-tagged versions of BiP as competitors decreased the BRET peak only when the BiP-IR was present (Fig. 1G, bottom) (n = 3 experiments; BiP-IR vs control: F(3,30) = 28.20, p < 0.0001, ANOVA; BiP vs control: F(3,30) = 28.20, p < 0.0001, ANOVA; BiP-AIR vs control: F(3,30) = 28.20, p = 0.3648, ANOVA). Moreover, there was no overt binding between GFP-BiP-IR and CB1R-Rluc when the S452D single mutation was introduced in the receptor (Fig. 1G, top).

Together, these data show that BiP interacts specifically with CB1R in vitro, both in purified-protein assays and in HEK-293T cells.

BiP modulates CB1R-evoked signaling

DMR is a powerful tool to assess the overall signal triggered by the agonist-evoked activation of a particular receptor in living cells (Fang et al., 2007). Indeed, we and others have previously used DMR to investigate CB1R-evoked signaling (Viñals et al., 2015; Moreno et al., 2018; Navarro et al., 2020). Here, by using HEK-293T cells expressing CB1R, we found a well-defined and saturating curve after adding the cannabinoid receptor-selective agonist WIN-55212-2 (Fig. 2A). Of note, coexpression of full-length BiP led to a strong inhibition of CB1R signaling (Fig. 2A) but did not alter the agonist-evoked response of two other Gαo-coupled receptors (CB2R and adenosine A1 receptor) that were used as controls (Fig. 3A). The effect of BiP on CB1R relied selectively on BiP-IR, as expressing this region rendered a comparable

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293T cells expressing CB1R-Rluc or CB1R-S452D-Rluc and increasing amounts of GFP-BiP-IR (top; a representative experiment is shown; n = 3), together or not with nontagged versions of BiP, BiP-IR, or BiP-ΔIR as competitors (bottom). **p < 0.01 from control vector by one-way ANOVA with Tukey’s multiple comparisons test (n = 3).
Figure 2. BiP modulates CB1R-evoked signaling. A, DMR experiments in HEK-293T cells expressing CB1R, together or not with BiP, BiP-IR, or BiP-ΔIR, and incubated with WIN-55212-2 (100 nM). A representative experiment is shown (n = 3). B, DMR experiments in HEK-293T cells expressing CB1R, together or not with BiP-IR, and incubated with endocannabinoids (10 μM; 2-AG, 2-arachidonoylglycerol; AEA, anandamide). A representative experiment is shown (n = 3). C, Coupling of CB1R to Gς subunits in membrane extracts from HEK-293T cells expressing CB1R, together or not with BiP-IR. *p < 0.05 from basal (dashed line), or #p < 0.05 from control vector; one-sample Student’s t test or unpaired Student’s t test, respectively (n = 3). D, cAMP concentration in HEK-293T cells expressing CB1R, together or not with BiP-IR. Cells were incubated first for 15 min with vehicle or WIN-55212-2 (100 nM), and then for 15 min with vehicle or forskolin (FSK; 500 nM). **p < 0.01 from vehicle, or ##p < 0.01 from FSK alone; two-way ANOVA with Tukey’s multiple comparisons test (n = 3). E, HEK-293T cells expressing CB1R, together or not with BiP-IR, were incubated for 5 or 15 min with vehicle or WIN-55212-2 (100 nM), and cell extracts were blotted on a phosphoprotein array. Two different times of membrane exposure are shown to allow an appropriate visualization of the main proteins affected (framed spots). A representative experiment is shown (n = 2; membranes from vehicle-treated cells are omitted for clarity). Heat map represents values of mean fold-activation by WIN-55212-2 over vehicle. F, Validation of some of the phosphoarray hits by conventional Western blotting in the same cell extracts used in D. A representative experiment is shown (n = 2). G, Coupling of CB1R to non-Gς subunits in membrane extracts from HEK-293T cells expressing CB1R, together or not with BiP-IR. *p < 0.05 from basal (dashed line), or **p < 0.01 from control vector; one-sample Student’s t test or unpaired Student’s t test, respectively (n = 3). H, Western blotting of phospho-ERK in HEK-293T cells expressing CB1R, and incubated for 5, 10, or 15 min with vehicle or WIN-55212-2 (100 nM). Top, Cells were preincubated for 30 min with vehicle or YM-254890 (1 μM). Bottom, Cells
inhibition, and no change was found with BiP-ΔIR (Fig. 2A).

