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5-HT₄ receptors: History, molecular pharmacology and brain functions

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Abstract

Twenty years ago, we started the characterization of a 5-HT receptor coupled to cAMP production in neurons. This receptor obviously had a different pharmacology to the other 5-HT receptors described at that time, i.e. the 5-HT₁, 5-HT₂, 5-HT₃ receptors. We proposed to name it the 5-HT₄ receptor. Nowadays, 5-HT₄ receptors are one of the most studied GPCRs belonging to the "rhodopsin" family. Thanks to the existence of a great variety of ligands with inverse agonist, partial agonist, agonist and antagonist profiles, the pharmacological and physiological properties of this receptor are beginning to emerge. Although some 5-HT₄ partial agonists have been on the market for gastro-intestinal pathologies, 5-HT₄ receptor drugs have still to be commercialized for brain disorders. However, since 5-HT₄ receptors have recognized effects on memory, depression and feeding in animal models, there is still hope for a therapeutic destiny of this interesting target in brain disorders.

1. Introduction

In July 1990, at the Second IUPHAR satellite meeting on Serotonin, held by the Serotonin Club in Basel, Switzerland, began a series of "Serotonin Club Irvine H. Page Lectures". S.J. Peroutka, a well-known and appreciated expert in the serotonin field gave a tribute to Dr. Irvine H. Page (Peroutka, 1991). S.J. Peroutka reminded younger colleagues that 5-hydroxytryptamine (5-HT) was successively called "vasotonin" (1933 – Bayliss and Ogden), "Enteramine" (1933 – Vialle and Erspamer), but that the modern name "serotonin" can be dated to Dr. Page's Science paper in 1948 (Rappoport *et al.*, 1948).

In 1985, Irvine H. Page wrote "*A long life has taught me that the natural history of one's active participation in a discovery is about 5–10 years. Then the subject grows complicated, new young faces appear with their better methods and they take over*" (Page, 1985).

Thus, I was very honoured when I received the Serotonin Club's invitation to give the Irvine H. Page Lecture, especially since we discovered the 5-HT₄ receptors (5-HT₄Rs) (Dumuis *et al.*, 1988a) 20 years ago with A. Dumuis and are still working on them, using, we hope, effective methods. The aim of this paper is to review 20 years of research on 5-HT₄Rs.

2. The pre-history of 5-HT₄Rs

My interest in neurotransmitter sensitive adenylate cyclase began more than 40 years ago when I came back to the Collège de France in Paris after post-doctoral training at Northwestern University in Chicago, where I was already working on G-protein coupled receptor desensitization. Paul Greengard had just published a paper on a dopamine sensitive adenylate cyclase in striatal membranes (Kebabian *et al.*, 1972). The possibility of using cAMP production, following receptor activation, to discover new neurotransmitter receptors and analyse their pharmacology, brain distribution and regulation was fascinating. I decided to interact with my new neighbouring neuroscientists and fantastic colleagues J. Glowinski and M. Hamon. In 1978, with M. Hamon, we described a post-synaptic 5-HT sensitive adenylate cyclase in different brain areas of rat and guinea-pig brain (Enjalbert *et al.*, 1978) (Fig. 1A). Of course, due to a lack of specific drugs, we were unable to pharmacologically characterize the receptors involved.

When I moved to Montpellier in 1982, I decided to use primary cultures of neurons and glial cells to follow up my work on neurotransmitter receptors coupled to second messengers (cAMP, IP₃, Ca²⁺, etc.). This was a very productive period since we discovered the metabotropic glutamate receptors in striatal neurons (Sladeczek *et al.*, 1985) and 5-HT₄Rs in colliculi neurons (Fig. 1B) (Dumuis *et al.*, 1988a).

3. History

3.1. From the "Naughty but nice period" (Clarke *et al.*, 1989) to "A place in the sun" period (Bockaert *et al.*, 1992)

In the 1980s, thanks to binding techniques, the molecular classification of 5-HT receptors took a definitive pathway. Three receptor classes were recognized at that time, the 5-HT₁, the 5-HT₂ and the 5-HT₃ (Bradley *et al.*, 1986). We decided that it was timely to characterize the 5-HT receptors positively coupled to an adenylate cyclase in primary cultures of colliculi neurons. We immediately noticed that the receptor involved was insensitive to 5-HT₁ and 5-HT₂ antagonists (Fig. 1C see also Dumuis *et al.*, 1988a) and that the only active antagonist was a 5-HT₃ antagonist (Tropisetron: ICS 205930) although with an IC₅₀ being incompatible with a 5-HT₃ receptor interaction (Fig. 1C). Interestingly, 5-carboxamidotryptamine (5-CT) was 50 times less potent than 5-HT (Fig. 1B). This incited us to replicate (Fig. 1D) the work of Shenker *et al.* (1987) who described, in guinea-pig hippocampal membranes, two 5-HT sensitive adenylate cyclases. One stimulated with high potency by 5-CT, 5-HT (and 8-OH-DAPT) that was identified at that time as "5-HT_{1A} receptor"-mediated (we now know that a 5-HT₇ receptor was involved) and the other stimulated with lower potency by 5-HT and 5-CT (Fig. 1D). We found that this latter was inhibited, like the 5-HT-sensitive adenylate cyclase of colliculi neurons, by high concentrations of Tropisetron but not by a specific 5-HT₃ antagonist MDL 72222 (Dumuis *et al.*, 1988b) (Fig. 1E). We concluded, in the 1988 Molecular Pharmacology paper (Dumuis *et al.*, 1988a) that until further classification of the 5-HT receptors is available, we propose to associate these receptors (in colliculi neurons and guinea-pig hippocampal membranes) with a novel category of receptors: the 5-HT₄.

In 1989, at the International Symposium on "Serotonin from cell biology to pharmacology and therapeutics" in Firenze, we presented these results that were received with scepticism by the serotonin nomenclature committee. Benzamides, such as metoclopramide, renzapride, cisapride and zacopride were rapidly recognized as potent agonists (Bockaert *et al.*, 1990). This was important because this formed a link between the 5-HT receptor coupled to adenylate cyclase and an unclassified prokinetic 5-HT receptor in guinea-pig ileum, insensitive to classical 5-HT₁₋₃ antagonists, stimulated by benzamides and blocked by high concentrations of Tropisetron (Clarke and Bockaert, 1993). This was "nice" (a new 5-HT receptor expressed both in brain and gastro-intestinal organs was likely to exist), but "naughty" because we named it 5-HT₄ without permission. Very rapidly, new specific antagonists were discovered, such as the benzamide SDZ 205557 and the benzimidazolone DAU 6215. The use of functional assays associated with the availability of these new drugs led to the characterization of the new 5-HT₄ receptor in rat oesophagus, guinea-pig colon, human and pig atrium and adrenocortical cells. The 5-HT₄ receptors earned a "place in the sun" in 1992 (Bockaert *et al.*, 1992).

