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β -arrestin1 phosphorylation by GRK5 regulates G protein-independent 5-HT₄ receptor signalling

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Running head: GRK5 inhibits 5-HT₄R-mediated ERK activation

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ABSTRACT

G protein-coupled receptors (GPCRs) have been found to trigger G protein-independent signalling. However, the regulation of G protein-independent pathways, especially their desensitization, is poorly characterized. Here, we show that the G protein-independent 5-HT₄ receptor (5-HT₄R)-operated Src/ERK pathway, but not the G_s pathway, is inhibited by G protein-coupled receptor kinase 5 (GRK5), physically associated with the proximal region of receptor' C-terminus in both HEK-293 cells and colliculi neurons. This inhibition required two sequences of events: the association of β-arrestin1 to a phosphorylated serine/threonine cluster located within the receptor C-t domain and the phosphorylation, by GRK5, of β-arrestin1 (at Ser⁴¹²) bound to the receptor. Phosphorylated β-arrestin1 in turn prevented activation of Src constitutively bound to 5-HT₄Rs, a necessary step in receptor-stimulated ERK signalling. This is the first demonstration that β-arrestin1 phosphorylation by GRK5 regulates G protein-independent signalling.

INTRODUCTION

GPCRs have been first characterized for their ability to activate G proteins and to engage G protein-dependent signalling pathways. The desensitization process, which controls the duration and the intensity of these G protein-mediated signals, has been extensively characterized during the last two decades. It requires G protein-coupled receptor kinase (GRK)-dependent phosphorylation of GPCRs, their uncoupling from the G protein, and subsequent recruitment of β -arrestins (β -arrest). This latter event promotes receptor endocytosis, precluding further G protein activation. Recently, additional signalling pathways have been discovered in addition to the classical G protein-dependent signalling responsible for second messenger generation. For instance, activation of the extracellular signal-regulated kinase (ERK) (Shenoy et al., 2006), Src (Heuss et al., 1999) (Barthet et al., 2007; Sun et al., 2007) and phospholipase D pathways (Cao et al., 1996) by ligands of certain GPCRs occurs independently of G protein activation and the generation of second messengers (see, for reviews, (Bockaert et al., 2004a; Heuss and Gerber, 2000; Kim et al., 2005; Lefkowitz and Shenoy, 2005; Premont and Gainetdinov, 2007)). The regulation and desensitization of G protein-independent signalling pathways are poorly characterized. In particular, a fundamental issue is to determine whether or not the desensitization of G protein-dependent and -independent signals are governed by common or distinct molecular mechanisms, and whether key molecules involved in the desensitization of G protein-dependent signalling such as GRKs and β -arrest are also important for G protein-independent signalling desensitization.

A few reports have described a role of GRKs in the regulation of G protein-independent ERK signalling. GRK2, the major GRK involved in recruitment of β -arrest by GPCRs, is also able to inhibit G protein-independent, β -arrest-dependent ERK activation by angiotensin II type 1A (AT_{1A}), V_2 vasopressin (V_2) and follicle-stimulating hormone (FSH) receptors (Hunton et al., 2005; Kara et al., 2006; Kim et al., 2005; Ren et al., 2005). In contrast, GRK5/6 promote rather than inhibit G protein-independent, β -arrest-mediated ERK activation by AT_{1A} , V_2 , β_2 -adrenergic (β_2 -AR) and FSH receptors (Kim et al., 2005; Ren et al., 2005; Shenoy et al.,

2006; Kara et al., 2006). In addition to their role in desensitization of G protein-dependent signals, both β -arr1 and β -arr2 can serve as platforms for the recruitment of specific signalling proteins. For instance, they have been identified as essential components involved in the activation of the ERK signalling pathway mediated by several GPCRs (DeWire et al., 2007). However, for certain GPCRs such as AT_{1A} receptor, β -arr1 can act as a dominant-negative inhibitor of β -arr2-dependent, receptor-operated ERK activation (Ahn et al., 2004a; Ahn et al., 2004b).

The 5-HT₄R is a GPCR, which signals via both G protein-dependent and -independent pathways. The major G protein-dependent pathway engaged by 5-HT₄R is a G_s/cAMP/PKA pathway, which is desensitized by GRK2 (Barthet et al., 2005). We have recently described a G protein-independent pathway activated by this receptor (the Src/ERK pathway) whose desensitization mechanism is unknown (Barthet et al., 2007).