This effect was again subverted when the S452D point mutation was inserted in CB1R (Fig. 3B), and was also evident, although with a slower kinetics, when the endocannabinoids anandamide and 2-arachidonoylglycerol were used as receptor agonists (Fig. 2B). Given the similar behavior of full-length BiP and BiP-IR, we used only BiP-IR for further signaling experiments.

CB1R activation modulates multiple signaling pathways, with cAMP/PKA, ERK, and PI3K/Akt/mTORC1 being the best characterized (Pertwee et al., 2010; Nogueras-Ortiz and Yudowski, 2016). We thus aimed to dissect in detail the inhibitory effect of BiP-IR on CB1R overall signaling observed in DMR assays. First, we found that BiP-IR did not alter markedly the archetypical Gα couplings of CB1R (Fig. 2C). In the absence of BiP-IR, the Gαq control vs Gαq-BiP-IR: t(25) = 1.730, p = 0.0959, t test; Gαi control vs Gαi-BiP-IR: t(14) = 0.2886, p = 0.7771, t test; Gβ/γ control vs Gβ/γ-BiP-IR: t(18) = 0.5927, p = 0.5607, t test; Gαs control vs Gαs-BiP-IR: t(27) = 4.950, p < 0.0001, t test), nor affected the WIN-55212-2-evoked reduction of forskolin-augmented cAMP concentration (Fig. 2D) (n = 3 experiments; control vs BiP-IR: vehicle, F(2,12) = 45.98, p < 0.0001, ANOVA; forskolin, F(2,12) = 45.98, p < 0.0001, ANOVA; WIN-55212-2 + forskolin, F(2,12) = 45.98, p = 0.0000, ANOVA). Next, we analyzed the phosphorylation (activation) state of major cellular protein kinases by using a phosphoprotein array. HEK-293T cells were transfected with the same constructs used in the aforementioned DMR assays, and subsequently treated with vehicle or WIN-55212-2. Among the different pathways activated by the cannabinoid, BiP-IR preferentially hampered the Akt/mTORC1 pathway (as inferred from Akt1/2-T308, PRAS40-T246, and p70S6K-T389 phosphorylation) and the ERK pathway (as inferred from ERK1/2-T202/Y204 phosphorylation) (Fig. 2E). The WIN-55212-2-mediated activation of CREB, an archetypical convergent substrate of the Akt/mTORC1 and ERK pathways, was also inhibited by BiP-IR (as inferred from CREB-S133 phosphorylation). We confirmed this BiP-mediated inhibition of CB1R-evoked signaling by analyzing pERK1/2-T202/Y204, pp70S6K-T389, and pCREB-S133 with conventional Western blotting (Fig. 2F). Accordingly, the PI3K inhibitor LY294002 and the MEK1 inhibitor U0126 blunted the WIN-55212-2-evoked DMR signal (Fig. 3C).