3.2. Pharmacology and molecular biology periods (1990–2002)

From 1990 onwards, most pharmaceutical companies and some academic groups synthesized a wide series of 5-HT₄ agonists and antagonists (for reviews see Bockaert *et al.*, 2004, 1997). Among the agonists, the first class includes substituted tryptamines as well as indole carbazimidamides (including maleate tegaserod "Zelnorm") which is prescribed for women suffering from irritable bowel syndromes with constipation, but recently withdrawn from the market because of possible cardio-vascular problems. The second class includes a long series of 2-methoxy-4-amino-5-chloro benzamides, such as metoclopramide, zacopride and cisapride. The latter has been on the market for gastro-oesophageal diseases and is still used with certain restrictions in some countries. A benzodioxane derivative the SL65.0155 is particularly potent for learning and memory (Moser *et al.*, 2002) and has reached phase IIb for Alzheimer's disease. The third class includes the benzimidazolones, such as BIMU8 and the fourth aryl ketones which has a compound, RS 67333 with a large alkyl group, known to easily cross the blood brain barrier. Another interesting agonist is a pyridine carboxamide, a very recently described pro-cognitive drug (VRX-03011) that is in phase II for Alzheimer's disease. Among the antagonists, GR 113808 was the first 5-HT₄R antagonist with a low affinity for 5-HT₃R and was used under a tritiated form [³H]GR 113808 for binding studies. Antagonist classes include benzoates (such as SDZ 205557), benzoate dioxane (such as SB 204070 and SB 207710) in which the 5-chloro has been substituted for a radioactive iodine ¹²⁵I, an excellent ligand for binding studies [¹²⁵I]SB 207710, benzimidazolones (DAU 6285) and aryl ketones. Finally, with Roche Laboratories, we found very potent inverse agonists (RO 116-0086 and RO 116-1148) which are des-amino, des-chloro benzoate dioxanes (Joubert *et al.*, 2002). Using either form [³H]GR 113808 and [¹²⁵I]SB 207710 brain distribution has been studied (for a review see Bockaert and Dumuis, 1997). The receptor is localized on neurons, the highest densities being in olfactory bulb, islands of Calleja, basal ganglia and accumbens, hippocampus, substantia nigra. Within the nigro-striatal pathway the receptor is localized both in cell bodies and terminals of GABA neurons. In the cortex, the hippocampus and the amygdala, 5-HT₄R are likely localized on cholinergic neurons (5-HT₄R stimulate acetylcholine release) but also on glutamatergic neurons (Bockaert *et al.*, 2004; Bockaert and Dumuis, 1997; Huang and Kandel, 2007).

The 5-HT₄R gene is the longest among the GPCR genes (700 kb) and consists of 38 exons (Bockaert *et al.*, 1997). Its 5' non-translated region is exceptionally long (>500 kb) and complex. The coding sequence includes at least 14 exons. To date, 10 functional splice variants have been described. For 9 of them, splicing gives rise to alternate C-terminal domains after a single position (L358) named a, b, c. One splice variant (h) is generated in the second extracellular loop. As some (such as h or i) do not present any frame stop codons, additional combinations probably remain to be discovered (Bockaert *et al.*, 2006b).

4. G protein-dependent and -independent signalling and interacting proteins

4.1. G protein dependent

Since 5-HT₄Rs were discovered following their capacity to activate adenylate cyclase, the 5-HT₄R-mediated Gs/cAMP/PKA signalling pathway is evidently the best studied (Fig. 2). In transfected cell lines, several other couplings have been found (see Bockaert *et al.*, 2006b) including coupling to G_q and G₁₃. However, such couplings have not yet been found in native cells. Following PKA activation, a series of ionic currents are modulated. These include a long-lasting inhibition of K⁺ currents (mediated by a PKA-dependent inhibition of phosphatases) which generates neuronal excitability and a decrease in spike accommodation (Ansanay *et al.*, 1995; Bockaert *et al.*, 2006b). cAMP produced by 5-HT₄Rs also activates the exchange factor Epac which activates α -secretase and the release of sAPP α (soluble amyloid precursor protein) via an Epac/Rap1/Ras pathway (Lezoualc'h and Robert, 2003).

4.2. G protein-independent

In cell lines as well as in colliculi neurons in culture, 5-HT₄Rs activated the extracellular signal-regulated kinase (ERK) (Barthet *et al.*, 2007; Mohler *et al.*, 2007; Restivo *et al.*, 2007). Curiously, we recently found that this activation was mostly Gs/cAMP/PKA-independent. Using pharmacological, genetic and molecular tools, we also demonstrated that the classical G proteins (G_q, G_i, G_o) and associated downstream messengers were not involved. In contrast, the 5-HT₄R-mediated ERK activation was dependent on Src tyrosine kinase and interestingly not dependent on b-arrestin which is found to mediate many G protein-independent ERK activations by GPCRs (Barthet *et al.*, 2007). We found that a 5-HT₄R/Src complex was formed which persisted upon endocytosis (Barthet *et al.*, 2005). The 5-HT₄R-mediated ERK stimulation may be important for 5-HT₄R-mediated long-term potentiation (LTP) (Bockaert *et al.*, 2006b; Huang and Kandel, 2007). The 5-HT₄R-dependent, cAMP/PKA-independent, activation of Src has also been found in intestinal cell lines (CaCo-2 and T84) 5-HT₄Rs (Gill *et al.*, 2005). In these cells, Src seems to activate a PLC/Ca²⁺/calmodulin pathway and finally controls the Na⁺/H⁺ exchanger (Gill *et al.*, 2005).

4.3. Associated proteins

Although some differences in signal transduction between the C-termini splice variants have been reported, this was found exclusively in cell lines but not in native cells. The physiological relevance, if any, of the splice variants remains to be elucidated (Bockaert *et al.*, 2006b). In an effort to make some progress in the possible different signalling of 5-HT₄R splice variants, we used a fishing and

proteomic approach to define the composition of the "receptosome" associated with the C-termini of three 5-HT₄R splice variants (Joubert *et al.*, 2004). Two of them, 5-HT_{4a}, and 5-HT_{4e} express a canonical recognition motif for PDZ domains at their C-termini. SCF, the C-terminal of 5-HT_{4a} may interact with class I PDZ domains, whereas VPV, the C-terminal of 5-HT_{4e} may interact with class II PDZ domains. The 5-HT_{4b} C-terminal (-SDT) shows no consensus interaction motif. Ten proteins have been found to interact with 5-HT_{4a}Rs. Among them, seven encompass one or several PDZ domains (Bockaert *et al.*, 2006a; Joubert *et al.*, 2004). The two more interesting ones were (i) SNX27 (sortin nexin 27) that belongs to the huge nexin family implicated in the regulation of membrane protein trafficking and (ii) NHERF (Na⁺/H⁺ exchanger regulatory factor). In fact, two splicing forms of SNX27 (a and b, also called Mrt1a and Mrtb) interact with 5-HT₄Rs and are localized in early endosomes. SNX27a is constitutively expressed, whereas SNX27b is induced by methamphetamine treatment (Kajii *et al.*, 2003). NHERF interacts with the FERM domain of activated ezrin. In fibroblast cells expressing NHERF and 5-HT₄Rs, ezrin was redistributed from the cytoplasm to microvilli and was co-localized with NHERF and 5-HT₄Rs (Joubert *et al.*, 2004).