Here, we investigated the regulation of the G protein-independent signalling of 5-HT₄R by GRKs. We showed that the G protein-independent Src/ERK activation by 5-HT₄R was inhibited by GRK5. This negative regulation was specific of the G protein-independent Src/ERK pathway, as GRK5 only played a marginal role in 5-HT₄R/G_s uncoupling (Barthet et al., 2007). Moreover, we demonstrated that GRK5 inhibited 5-HT₄R-mediated Src/ERK activation via direct phosphorylation of β -arr1 bound to a S/T cluster located within its C-terminal domain (C-t).

RESULTS

Inhibition of the 5-HT₄R-stimulated G protein-independent Src/ERK pathway by GRK5

We previously identified GRK2 as the major GRK responsible for the desensitization of the 5-HT₄R-mediated G_s pathway (Barthet et al., 2005). Here, we have searched for a GRK able to inhibit the 5-HT₄R-mediated G protein-independent Src/ERK pathway without affecting the 5-HT₄R-mediated G_s pathway.

We focused on GRK5 because its membrane recruitment at the plasma membrane does not depend on G proteins. Co-expression of GRK5 with 5-HT₄R in human embryonic kidney (HEK)-293 cells did not significantly reduce cAMP formation evoked by 5-HT (Supplementary Figure S1A). In contrast, GRK5 expression strongly attenuated phosphorylation of ERK induced by 5- and 30-min exposures to 10 μM 5-HT (Fig. 1 and Supplementary Figure S1B). Moreover, GRK5 expression prevented 5-HT-induced activation of Src, as assessed by its phosphorylation on Tyr⁴¹⁶ (p-Y⁴¹⁶-Src, Fig. 1). These inhibitory effects depended on GRK5 activity since expression of a kinase-dead GRK5 mutant (K²¹⁵R) did not reduced receptor-mediated phosphorylation of Src and ERK (Fig. 1). In contrast, expression of GRK5 (K²¹⁵R) enhanced ERK phosphorylation (+ 30 ± 11%, n = 6, Fig. 1B). This observation likely reflects a dominant negative effect of over-expressed GRK5 (K²¹⁵R) on the inhibition of the ERK pathway elicited by endogenous GRK5.

Role of a S/T cluster within the 5-HT₄R C-terminus on GRK5-mediated inhibition of the receptor-operated ERK pathway

The 5-HT₄R C-t encompasses several S/T residues, which are potential GRK5 phosphorylation sites. We first examined the possible role of these residues in GRK5-mediated inhibition of ERK by generating several 5-HT₄R truncated mutants (Fig. 2A). GRK5 failed to inhibit ERK phosphorylation induced by 5-HT in cells expressing either the Δ329 mutant lacking the entire C-terminus or the Δ346 mutant lacking a S/T cluster

(residues 347-355, Fig. 2A). Deletion of the S/T cluster likewise prevented inhibition, by GRK5, of Src phosphorylation elicited by 5-HT (Fig. 2B). GRK5 still inhibited phosphorylation of ERK induced by 5-HT in cells expressing either the truncated receptor lacking its PDZ ligand (Δ SCF; Fig 2A) with a putative phosphorylated site (S³⁸⁵) or the Δ 358 mutant comprising the S/T cluster and lacking the last four scattered S/T residues, but not in cells expressing the corresponding truncated receptor in which all S/T residues of the cluster have been mutated into alanine (Δ 358-Ala, Fig. 2A).

Collectively, these results indicate that the S/T cluster (residues 347-355), that was previously shown to bind to β -arr (Barthet et al., 2005), constitutes a key molecular determinant implicated in the regulation of ERK activation by GRK5. Further supporting its essential role in the regulation by GRK5 of the ERK pathway, progressive deletion of the S/T residues within the cluster concomitantly reduced the GRK5-mediated inhibition of ERK phosphorylation (supplementary Figure S2).