To study how BiP selectively alters CB1R-mediated signaling independently of Gαq/11 proteins, we evaluated the coupling of the receptor to non-Gαq/11 G-proteins. Of note, we found that CB1R also coupled to Gαq/11, and this association was impaired by BiP-IR (Fig. 2G) (n = 3 experiments; Gαq/11 control vs Gαq/11-BiP-IR: t(26) = 3.238, p = 0.0033, t test; Gαi control vs Gαi-BiP-IR: t(9) = 0.2220, p = 0.8299, t test; Gαs control vs Gαs-BiP-IR: t(9) = 0.9241, p = 0.3825, t test; Gαβ/γ control vs Gαβ/γ-BiP-IR: t(18) = 0.3941, p = 0.6981, t test). Moreover, WIN-55212-2-mediated ERK activation was mitigated by either pharmacological blockade of Gαq/11 (with the drug YM-254890) or genetic interference of Gαq/11 signaling (with a dominant-negative GFP-GRK2 construct) (Andradas et al., 2016) (Fig. 2H). Likewise, YM-254890 and dominant-negative Gαq/11 reduced the WIN-55212-2-evoked DMR response (Fig. 2F). We next analyzed the coupling of CB1R to Gαq/11 in hippocampal extracts from adult BiP−/− (hereafter BiP-WT) and BiP+/− (hereafter BiP-ΔIR) mice (very early embryonic lethality occurs in BiP−/− mice (Luo et al., 2006).) In line with the aforementioned data from HEK-293T cells, CB1R showed a preference for Gαq/11 coupling in BiP-ΔIR mice compared with their BiP-WT littermates (Fig. 2F) [BiP-WT (n = 5 mice) vs BiP-HE (n = 6 mice); t(29) = 7.268, p = 0.00034, t test]. Together, these data show that BiP-IR affects CB1R-evoked signaling through the selective attenuation of an “alternative” Gαq/11 protein-driven module, while leaving the “classical” Gαq/11 protein-driven module essentially unaffected.
enriched pyramidal cell layer (0.4 ± 0.7%) of the BiP-positive cells coexpressed vGluT1; n = 4 mice, t(6) = 18.48, p < 0.0001 from BiP-GAD65/67+ cells, t test) (Fig. 5C,D).

In the DG, the distribution of BiP mRNA between disseminated GAD65/67 mRNA-expressing neurons (Fig. 5A,B) and vGluT1 mRNA-expressing neurons (Fig. 5C,D) was more balanced, although again with a preference toward inhibitory cells (47.0 ± 9.9% and 30.0 ± 7.2% of the BiP-positive cells coexpressed GAD65/67 or vGluT1, respectively; n = 4 mice, t(6) = 1.392, p = 0.2133, t test).

The most widely reported subcellular localization of BiP is the ER lumen, while CB1R is largely located at the plasma membrane, and its CTD faces the cytoplasm since its biosynthesis starts on the ER. To assess this apparent inconsistency, we performed subcellular fractionation experiments in mouse brain samples. Analysis of hippocampal, striatal, and cortical tissue extracts showed that BiP is present not only in the ER but also in the cytosolic fraction (Fig. 6A,B) [Hippocampus: cytosol (n = 4 mice) vs ER (n = 3 mice), F(2,8) = 21.50, p = 0.0004, ANOVA; striatum: cytosol (n = 4 mice) vs ER (n = 3 mice), F(2,8) = 6.232, p = 0.0234, ANOVA; cortex: cytosol (n = 4 mice) vs ER (n = 4 mice), F(2,9) = 2.858, p = 0.09993, ANOVA]. This observation supports the notion that cytoplasmic BiP binds to CB1R-CTD, and aligns with previous reports showing that not all BiP functions can be attributed to its interaction with ER-resident proteins (Belli et al., 1999; Cha-Molstad et al., 2015; Shim et al., 2018; Yoon et al., 2018), and that a population of BiP molecules is found adjacent to the plasma membrane (Tsai et al., 2015). As the majority of CB1R resides at the presynapse, where it controls neurotransmitter release (Piomelli, 2003), we also evaluated whether CB1R-BiP complexes are present in this subcellular location. PLA analyses revealed a pronounced positive signal in synaptosomes from the hippocampal, striatum, and cortex of CB1R-WT mice, but not of CB1R-KO littermates (Fig. 6C).