5. Mechanisms of 5-HT₄R desensitization

Many years ago, we described in colliculi neurons (Ansanay *et al.*, 1992) and rat oesophagus (Ronde *et al.*, 1995) that 5-HT₄Rs rapidly desensitized (more than 60% in 5 min). The desensitization (uncoupling) was homologous and not reproduced by cAMP. We recently decided to further analyse the mechanisms involved (Barthet *et al.*, 2005). However, in HEK 293 and COS-7 cells transfected with 5-HT₄Rs, we found that no significant uncoupling of the receptor occurred upon stimulation (Barthet *et al.*, 2005). We found that this was due to the low concentration of the GRK2 in HEK293 and COS-7 cells, a GPCR kinase which is highly expressed in neurons and brain. Co-transfection of HEK 293 or COS-7 cells with GRK2 was sufficient to reproduce the rapid and profound 5-HT₄R uncoupling (Barthet *et al.*, 2005). In contrast, the endocytosis of 5-HT₄R which is a phenomenon dissociated from uncoupling required only "low concentrations" of GRK2 found in HEK 293 and COS-7 cells. The uncoupling and endocytosis were independent and dependent on GRK2 kinase activity, respectively. Thus, phosphorylation of a Ser/Thr cluster, in the C-terminal, and common to all splice variants was required for endocytosis but not for uncoupling. Endocytosis of 5-HT₄Rs required both β-arrestin and dynamin. We found no difference in uncoupling and endocytosis among the different 5-HT₄R splice variants.

We recently found (manuscript in preparation) that desensitization of the G-protein-independent 5-HT₄R-stimulated Src kinase activation required GRK5 instead of GRK2.

6. From constitutive activity (CA) to receptor activation

The molecular mechanism by which agonists, antagonists and inverse agonists activate and inactivate GPCRs is a key question in pharmacology. 5-HT₄Rs are particularly interesting for such studies because of the long series of compounds of different chemical classes which are available.

Another interesting and almost unique property of 5-HT₄Rs is their high CA (Claeysen *et al.*, 1999; Bockaert *et al.*, 2005).

Compared to β_2 -adrenergic receptors (β_2 -ARs), all C-termini splice variants of 5-HT₄R have a very high CA (Fig. 3A). The shorter is the C-terminal, the higher is the CA. Thus, the C-terminal is a key regulator of the CA. Truncation of the C-terminus further increases the CA. The C-termini of 5-HT₄Rs are key element of activation, but certainly not the only one. Comparison of the crystal structures of inactive rhodopsin (bound by the inverse agonist cis-retinal) and partially active rhodopsin (metarhodopsin I) (Ruprecht *et al.*, 2004), as well as site-directed mutagenesis of histamine H1 associated with molecular modelling (Jongejan *et al.*, 2005), proposed that activation of GPCRs includes the disruption of a hydrogen bond between two well-conserved residues W6.48 and D2.50. This disruption triggers the conformational transition of N7.49 towards D2.50 and ultimately, leads to the disruption of the "ionic lock" between R3.50 and D/E3.49 as well as with additional D/E 6.30 (Fig. 3C). The W6.48 which is in the gauche⁺ (g⁺) rotamer pointing to TM 7 (TM = transmembrane) in the inactive state is submitted to a "toggle switch" and is in the trans (*t*) rotamer conformation pointing to TM5 in the activated state. Studies on histamine H1 (Jongejan *et al.*, 2005) and 5-HT₄Rs (manuscript in preparation) indicate that T3.36 is also submitted to a "concerted toggle switch" with W6.48. Interestingly, among the amine receptors, only very few receptors have a Threonine at position 3.36 (1%), all other 5-HT receptors have a Ser or a Cys at that 3.36 location. β_2 -AR has an alanine (Fig. 3B), which may account for the low basal activity of this receptor.

We found that binding of 5-HT and other indole-amine derivatives was totally dependent on the ionic interaction between the protonated amine of the side chain and the aspartate (A) at position 3.32 (D.32). In contrast, binding and activation of benzamides, such as S-zacopride, and benzimidazolones, such as BIMU8, did not depend on the presence of D3.32. Thus, the D3.32A mutant was the first RASSL (receptor activated solely by synthetic ligands) coupled to G_s (Claeysen *et al.*, 2003). Interestingly, some neutral or weak partial agonists were almost full agonists on the RASSL. Site-directed mutagenesis and molecular modelling, performed in collaboration with L. Pardo (manuscript in preparation), indicate that the BIMU8 agonist triggers the concerted toggle switch of T3.36 and W6.48 by forming a hydrogen bond with W6.48, whereas the benzamides induced this concerted switch by forming a hydrogen bond with T.3.36.

7. Brain functions

Although 5-HT₄Rs control many important functions at the periphery, including those of the gastro-intestinal and urinary tracts, human heart and adrenal gland, we will focus this review on three brain functions which are emerging and could be relevant in therapy: memory and cognition, mood, behaviour and feeding.

7.1. Learning and memory

A great number of studies indicate pro-cognitive effects of 5-HT₄R agonists both on short-term memory (such as social olfactory memory) (Fig. 4A) or long-term olfactory memory (such as olfactory associative memory) (Fig. 4B) (for a review see Bockaert *et al.*, 2004). Increase in memory acquisition also includes auto-shaping task, object recognition, Morris water-maze task when the inter-trial intervals were high (2 h), delayed matching performance and impeded spontaneous alteration scores. In addition, 5-HT₄R activation reduces deficit in memory induced by atropine, scopolamine and 5-HT₄R antagonists (for a review see Bockaert *et al.*, 2004).

The cellular basis of such learning and memory effects may be an increase in acetylcholine release found in frontal cortex and hippocampus and an increase in LTP which has been described in hippocampus and amygdala (Bockaert *et al.*, 2004; Huang and Kandel, 2007). Moreover, other recent reports further support this notion that 5-HT₄Rs play a role in memory. They reported an association between 5-HT₄R mRNA and protein expression in cortical areas, hippocampus, olfactory tubercles on one hand and memory consolidation on the other hand (Pérez-García *et al.*, 2006; Manuel-Apolinar *et al.*, 2005).

In addition to these effects on learning and memory, an effect of 5-HT₄Rs on non-amyloidogenic metabolism pathway of APP via stimulation of the α -secretase has been described (Lezoualc'h and Robert, 2003; Cachard-Chastel *et al.*, 2007). In correlation with the precedent data, a recent report by Cho and Hu (2007) demonstrated that a selective 5-HT₄ partial agonist, RS 67333, inhibits the generation of the β -amyloid peptide (A β) in primary cortical neurons.