We then analyzed agonist-dependent phosphorylation sites on the receptor by tandem mass spectrometry (MS/MS). HEK-293 cells expressing HA-tagged 5-HT₄R and GRK5 constructs were treated or not with 5-HT for 10 min. Receptors were then immunoprecipitated on anti-HA agarose beads. Immunoprecipitated receptors were resolved by SDS-PAGE and digested in-gel with trypsin. In control cells (not treated with 5-HT), analysis of duplicate samples revealed the presence of a non-phosphorylated form of the peptide comprising the S/T cluster (R³³⁶-R³⁵⁹). In contrast, several versions of the peptide were identified in cells exposed to 5-HT: the non-phosphorylated one and three phosphorylated forms with one, two and three phosphates attached, respectively. Loss of phosphate upon fragmentation indicated phosphorylation of S³⁵⁴ in the mono-phosphorylated peptide (Fig. 3B) and the presence of an additional phosphorylated residue within the S³⁴⁷TTT³⁵⁰ motif in the peptide with two phosphates attached (Fig. 3C). The tri-phosphorylated peptide incorporated an additional phosphate within the S³⁴⁷TTT³⁵⁰ motif (not illustrated). These results indicated sequential phosphorylation of the peptide, first on S³⁵⁴ and then in the S³⁴⁷TTT³⁵⁰ motif.

Physical association of GRK5 with 5-HT₄Rs, a necessary step in GRK5-mediated-inhibition of 5-HT₄R-operated ERK signal

We next determined whether GRK5 physically interacted with 5-HT₄R. GRK5/5-HT₄R interaction was first investigated in an *in vitro* binding assay using purified GRK5 and recombinant S-tagged receptors immobilized on a S-protein agarose column (Baneres et al., 2005). 5-HT induced association of GRK5 with 5-HT₄R, as assessed by the lack of GRK5 detection in the flow-through fraction when 5-HT was present (FT, Fig. 4A). Moreover, a greater amount of GRK5 was co-eluted with the receptor compared with sample not treated with 5-HT (E, Fig. 4A). In contrast, leukotriene B₄ failed to induce association of GRK5 with immobilized, recombinant BLT1 receptors (Fig. 4A), indicating that GRK5 does not interact with every GPCR upon activation by its cognate agonist.

These results indicate that 5-HT promotes *direct* interaction of GRK5 with 5-HT₄Rs. We then explored the molecular determinants involved in interaction of GRK5 with 5-HT₄Rs in HEK-293 cells by co-immunoprecipitation. GRK5 co-immunoprecipitated with 5-HT₄R and the amount of GRK5 was enhanced upon 5-HT exposure (Fig. 4B). GRK5 did not co-immunoprecipitate with the Δ 329 truncation mutant lacking the entire C-terminus in presence of 5-HT (Fig. S3), whereas the Δ 346 mutant that lacks the S/T (347-355) cluster phosphorylated by GRK5 (Fig. S2) still interacted with GRK5 (Fig. 4B). Thus, GRK5 can bind to 5-HT₄Rs without the presence of the S/T cluster substrates. However, note that 5-HT did not stimulate GRK5 binding to the Δ 346 mutant. A previous study has shown that acidic residues located upstream GRK phosphorylation sites participate in the recruitment of GRKs by several GPCRs (Berrada et al., 2000). A series of acidic residues located in the juxtamembrane region of 5-HT₄R C-t (D³³⁰DE³³²) was likewise critical for GRK5 recruitment by 5-HT₄Rs. Indeed, mutation of these residues into alanine in WT and Δ 346 receptors strongly reduced GRK5 recruitment (Fig. 4B). Collectively, these results identified the proximal region of the 5-HT₄R C-t (amino-acids 330-346) as the GRK5 binding sequence and the D³³⁰DE³³² motif as the most important determinant. To further explore the

role of GRK5/5-HT₄R interaction, we synthesized an interfering peptide (Inh-Pep for inhibitor peptide) comprising the GRK5 binding site (residues 330-345, Fig. 2A). The peptide was N-terminally fused to the transduction domain of the TAT protein from HIV Type 1 to allow its intracellular delivery (Aarts et al., 2002). Treatment of HEK-293 cells co-transfected with 5-HT₄R and GRK5 with Inh-Pep (10 μM, 1 hr) reduced 5-HT₄R/GRK5 co-immunoprecipitation (Fig. 4C). In non GRK5 transfected cells, Inh-Pep increased by 50 % the 5-HT₄R-stimulated ERK phosphorylation compared to the 5-HT₄R-stimulated ERK phosphorylation measured in cells treated with a control TAT-derived peptide (including the 5-HT_{2C} receptor C-t) (Fig. 4D). This effect likely reflected competition of Inh-Pep with endogenous GRK5 and reversal of its inhibitory effect.