Next, to obtain a detailed neuroanatomical map of CB1R-BiP protein complexes, we conducted in situ PLA assays on brain slices from various genetic mouse models of conditional loss or gain of CB1R expression (Fig. 7A). We first used hippocampi from conditional CB1R-KO models (Marsicano et al., 2002) (Fig. 7B-G). PLA experiments conducted on hippocampal sections from control adult CB1Rfloxedfloxed (hereafter CB1R-floxed) mice showed that 63.2 ± 4.7% and 62.9 ± 11.2% of the cells contained positive puncta in the DG and CA1, respectively (n = 6 or 7 fields from 3 different mice, t(12) = 0.074, p = 0.9424, t test). This signal was strongly reduced in sections from CB1RfloxedfloxedCMV-Cre (hereafter CB1R-KO) mice (DG: 14.8 ± 5.0%; n = 6 fields from 3 different mice, F(3,23) = 109.6, p < 0.0001 from CB1R-floxed mice, ANOVA; CA1: 18.8 ± 4.5%; n = 7 fields from 3 different

CB1R-BiP complexes reside on GABAergic terminals of the mouse brain

It is well established that CB1R resides largely on terminals of GABAergic neurons (Marsicano and Lutz, 1999; Katona and Freund, 2008). However, the precise neurochemical phenotype of BiP-expressing cells remains unclear (compare Jin et al., 2018). Hence, we analyzed the expression of BiP mRNA in GABAergic versus glutamatergic neurons by ISH histochemistry. BiP mRNA was localized throughout the mouse brain (Fig. 4A), showing a more ubiquitous expression pattern than CB1R mRNA (Fig. 4B). Of note, nearly all the hippocampal high CB1R mRNA-expressing cells were also positive for BiP mRNA [93.7 ± 1.7% in the CA1/3 areas and 94.6 ± 3.4% in the dentate gyrus (DG); n = 4 mice, t(6) = 0.2487, p = 0.8119, t test] (Fig. 4C,D).

In the CA1/3 hippocampal areas, as reported for CB1R mRNA (Marsicano and Lutz, 1999), BiP mRNA showed a high colocalization with GAD65/67 mRNA (81.6 ± 4.4% of the BiP-positive cells coexpressed GAD65/67; n = 4 mice) (Fig. 5A,B), while colocalization with vGluT1 mRNA was hardly detectable in the scattered BiP-expressing cells adjacent to the BiP/vGluT1 mRNA-