Interestingly, two 5-HT₄R partial agonists, the SL 65.0155 from Sanofi-Aventis (Moser *et al.*, 2002) and VRX-03011 (Epix Pharmaceuticals; Mohler *et al.*, 2007) which have high pro-mnesic properties in rodents have reached clinical phase II for the treatment of Alzheimer's disease. Both compounds act synergically with cholinesterase inhibitors on rodent memory. All these data are in perfect correlation with previous reports showing that there is indeed a marked loss of 5-HT₄R binding sites in cortical and hippocampal regions in the Alzheimer brain (Reynolds *et al.*, 1995; Wong *et al.*, 1996).

Finally, we have recently found, in collaboration with French and Italian colleagues, that SL65.0155 enhances simultaneously olfactory discrimination performance and associated spine growth an effect blocked by the RS 39604 antagonist (Fig. 4B). SL65.0155 has no effect alone (Restivo *et al.*,

2007). Spine growth and density have been found to be associated with LTP induction and are considered to be a possible cellular basis of memory formation (for a review see Alvarez and Sabatini, 2007). It is also tempting to make a link between 5-HT₄R-induced cAMP formation and spine density. Indeed, cAMP reduces phosphorylation of cyclin-dependent kinase 5 (cdk5) site in the Wiskott–Aldrich syndrome protein (Wave1) and increases spine density in a Wave1-dependent manner (Kim *et al.*, 2006).

7.2. Control of mood, putative antidepressant role of 5-HT₄R agonists

All antidepressant treatments and especially serotonin reuptake inhibitors (SSRIs) increase the efficacy of 5-HT transmission at the post-synaptic levels and finally induce post-synaptic 5-HT receptors activation. Unfortunately, the initial elevation of 5-HT concentration triggered by SSRIs induces the stimulation of 5-HT_{1A} receptors localized on cell bodies of 5-HT neurons in the raphe, inhibiting their firing and counteracting the facilitation of 5-HT transmission (Fig. 5A). Thus, the 3–6 weeks delay before the onset of the therapeutic action of the antidepressant corresponds to the time needed for 5-HT_{1A} receptor desensitization. Compounds that directly and rapidly stimulate the firing activity of 5-HT neurons are expected to be swiftly acting antidepressants. In fact, 5-HT₄R agonists have been found to exert positive tonic and phasic effects on the firing of a sub-population of 5-HT neuron of the dorsal raphe nucleus (DRN) when injected at the periphery but not directly at the raphe level (Lucas *et al.*, 2005; Lucas and Debonnel, 2002; Conduetier *et al.*, 2006). This suggests that the effect was mediated by 5-HT₄R localized elsewhere. Note also that 5-HT₄R knock-out mice have reduced spontaneous activity of 5-HT dorsal neurons. Injection of the herpes simplex virus (HSV) coding for 5-HT₄R increased DRN 5-HT neuronal mean activity when injected in the medial pre-frontal cortex (mPFC) but not in the striatum or hippocampus (Lucas *et al.*, 2005) (Fig. 5B). Thus, 5-HT₄R of the mPFC, probably localized on some pyramidal neurons known to innervate the DRN, exert a tonic and phasic stimulatory action on DRN which surprisingly did not seem to desensitize (Fig. 5A). Thus, as expected citalopram, a SSRI, was far more potent in inhibiting DRN firing in 5-HT₄R knock-out mice than in WT mice (Conduetier *et al.*, 2006).

Recently, the group of G. Debonnel investigated the possibility that RS 67333 and prucalopride, two 5-HT₄R agonists, could have antidepressant activity. They found that acute injection of both drugs, like citalopram, reduced the immobility time in the forced-swimming test, and that the inhibition of 5-HT neuron firing rate, by citalopram, was shifted to the right by RS 67333 (Fig. 5C, D). In addition, after 3 days of injection of RS 67333, an increase in 5-HT release in CA3 neurons of hippocampus, measured by the enhancement of post-synaptic 5-HT_{1A}R activity, was observed. A 3-day treatment with RS 67333 significantly enhanced the mitogenesis in the sub-granular zone (SGZ) of the hippocampus, an effect also associated with long-term (3–6 weeks) SSRI treatment. A 3-day period of treatment with citalopram was insufficient to produce such an effect. Altogether, these findings illustrate that 5-HT₄R agonists could be considered to be a putative class of antidepressants.

7.3. Feeding behavior

Looking for a phenotype associated with invalidation of 5-HT₄Rs in mice, we first found that the absence of this receptor attenuated stress-induced hypophagia and novelty-induced exploratory activity (Compan *et al.*, 2004). This suggests that 5-HT₄Rs may be involved in stress-induced anorexia. Following this idea and the observation that 5-HT₄Rs are highly expressed in nucleus accumbens (NAc), we recently found that direct stimulation of 5-HT₄Rs in the NAc reduced the physiological drive to eat and increased CART (cocaine- and amphetamine-regulated transcript) mRNA content in fed and food-deprived WT but not knock-out mice (Fig. 6A–C). CART is an anorectic peptide. 5-HT₄Rs control CART mRNA expression via a cAMP/PKA signalling pathway. We also found, using WT and knock-out mice, that the anorectic effect of 3,4-N-methylene-dioxymethamphetamine (MDMA; the active principle of ecstasy) involves 5-HT₄Rs (Fig. 6D). Finally, we found that the 5-HT₄Rs and MDMA-induced anorexia were both reduced by injecting CART siRNA into the NAc (Fig. 6E). Collectively, these results demonstrate that the 5-HT₄R-mediated up-regulation of CART in the NAc triggers the appetite-suppressant effects of ecstasy.

8. Conclusion

Twenty years after their first description, 5-HT₄Rs still have some mysteries to be discovered and safe 5-HT₄R drugs for clinical use are still to be developed. Among the mysteries, we can quote:

- (1) The incredible length of the gene and the number of splice variants. Why is there such a diversity?
- (2) The high constitutive activity of 5-HT₄Rs. Are 5-HT₄Rs constitutively active in some neurons or neuronal compartments? If so, what roles do they play? Does an endogenous inverse agonist effectively exist?

The clinical use of 5-HT₄R drugs has encountered some difficulties. Some drugs like cisapride or maleate tegaserod have been on the market for gastro-oesophageal reflux, constipation or irritable bowel syndromes, but were removed from the market because of their adverse cardiac problems, probably unrelated to their action on 5-HT₄Rs. The tentative to use of 5-HT₄R partial agonists for cognitive deficiencies particularly, but not exclusively, in Alzheimer's disease is still ongoing. The use of 5-HT₄R ligands in feeding disorders (bulimia or anorexia) but also in depression is still an ongoing continual challenge. Finally, 5-HT₄Rs constitute an excellent "model" of GPCR for molecular pharmacology studies. This is due to the great number of agonists, antagonists and inverse agonists of diverse chemical structures available, the generation of mutants, including a very simple and potent RASSL which may be used in gene therapy and the possibility of obtaining mg amounts of pure, native and functional 5-HT₄R proteins (Baneres *et al.*, 2005).