β-arrestin1 is essential for GRK5-mediated inhibition of the 5-HT₄R-operated Src/ERK pathway

Our data indicated that association of GRK5 with the proximal region of 5-HT₄R C-t (sequence 330-346) was required but was not sufficient. Phosphorylation of S/T residues within the S/T cluster (residues 347-355) was also essential. Since this cluster is known to bind to β-arrestins (Barthet et al., 2005), we explored a possible role of β-arrestins in the GRK5 effect. WT receptor interacted with both endogenous β-arrestin1 and 2 (Fig. 5A). This association was increased by 5-HT (Fig. 5A). The Δ346 mutant slightly interacted with endogenous β-arrestin2, but not with β-arrestin1. Furthermore, the association of β-arrestin2 with the mutant was not increased upon 5-HT exposure (Fig. 5A and S4). Transfection of HEK-293 cells with siRNA directed against β-arrestin1, which strongly decreased β-arrestin1 expression compared with control siRNA-transfected cells, markedly impaired GRK5-mediated inhibition of the 5-HT₄R-operated activation of the ERK pathway (Fig. 5B and C). To further confirm that β-arrestin1 was essential for GRK5-mediated inhibition of ERK signalling, we transfected mouse embryonic fibroblasts (MEF) lacking β-arrestin1 and β-arrestin2 (β-arrestin1/2^{-/-}) with 5-HT₄R. As these cells endogenously express various 5-HT receptors, 5-HT₄R were stimulated by BIMU8 (a selective 5-HT₄R agonist) instead of 5-HT. Overexpression of

GRK5 did not inhibit the 5-HT₄R-mediated activation of the ERK pathway in β -arr1/2^{-/-} MEF cells (Fig. 6). This inhibition was rescued by co-transfecting cells with β -arr1 and to a much lesser extent with β -arr2.

The phosphorylated β -arrestin1 (p-S⁴¹²- β -arr1) is required for the GRK5-mediated inhibition of 5-HT₄R-operated ERK signalling

We have shown that GRK5-mediated inhibition of 5-HT₄R-operated ERK signalling depends on phosphorylation of the S/T cluster (residues 347-355) of 5-HT₄R C-t and on β -arr1 binding to the receptor. However expression of GRK5 did not further increase the association of β -arr1 to the receptor upon 5-HT exposure (Fig. 7A, B). Thus, the mechanism by which GRK5 inhibited the 5-HT₄R-induced ERK signalling (which is dependent on β -arr1) was obviously not a simple "increase" in β -arr1 recruitment by the S/T cluster (residues 347-355).

Insulin-induced desensitization of ERK activation by G α_i -coupled receptors has been shown to require phosphorylation of β -arr1 at S⁴¹² (p-S⁴¹²- β -arr1). ERK itself was implicated in insulin-induced β -arr1 phosphorylation (Hupfeld et al., 2005), consistent with previous findings indicating that ERK1/2 phosphorylate β -arr1 at Ser⁴¹² (Lin et al., 1999). Thus, we hypothesized that p-S⁴¹²- β -arr1 rather than unphosphorylated β -arr1 mediates the inhibition, by GRK5, of 5-HT₄R-operated ERK signalling. We first examined whether β -arr1 associated with 5-HT₄R was phosphorylated at S⁴¹² using an antibody against p-S⁴¹²- β -arr1. P-S⁴¹²- β -arr1 co-immunoprecipitated with 5-HT₄R upon exposure of HEK-293 cells to 5-HT (Fig. 7C). The amount of p-S⁴¹²- β -arr1 co-immunoprecipitated with 5-HT₄R was largely increased in cells co-expressing GRK5 (Fig. 7E). Moreover, association of p-S⁴¹²- β -arr1 with 5-HT₄R, which was transient in HEK-293 cells transfected with 5-HT₄R, was prolonged in cells co-expressing GRK5 and persisted for at least 10-min 5-HT stimulation (Fig. 7D). Furthermore, GRK5 impaired 5-HT₄R internalization (Fig. S5), this observation could be related to the presence of p-S⁴¹²- β -arr1 bound to the receptor as previously reported by Luttrell et al (Luttrell et al, 1999). Even though the magnitude of 5-HT₄R-induced ERK

phosphorylation decreased in the presence of GRK5, we could not exclude that ERK1/2 exerted an inhibitory feedback control by phosphorylating β -arr1 at Ser⁴¹². To investigate whether ERK1/2 contributed to β -arr1 phosphorylation, we transfected MEK1(K⁹⁷A), a dominant negative MEK. Expression of MEK1(K⁹⁷A) did not affect the ratio of p-S⁴¹²- β -arr1/ β -arr1 co-immunoprecipitated with 5-HT₄R (Fig. 7E). Similar conclusion was obtained in cells treated with MEK inhibitors U0126 (Fig. S6) and PD 98059 (not shown).