Figure 4. Expression of BiP and CB1R mRNA in the mouse brain. A, B, Representative autoradiographic images of coronal sections from adult mouse brain showing the mRNA hybridization pattern of BiP (A) and CB1R (B). CA, Cornu ammonis; DG, dentate gyrus; Str, striatum; Cx, cortex; Cb, cerebellum. C, Distribution of CB1R mRNA in the mouse hippocampus. C1, Representative dark field image from a section hybridized with 33P-labeled oligonucleotide probes for CB1R mRNA. Arrows point to some double-labeled cells. D, Quantification of CB1R mRNA-positive cells that coexpress BiP mRNA (n = 4 mice per group).
mice, \( F_{(3,24)} = 40.86, p < 0.0001 \) from CB1R-KO mice, ANOVA). In conditional KO mice in which the gene encoding CB1R had been selectively deleted from forebrain GABAergic neurons (CB1R<sup>KO</sup>; hereafter GABA-CB1R-KO), we found a notable decrease in the percentage of cells expressing positive dots (DG: 31.9 ± 6.2%; \( n = 7 \) fields from 3 different mice, \( F_{(3,23)} = 109.6, p < 0.0001 \) from CB1R-R floxed mice, ANOVA. CA1: 33.9 ± 7.8%; \( n = 7 \) fields from 3 different mice, \( F_{(3,24)} = 40.86, p < 0.0001 \) from CB1R-R floxed mice, ANOVA). In contrast, sections from mice in which the gene encoding CB1R had been selectively deleted from dorsal telencephalic glutamatergic neurons (CB1R<sup>KO</sup>; hereafter Glu-CB1R-KO) displayed a similar pattern of PLA staining than their CB1R-R floxed counterparts (DG: 58.6 ± 5.9%; \( n = 7 \) fields from 3 different mice, \( F_{(3,22)} = 151.4, p < 0.0001 \), ANOVA; Glu-CB1R-R floxed mice, ANOVA). Comparable overall data were obtained in sections from mouse striatum (Fig. 8B,D) [CB1R-KO (\( n = 7 \) fields from 3 different mice) vs CB1R-R floxed (\( n = 7 \) fields from 3 different mice); \( F_{(3,22)} = 151.4, p < 0.0001 \), ANOVA; GABA-CB1R-R floxed (\( n = 6 \) fields from 3 different mice) vs CB1R-R floxed (\( n = 6 \) fields from 3 different mice); \( F_{(3,22)} = 0.3052 \), ANOVA; Glu-CB1R-R floxed (\( n = 6 \) fields from 3 different mice) vs CB1R-R floxed (\( n = 6 \) fields from 3 different mice); \( F_{(3,22)} = 0.3465 \), ANOVA; CB1R-R floxed (\( n = 6 \) fields from 3 different mice) vs CB1R-R floxed (\( n = 6 \) fields from 3 different mice); \( F_{(3,22)} = 0.9279 \), ANOVA). As in the aforementioned conditional KO mouse experiments, these CB1R gene expression-rescue data in the mouse hippocampus displayed a similar global pattern in the mouse striatum (Fig. 8C,D) [CB1R-R floxed (\( n = 7 \) fields from 3 different mice) vs CB1R-R floxed (\( n = 7 \) fields from 3 different mice); \( F_{(3,22)} = 230.5, p < 0.0001 \), ANOVA; GABA-CB1R-R floxed (\( n = 6 \) fields from 3 different mice) vs CB1R-R floxed (\( n = 7 \) fields from 3 different mice); \( F_{(3,22)} = 323.0, p < 0.0001 \), ANOVA; GABA-CB1R-R floxed (\( n = 6 \) fields from 3 different mice) vs CB1R-R floxed (\( n = 7 \) fields from 3 different mice); \( F_{(3,22)} = 323.0, p < 0.0001 \), ANOVA].