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Figure legends

Figure 1

Some historical experiments which have characterized a neuronal 5-HT receptor coupled to adenylate cyclase as new 5-HT receptors that we called 5-HT₄Rs. (A) Dose-response curves for 5-HT sensitive adenylate cyclase in colliculi homogenates. Modified from Enjalbert *et al.* (1978). (B) Effects of various concentrations of 5-HT and 5-CT (5-carboxamidotryptamine) on cAMP production in colliculi neurons in primary cultures. Modified from Dumuis *et al.* (1988a). (C) Effect of a series of 5-HT antagonists on the 5-HT-stimulated cAMP production in colliculi neurons in primary cultures. The 5-HT concentration was 1 mM. Modified from Dumuis *et al.* (1988a). (D) Stimulation of adenylate cyclase activity of adult guinea-pig hippocampal membranes by 5-HT and 5-CT. Modified from Dumuis *et al.* (1988a). (E) Inhibition of 5-CT-stimulated adenylate cyclase activity in adult guinea-pig hippocampal membranes by Tropicsetron at two 5-CT concentrations: 0.3 and 100 mM. Modified from Dumuis *et al.* (1988a).

Figure 2

A general schema of G_s-dependent and G_s-independent signalling and desensitization of 5-HT₄Rs.

Figure 3

Constitutive activity and activation of 5-HT₄Rs. (A) Mouse 5-HT₄R (m5-HT₄Rs) splice variants exhibited high but also different constitutive activities. Comparison with the constitutive activity of human β_2 -adrenergic receptors (β_2). Modified from Claeysen *et al.* (1999). (B) Nature of the residue at position 3.36 in amine receptors. The high constitutive activity of 5-HT₄Rs may be due to the presence of a T at this position (Jongejan *et al.*, 2005). (C) Proposed hydrogen bond network linking D2.50-W6.48 through two water molecules in the inactive conformation of rhodopsin. This link is disturbed during activation. Modified from Jongejan *et al.* (2005).

Figure 4

5-HT₄Rs and memory. (A) Role of 5-HT₄Rs in social memory. Social recognition of juvenile conspecifics by adult rat during 5 min (first exploration period (P1)) and at a delay of 30 (P2 = 30) and 120 (P2 = 120) min. At the 30 min delay between P1 and P2, adults recognized the juvenile as indicated by a reduction of the exploration period ($P2/P1 < 1$), whereas after a 120 min delay, all adults have lost their memory of juveniles. The recognition of juveniles was individual-specific, a different juvenile was recognized as a new individual after 30 min ($P2/P1 = 1$). BIMU1 (10 mg/kg) injected after the first presentation enhanced short-term memory (i.e. recognition of the identical but not the different juvenile after a 2-h delay). Modified from Letty *et al.* (1997). (B) Involvement of 5-HT₄Rs in olfactory memory. In this task, rats deprived of water for 48 h were trained to make two odor-reward associations. One arbitrarily odor is designed as positive (S+) and the other as negative (S-). Rats had to approach the odor

and water only when the odor was positive. Approach to the negative odor resulted in presentation of non-adversive light and water was not delivered. Individual trials were presented in a quasi-random fashion. Mean performance obtained across the five sessions of 60 trials by rats injected with BIMU1 (10 mg/kg) or saline (control) after the session 3 are indicated. In the reversal session, rats were tested 1 month after the injection of BIMU1 or saline (control) with reversal of the valence of the previous learned odors. Rats injected with BIMU1 are less efficient than naive rats in learning this reverse test likely because they still “remember” the previous odor association. Modified from Marchetti-Gauthier *et al.* (1997). (C) Mice were trained to discriminate between two odors as in B. In the "trained" group the positive odor was associated with the reward (water) in 100% of the trials. In the "pseudo-trained group there was no positive odor as each odor was randomly associated with the reward on 50% of the trials". Golgi–Cox impregnated oblique dendrites of CA1 pyramidal neurons are shown. Statistical analysis (Restivo *et al.*, 2007) indicates that the spine density was not different between control and pseudo-trained mice, whereas there was a difference between pseudo-trained and trained, between trained plus saline and trained plus SL65.0155. Modified from Restivo *et al.* (2007).

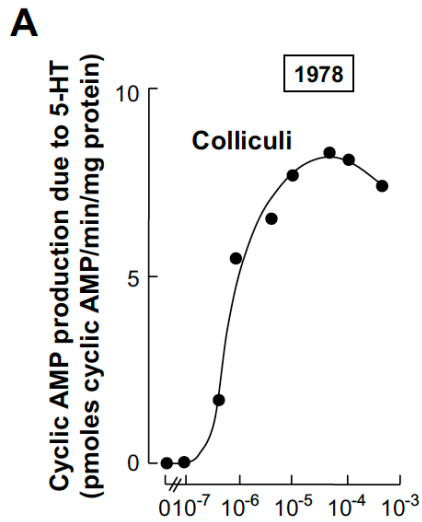
Figure 5

5-HT₄Rs and depression. (A) Localisation of 5-HT receptors controlling activity of 5-HT dorsal raphe nucleus (DRN). 5-HT_{1A}Rs are on cell bodies of 5-HT neurons whereas 5-HT₄Rs are not. We hypothesized that 5-HT₄Rs which stimulate the activity of 5-HT neurons are localized in the medial pre-frontal cortex (mPFC) (see Lucas *et al.*, 2005). (B) Mean firing rate of DRN. Control: integrated firing rate histogram showing a sample of DRN in sham-operated rat. Herpes simplex virus (HSV) HSV-5-HT₄Rs in mPFC: integrated firing rate histogram showing a sample of DRN in rats injected with coding 5-HT₄Rs, in mPFC. The effect of various injections of the virus in the mPFC, striatum (Str), hippocampus (Hip) and with a virus coding Lac-Z in the mPFC. Modified from Lucas *et al.* (2005). (C) Effect of citalopram, a SSRI (10 mg/kg), and two 5-HT₄Rs agonists, prucalopride (2.5 mg/kg) and RS 67333 (1.5 mg/kg) on the time spent immobile in the forced-swimming test. Modified from Lucas *et al.* (2007). (D) A 3-day treatment period with RS 67333 reduced the inhibition of 5-HT neuron firing induced by citalopram, via 5-HT_{1A} receptor activation. Modified from Lucas *et al.* (2007).

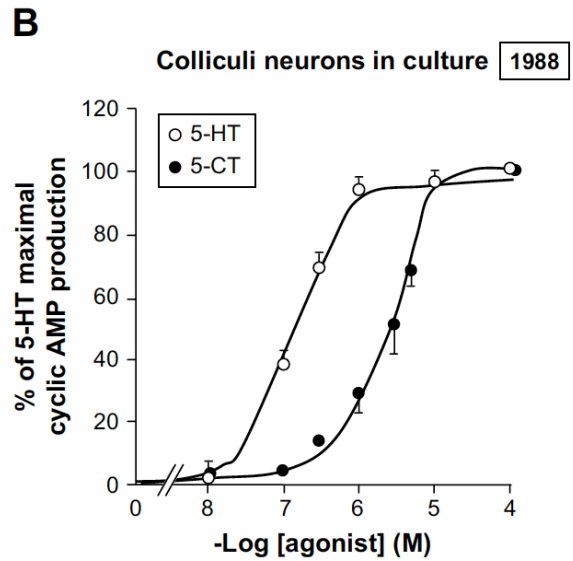
Figure 6

5-HT₄Rs and feeding (modified from Jean *et al.*, 2007). (A) Coronal midbrain section showing the nucleus accumbens (NAc) in which drugs and siRNA were injected. A schematic signalling pathway showing the central role of 5-HT₄Rs in MDMA (3,4-methylene-dioxymethamphetamine) (and likely cocaine) in inhibition of feeding via a cAMP/PKA synthesis of CART. (B) Direct injection of the 5-HT₄R agonist BIMU8 in NAc inhibited food intake in food-deprived mice. The same injection stimulated CART synthesis. Food intake was measured between 1 and 3 h after treatment. (C) An i.p. injection of MDMA increased CART mRNA content in NAc of WT but not in 5-HT₄R knock-out mice.