No p-S⁴¹²- β -arr1 bound to the receptor was detected in cells co-transfected with GRK5 (K215R) (Fig. 7C), indicating that GRK5 catalytic activity was critical for binding and/or phosphorylation of p-S⁴¹²- β -arr1 (Fig. 7C). Inhibition, by GRK5, of 5-HT₄R-mediated ERK signalling in β -arr1, 2^{-/-} MEF cells was only rescued by transfection of cells with β -arr1 but not with the S⁴¹²A- β -arr1 mutant (Fig. 6). Collectively, these observations support the essential role of β -arr1 phosphorylation in the negative regulation, by GRK5, of 5-HT₄R-mediated ERK signalling.

GRK5 directly phosphorylates β -arrestin1

Since both p-S⁴¹²- β -arr1 and GRK5 kinase activity were involved in the negative regulation of the Src/ERK pathway, we examined whether GRK5 directly phosphorylated β -arr1 in an *in vitro* kinase assay using purified recombinant β -arr1. We first compared the ability of GRK2 and GRK5 to phosphorylate purified β -arr1. As shown in Fig. 8A, GRK5 was more efficient than GRK2 to phosphorylate β -arr1. Analysis of β -arr1 phosphorylation state by immunoblotting indicated that GRK5, but not GRK2, phosphorylated β -arr1 at S⁴¹² (Fig. 8A). Further supporting a direct phosphorylation of S⁴¹² by GRK5, the GRK5-dependent ³²P incorporation in purified S⁴¹²D β -Arr1 mutant was strongly reduced, compared with that measured in WT β -Arr1 (Fig. 8B). Using equivalent amounts of kinase, GRK5 was as efficient as ERK2 to promote β -Arr1 phosphorylation at S⁴¹² (Fig 8C).

GRK5 inhibits 5-HT₄R-mediated ERK signalling by preventing activation of Src constitutively associated with the receptor

Several mechanisms have been involved in activation of the Src/ERK pathway by GPCR ligands (Cao et al., 2000; Luttrell and Luttrell, 2004). For instance, activation of ERK signalling by β_2 -ARs is dependent on the formation of β_2 -AR/ β -arr1 complex, which subsequently recruits and activates Src (Luttrell et al., 1999; Luttrell et al., 2001). In contrast, 5-HT₄Rs recruited Src independently of β -arr1. Indeed, purified Src associated with recombinant S-tagged 5-HT₄Rs immobilized on a S-protein agarose column (Fig. 9A). Equal amounts of Src bound to 5-HT₄R in absence and presence of 5-HT (Fig. 9A), indicating that 5-HT₄R/Src interaction was direct and independent of receptor activation. Corroborating this finding, Src co-immunoprecipitated with 5-HT₄Rs expressed in HEK-293 cells treated or not with 5-HT (Fig. 9B). Exposure of cells to 5-HT activated Src bound to the receptor, as indicated by the increased amount of p-Y⁴¹⁶-Src co-immunoprecipitated with 5-HT₄R (Fig. 9B). Both basal and 5-HT-stimulated phosphorylations of Src associated with 5-HT₄Rs were strongly inhibited by GRK5 over-expression (Fig. 9B). Note that phosphorylation of Src, bound to 5-HT₄Rs, was independent of β -arr1, as indicated by experiments performed in β -arr1/2^{-/-} MEF cells (Fig. 9C), and in HEK-293 cells expressing P⁹¹G-P¹²¹E- β -arr1, which weakly binds to Src ((Luttrell et al., 1999) (Fig 9B). Moreover, inhibition by GRK5 of the 5-HT₄R-operated Src/ERK pathway was likewise independent of the interaction of Src with β -Arr, as it was not affected by expression of P⁹¹G-P¹²¹E- β -arr1 (Fig. 9B).