We subsequently made use of a Cre-mediated, lineage-specific, CB1R gene expression-rescue strategy from a CB1R-null background (hereafter Stop-CB1R mice) (De Salas-Quiroga et al., 2015; De Giacomo et al., 2020a) (Fig. 7C-G). PLA assays in hippocampal sections from these mice showed, as expected, a marginal CB1R-KO-like background signal (DG: 20.1 ± 3.2%, CA1: 21.2 ± 3.2%; \( n = 5 \) or 7 fields from 3 different mice, respectively; \( t_{(10)} = 0.5326, p = 0.6060, t \) test). In line with the data from conditional KO mice, rescuing CB1R gene expression in Stop-CB1R mice with a constitutive Cre recombinase (Stop-CB1R<sup>Ella-Cre</sup>, hereafter, CB1R-RS) restored CB1R-Bip complexes to the levels of control CB1R-floxed mice (DG: 59.6 ± 5.5%, CA1: 58.5 ± 5.8%; \( n = 5 \) or 7 fields from 3 different mice, respectively; \( F_{(3,24)} = 94.99, p < 0.0001 \), ANOVA; and \( F_{(3,22)} = 121.6, p < 0.0001 \), ANOVA, respectively). This effect was paralleled in brain sections from conditionally rescued Stop-CB1R<sup>Dlx5/6-Cre</sup> (hereafter, GABA-CB1R-RS) mice [DG: 58.1 ± 6.6%; \( n = 7 \) fields from 3 different mice; \( F_{(3,24)} = 94.99, p = 0.9279 \) from CB1R-RS mice, ANOVA. CA1: 56.9 ± 5.5%; \( n = 7 \) fields from 3 different mice; \( F_{(3,22)} = 121.6, p = 0.8400 \) from CB1R-RS mice, ANOVA], but not from conditionally rescued Stop-CB1R<sup>Dlx5/6-Cre</sup> [hereafter, Glu-CB1R-RS mice (DG: 21.1 ± 3.2%; \( n = 7 \) fields from 3 different mice; \( F_{(3,22)} = 94.99, p < 0.0001 \) from CB1R-RS mice, ANOVA. CA1: 20.2 ± 2.5%; \( n = 7 \) fields from 3 different mice; \( F_{(3,22)} = 121.6, p < 0.0001 \) from CB1R-RS mice, ANOVA]. As in the aforementioned conditional KO mouse experiments, these CB1R gene expression-rescue data in the mouse hippocampus displayed a similar global pattern in the mouse striatum (Fig. 8C,D) [Stop-CB1R<sup>R floxed</sup> (\( n = 7 \) fields from 3 different mice) vs CB1R-RS (\( n = 7 \) fields from 3 different mice); \( F_{(3,22)} = 230.5, p < 0.0001 \), ANOVA; GABA-CB1R-RS (\( n = 6 \) fields from 3 different mice) vs CB1R-RS (\( n = 7 \) fields from 3 different mice); \( F_{(3,22)} = 323.0, p < 0.0001 \), ANOVA].
BiP affects CB1R function in vivo
THC induces numerous behavioral changes in laboratory animals and humans. The combination of hypolocomotion, analgesia, catalepsy, and hypothermia, usually designated as the "cannabinoid tetrad," has evolved as a powerful tool to identify pharmacological or genetic interventions that target CB1R (Martin, 1986; Metna-Laurent et al., 2017). Previous studies have shown that these four behavioral traits rely selectively on the activation of CB1R molecules located on various populations of glutamatergic or dopamine D1 receptor-expressing projection neurons, but not on GABAergic interneurons, thus allowing a neurobiological correlate between CB1R cellular expression and function (Monory et al., 2007; De Giacomo et al., 2020a). We studied the "cannabinoid tetrad" in BiP-HET and BiP-WT littermates (Fig. 9A), and found that acute THC injection (10 mg/kg, i.p.) elicited the four archetypical effects of the "cannabinoid tetrad" to the same extent in BiP-HET and BiP-WT animals (Fig. 9, left panels) [Hypolocomotion: BiP-WT-vehicle (n = 10 mice) vs BiP-WT-THC (n = 10 mice), F(1,35) = 0.7219, p = 0.4055, ANOVA; BiP-HET-vehicle (n = 10 mice) vs BiP-HET-THC (n = 10 mice), F(1,35) = 3.145, p = 0.0831, ANOVA]. In addition, following a 5 day sustained treatment, BiP-HET and BiP-WT mice developed a comparable tolerance to THC (Fig. 9, right panels) [Hypolocomotion: BiP-WT-vehicle (n = 10 mice) vs BiP-WT-THC (n = 10 mice), F(1,35) = 0.7040, p < 0.0010, ANOVA; BiP-HET-vehicle (n = 10 mice) vs BiP-HET-THC (n = 10 mice), F(1,35) = 1.867, p = 0.1788, ANOVA; BiP-WT-vehicle (n = 9 mice) vs BiP-WT-THC (n = 9 mice), F(1,33) = 0.7068, p = 0.4033, ANOVA; BiP-HET-vehicle (n = 9 mice) vs BiP-HET-THC (n = 9 mice), F(1,33) = 0.8899, p = 0.3504, ANOVA].

Together, these data support the interaction between CB1R and BiP in three key regions of the mouse brain, and, more specifically, a restricted occurrence of CB1R-BiP complexes in GABAergic neurons.
As the CB₁R-BiP complexes reside selectively on GABAergic neurons (see above), it is not surprising that the deletion of a BiP allele does not modify any of the classical "cannabinoid tetrad" behavioral traits. Of note, anxiety-like behaviors induced by cannabinoid intoxication have been shown to rely selectively on the activation of CB₁R molecules located on GABAergic interneurons (Rey et al., 2012; De Giacomo et al., 2020a,b). Because the open-field test of the "cannabinoid tetrad" can also be used...
to define anxious phenotypes by evaluating the relative ambulation of the animals across the center of the arena (Seibenhener and Wooten, 2015), we conducted these analyses in our experimental setting. A single THC injection reduced the ambulation of the mice across the center of the arena equally in BiP-HET and BiP-WT mice (Fig. 10A, left) [BiP-WT-vehicle (n = 20 mice) vs BiP-WT-THC (n = 17 mice): $F_{(1,73)} = 32.35$, $p = 0.0164$, ANOVA; BiP-HET-vehicle (n = 20 mice) vs BiP-HET-THC