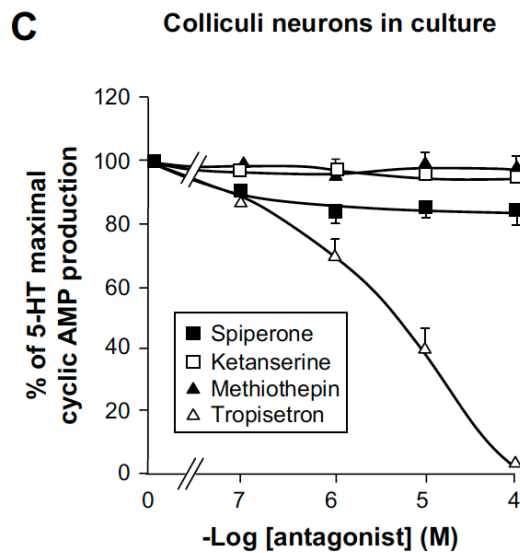
(D) In food-deprived mice, the i.p. injection of MDMA decreased food intake of WT but not 5-HT₄R knock-out mice. Food intake was measured for 3 h following the treatment. (E) The anorectic effects of BIMU8 and MDMA were reduced when CART was knocked down in the NAc using siCART. Food intake was measured for 1 h after treatment.



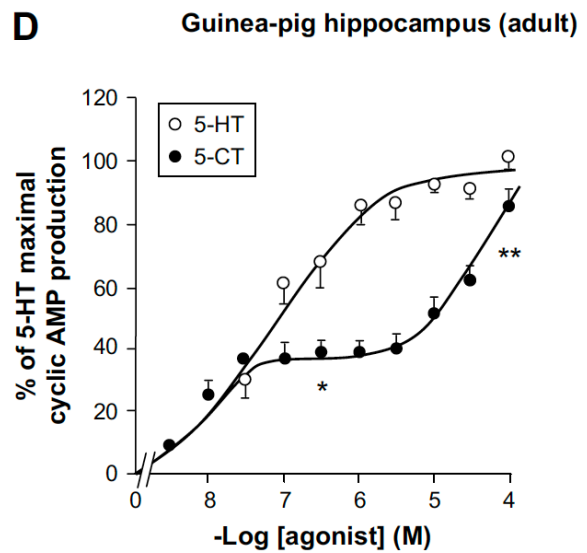
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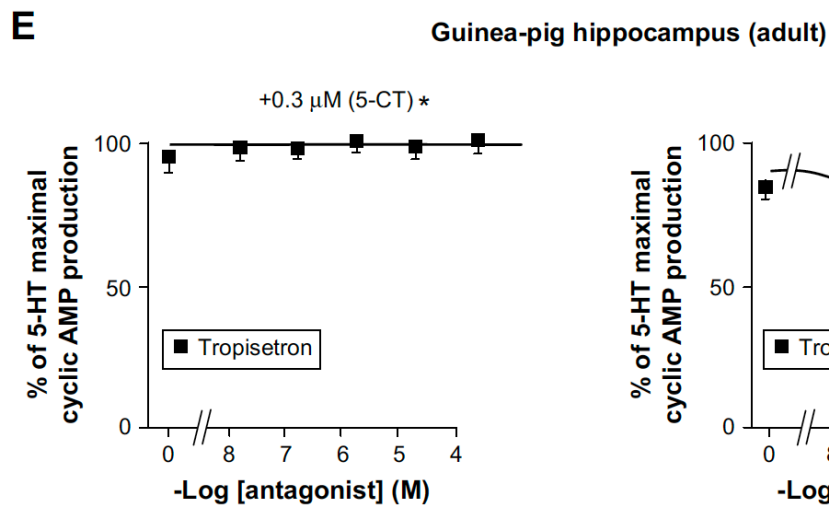
From Dumuis et al (1988) *Molecular Pharmacology*



From Dumuis et al (1988) *Molecular Pharmacology*



From Dumuis et al (1988) *Molecular Pharmacology*



From Dumuis et al (1988) *Molecular Pharmacology*

Figure 1

5-HT₄ signalling

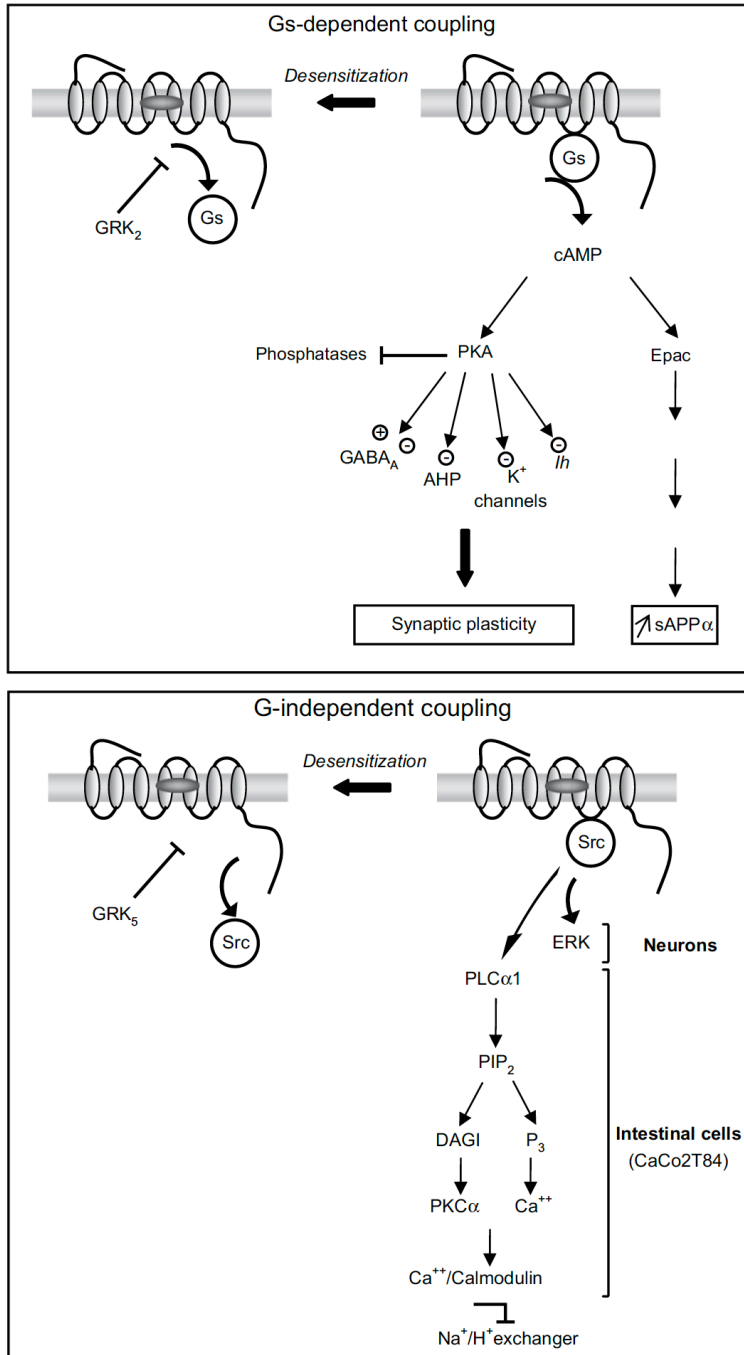
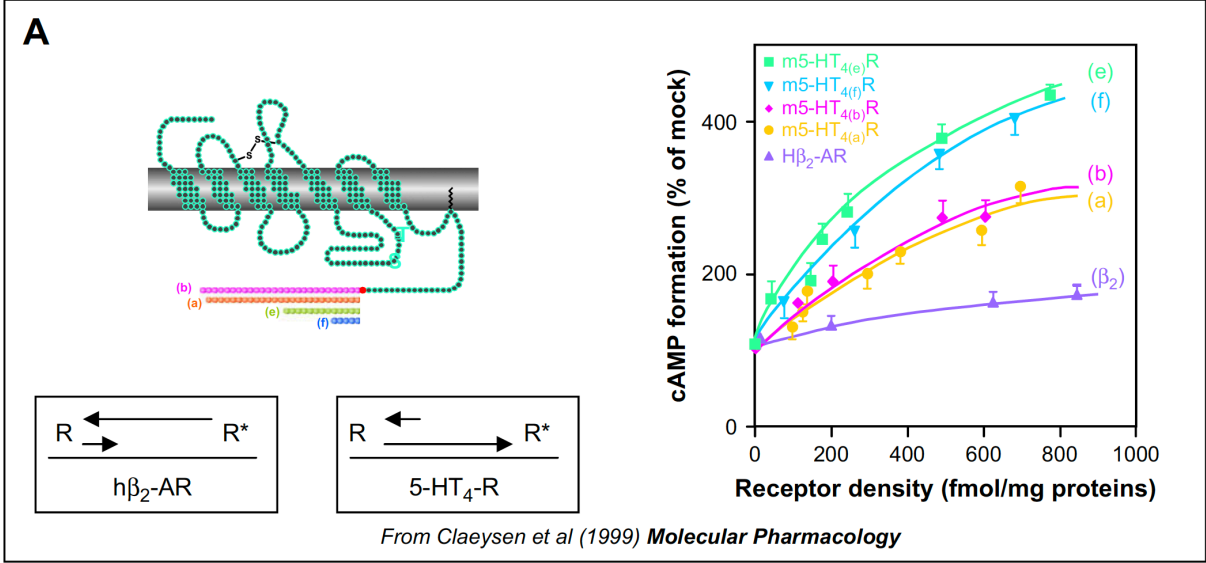


Figure 2



B

| Amine receptors | |
|-----------------|--------------------|
| T 3.36 | 1% |
| C 3.36 | 56% |
| S 3.36 | 31% |
| A 3.36 | β ₂ -AR |

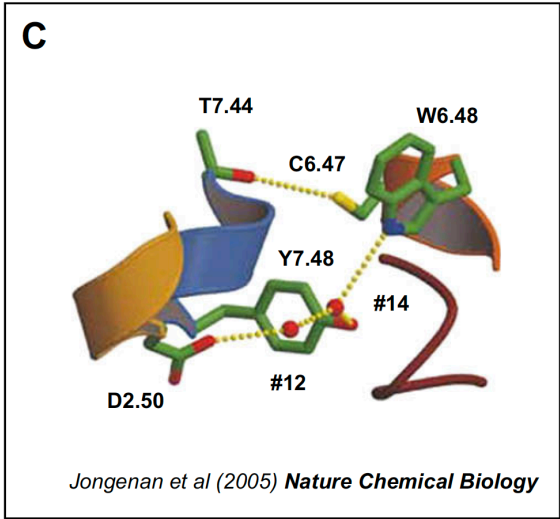
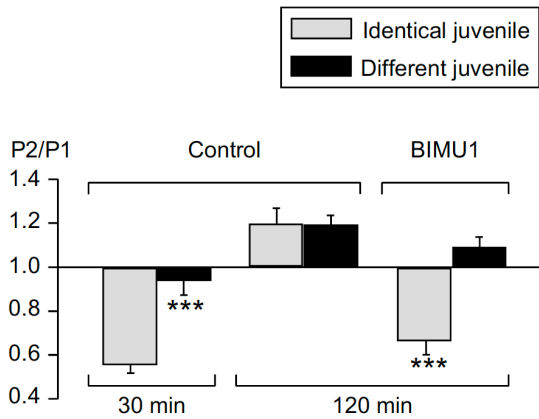


Figure 3

5-HT₄ receptor and memory

A

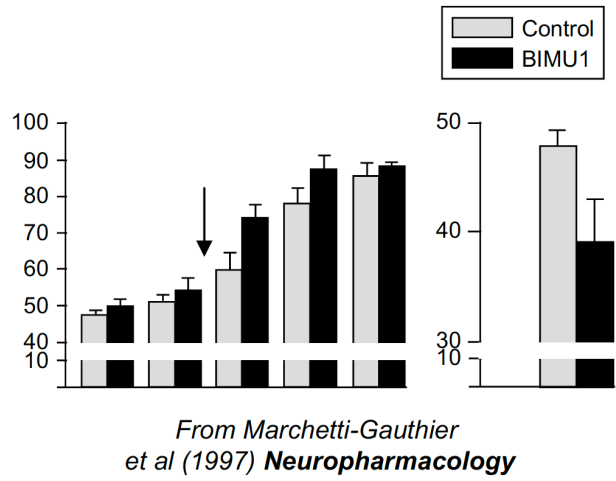
Short-term olfactory memory



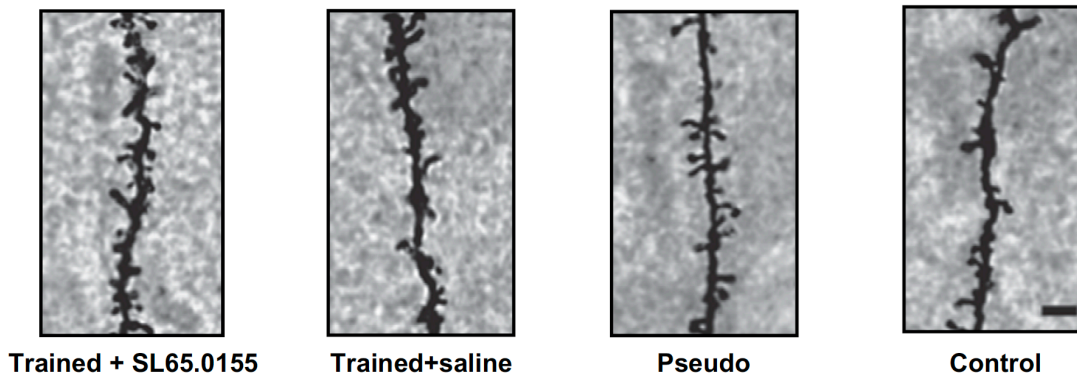
From Letty et al (1997) *Neuropharmacology*