Figure 8. CB1R-BiP complexes reside on GABAergic terminals of the mouse striatum and cortex. A, PLA experiments were conducted on striatal and cortical sections from 3- to 4-month-old mice of different genotypes. Representative low-magnification image and selected regions for analysis are shown. Image credit: Allen Institute. In the rest of the panels, CB1R-BiP complexes are shown as red dots, and nuclei are colored in blue by DAPI staining. B, Representative images of striatal sections from CB1R-floxed, CB1R-KO, GABA-CB1R-KO, and Glu-CB1R-KO mice. C, Representative images of striatal sections from Stop-CB1R, CB1R-RS, GABA-CB1R-RS, and Glu-CB1R-RS mice. D, Quantification of the number of cells containing one or more dots expressed as the percentage of the total number of cells (DAPI-stained nuclei) in striatal sections. **p < 0.01 from the corresponding CB1R-floxed group or the corresponding CB1R-RS group by one-way ANOVA with Tukey’s multiple comparisons test (n = 6 or 7 fields from 3 different animals per group). E, Representative images of cortical sections from CB1R-floxed, CB1R-KO, GABA-CB1R-KO, and Glu-CB1R-KO mice. F, Representative images of cortical sections from Stop-CB1R, CB1R-RS, GABA-CB1R-RS, and Glu-CB1R-RS mice. G, Quantification of the number of cells containing one or more dots expressed as the percentage of the total number of cells (DAPI-stained nuclei) in cortical sections. **p < 0.01 from the corresponding CB1R-floxed group or the corresponding CB1R-RS group by one-way ANOVA with Tukey’s multiple comparisons test (n = 6 or 7 fields from 3 different animals per group).
(n = 20 mice): $F_{(1,73)} = 32.35, p < 0.0001$, ANOVA. However, after a 5 d continuing THC treatment, the ambulation across the center of the arena remained lowered by acute THC in BiP-HET mice but not in their BiP-WT littermates (Fig. 10A, right) [BiP-WT-vehicle (n = 20 mice) vs BiP-WT-THC (n = 18 mice): $F_{(1,74)} = 20.54, p = 0.5226$, ANOVA; BiP-HET-vehicle (n = 20 mice) vs BiP-HET-THC (n = 20 mice): $F_{(1,74)} = 20.54, p < 0.0001$, ANOVA].

To provide further support to the control of CB1R-mediated anxiety by BiP, we used the elevated plus maze test, a widely recognized measure of anxiety that served originally to define the anxiogenic activity of the CB1R pool located on GABAergic neurons (Rey et al., 2012). We injected BiP-WT and BiP-HET mice with vehicle or THC (10 mg/kg, i.p.), and found that the drug induced only an anxiogenic trend in BiP-WT mice but a significant anxiogenic effect in BiP-HET littermates, as evidenced by the decrease in both the number of entries (Fig. 10B, left) [BiP-WT-vehicle (n = 27 mice) vs BiP-WT-THC (n = 20 mice): $F_{(1,86)} = 11.51, p = 0.1471$, ANOVA; BiP-HET-vehicle (n = 21 mice) vs BiP-HET-THC (n = 22 mice): $F_{(1,86)} = 11.34, p = 0.0470$, ANOVA] and the time of permanence (Fig. 10B, right) in the open arms of the device [BiP-WT-vehicle (n = 27 mice) vs BiP-WT-THC (n = 20 mice): $F_{(1,86)} = 11.15, p = 0.00155$, ANOVA].

Together, these data support that BiP, by interacting with CB1R on GABAergic neurons, modulates anxiety-like behaviors on cannabinoid administration.

**Discussion**

Here, we show that BiP interacts specifically with CB1R-CTD. BiP is known to interact with some GPCRs during their folding (Siffroi-Fernandez et al., 2002; Mizrachi and Segaloff, 2004; Langer et al., 2008), and has been found associated to melanocortin MC4 receptors at the plasma membrane (Yoon et al., 2018). The CB1R-BiP interaction occurs between a short amino-acid stretch in the CB1R-CTD and the BiP-SBDa domain. The latter domain, to our knowledge, has never been implicated in the binding of BiP to membrane receptors. As the protein-binding/refolding function of BiP is usually ascribed to its SBDβ domain (Yang et al., 2015, 2017), we cannot rule out that additional proteins interact through this region.
CB₁R-evoked signaling is markedly affected by BiP binding. This finding contrasts with the subtle effect of CRIP1α on CB₁R/G-protein coupling (Blume et al., 2015), and with the BiP-mediated facilitation of melanocortin MC₄ receptor activation (Yoon et al., 2018). Accruing evidence has linked ERK and Akt/mTORC1 activation to various key CB₁R-evoked effects in the brain (Rubino et al., 2007; Guegan et al., 2013; Puighermanal et al., 2013; Blázquez et al., 2020). However, the possible relevance of Ga₉/₁₁ protein in CB₁R neurobiological action remains unclear (Diez-Alarci et al., 2016). Our data unveil an unprecedented functional coupling of CB₁R signaling to Ga₉/₁₁, as well as a selective hampering effect of BiP on it. Interestingly, regions analogous to CB₁R helix 9, which overlaps with the BiP-binding site, have been reported to act as Ga₉/₁₁-binding sites in rhodopsin (Murakami and Kouyama, 2008) and bradykinin B₂ receptor (Pisochio et al., 2005). Thus, it is conceivable that in CB₁R the binding of BiP constitutes a competitive sterie impedance to achieve Ga₉/₁₁ binding and activation.

Our detailed mapping of CB₁R-BiP complexes in the mouse brain shows that GABAergic neurons constitute the foremost cell population expressing these complexes. This is in line with a previous high-throughput proteomic study showing that BiP coimmunoprecipitates with CB₁R in mouse GABAergic neurons (Mattheus et al., 2016). It is worth noting that, despite their low CB₁R/G-protein coupling efficacy (Steindel et al., 2013), GABAergic terminals contain large amounts of CB₁R (Marsicano and Lutz, 1999; Katona and Freund, 2008) likely displaying a high tonic activity (Roberto et al., 2010). Given its inhibitory role, we speculate that BiP binding may represent a counterpoint to ensure a balanced CB₁R activity in the physiological control of glutamatergic/GABAergic neurotransmission. More specifically, THC-elicited anxiety relies on mTORC1 activation on engagement of CB₁R on hippocampal GABAergic interneurons (Rey et al., 2012; Puighermanal et al., 2013; De Giacomo et al., 2020a,b). In addition, a role of Ga₉/₁₁ protein-coupled receptors (e.g., serotonin 5-HT₂C receptor) in the induction of anxiety has been suggested (Mazzone et al., 2018). Thus, we propose that the THC-evoked high-input activation of a restricted Ga₉/₁₁-coupled pool of CB₁R molecules located on hippocampal GABAergic interneurons, via the mTORC1 signaling axis, triggers anxiety-like behaviors, a process plausibly controlled by BiP binding to CB₁R at the presynapse. This would provide an unprecedented mechanism for spatially selective control of CB₁R signaling in the brain, and supports...
that favoring CB1-R-BiP association would reduce anxiety, a frequent negative effect of CB1-R overactivation. As CB1-R-BiP complexes also reside on GABAergic neurons in other brain regions as the cortex and striatum, the possibility that BiP binding controls additional CB1R-related behaviors remains to be determined.

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