B

Long-term associative memory



C

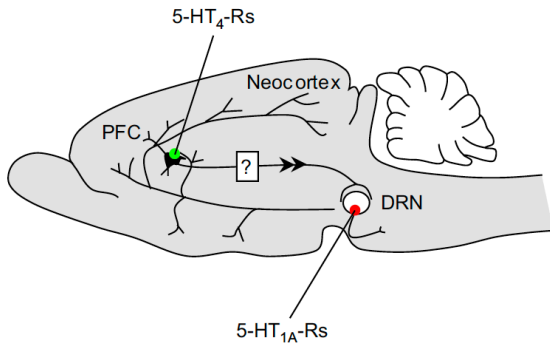


From Restivo et al (2007) *Neuropsychopharmacology*

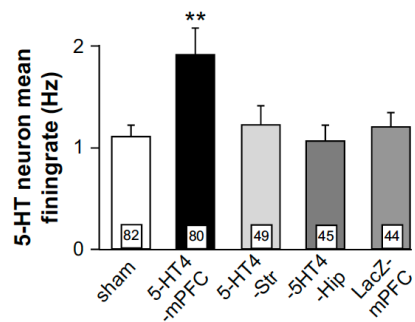
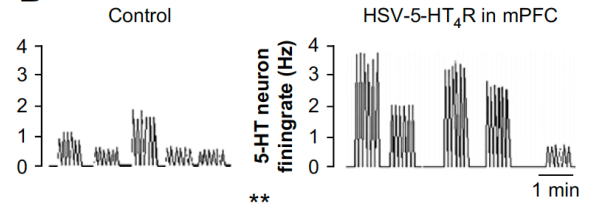
Figure 4

5-HT₄ receptor and depression

A

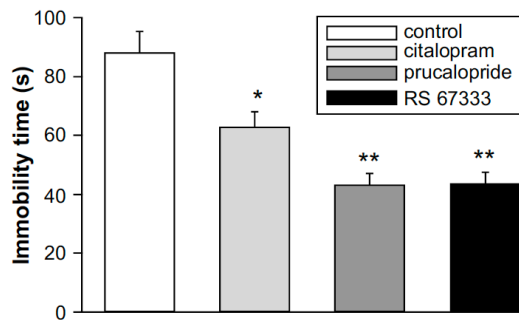


B



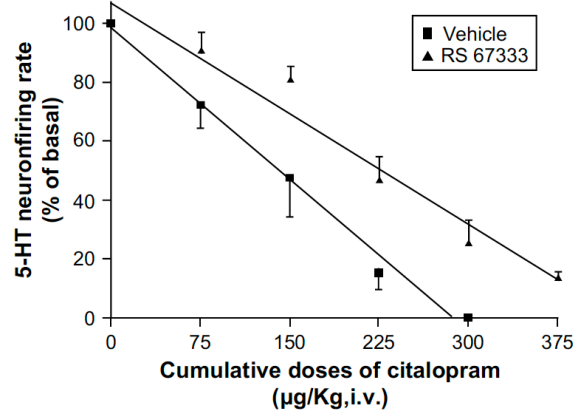
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C



From Lucas et al (2007) *Neuron*

D

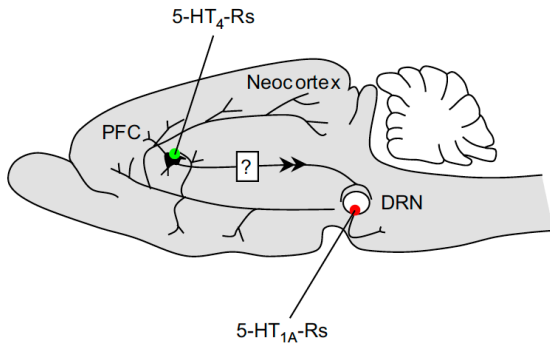


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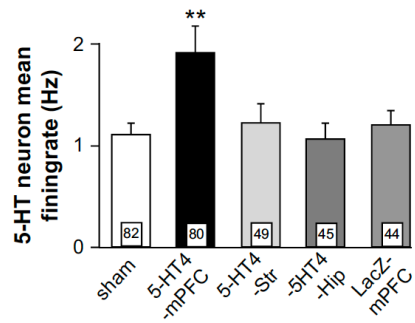
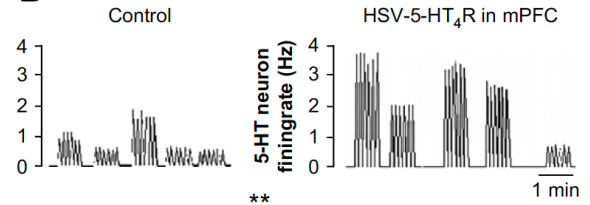
Figure 5

5-HT₄ receptor and depression

A

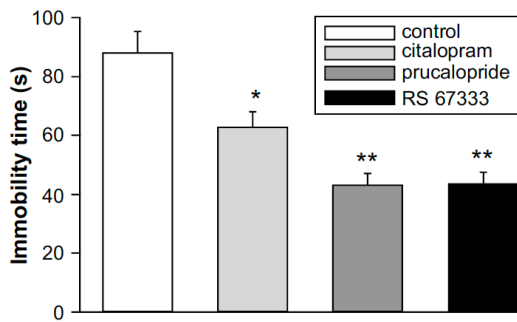


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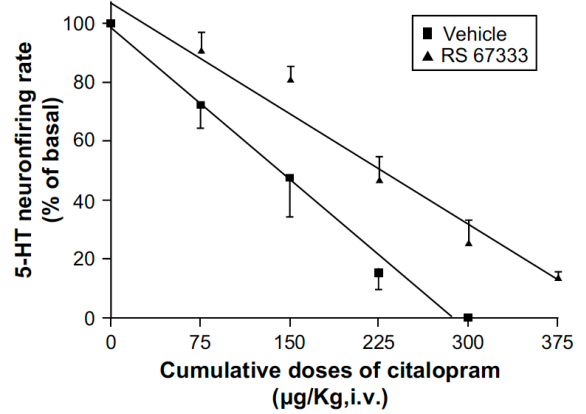
From Lucas et al (2005) *Biology Psychiatry*

C



From Lucas et al (2007) *Neuron*

D



From Lucas et al (2007) *Neuron*

Figure 6