Effect of GRK5 on endogenous 5-HT₄R-mediated ERK signalling in neurons

Finally, we examined whether the regulation of 5-HT₄R-mediated ERK signalling by GRK5 also occurs in neurons expressing native 5-HT₄Rs. Native HEK-293 cells and colliculi neurons expressed nearly similar amount of GRK5 (Fig. 10A). We have shown, in HEK-293 cells, that a TAT cell-permeant Inh-Pep comprising the GRK5 binding site inhibited GRK5 binding to the receptor (Fig. 4C) and thus, increased 5-HT₄R-stimulation of the ERK

pathway (Fig. 4D). Interestingly, the Inh-Pep had a similar effect on colliculi neurons: this treatment significantly enhanced ERK activation induced by maximally effective concentration of BIMU8, compared to cells treated with the control peptide ($+35 \pm 6 \%$; $n = 4$, $P < 0.05$, Fig. 10B). Over-expressing GRK5 in colliculi neurons clearly inhibited, as in HEK-293 cells, ERK pathway without affecting the $G_s/cAMP$ pathway (Fig. 10C). Finally, as observed in HEK-293 cells, transfection of neurons with GRK5 also attenuated 5-HT₄R endocytosis as shown in Supplementary Figure S5).

DISCUSSION

Like many biological processes, the GPCR activity represents a coordinated balance between molecular mechanisms governing activation and those governing inactivation. Any deregulation of this balance may lead to pathological situations. The activation of G protein-dependent signalling by GPCRs is controlled by a well-described desensitization process, a phenomenon governed by a complex sequence of events including G protein-uncoupling, receptor phosphorylation, β -arr recruitment and receptor internalization *via* clathrin coated pits (DeWire et al., 2007); (Reiter and Lefkowitz, 2006). Recently, some GPCRs have been shown to signal *via* non G protein-dependent pathways (Brzostowski and Kimmel, 2001; Heuss and Gerber, 2000) following their interaction with GIPs (GPCR interacting proteins) such as β -arrestins, Src, NHERF and many others (Bockaert et al., 2004a; Bockaert et al., 2004b). One of the most studied G protein-independent signalling is the ERK pathway. The most classical mechanism by which GPCRs activate ERK independently of G proteins is *via* their direct interaction with β -arrestins, a process followed by receptor endocytosis and recruitment of the Src/Raf/MEK machinery (Luttrell et al., 1999; Luttrell et al., 2001).

We have recently shown that 5-HT₄Rs activate ERK through an original mechanism independently of both G proteins and β -arrestins. This mechanism involves activation of Src tightly associated with the receptor (Barthet et al., 2007 and Fig 9). A similar mechanism has been reported for β_2 -AR (Sun et al., 2007).

In spite of accumulating data on the different routes by which GPCRs activate the ERK pathway in a G protein-independent manner, the question of their regulation is relatively unknown. Nonetheless, these studies focused on GPCRs that activate ERK via interaction with β -arrestins (AT_{1A}, V₂, β_2 -AR and FSH receptors) (Kara et al., 2006; Kim et al., 2005; Ren et al., 2005; Shenoy et al., 2006). Others findings reported a negative feedback regulation of β -arrestin-mediated ERK activation via a direct phosphorylation of β -arr1 by ERK (Lin et al., 1999) (Hupfeld et al., 2005).

Here, we have addressed the important issue of the mechanisms involved GRK5 in the negative regulation of the 5-HT₄R-mediated activation of the ERK pathway. We paid particular attention to GRK5, as its recruitment to the plasma membrane is G protein-independent. GRK5 is constitutively targeted to the cell surface *via* the interaction with phospholipids (Kunapuli et al., 1994) (Thiyagarajan et al., 2004). We found that over-expression of GRK5 potently inhibited the G protein-independent pathway, not only in HEK-293 cells but also in neurons, without significantly affecting the coupling to G_s pathway. Using purified GRK5 and 5-HT₄Rs, we showed that these two proteins interacted directly and that this interaction was promoted by 5-HT. In a cellular context, a constitutive interaction was observed although 5-HT increased the amount of complexes formed. Constitutive 5-HT₄R-GRK5 interaction may be due, at least in part, to basal "constitutive" activity that we have previously described (Claeysen et al., 1999). Indeed, the Δ 346 mutant, exhibiting a higher constitutive activity than WT receptors, recruited a higher amount of GRK5 than WT receptors in absence of 5-HT. We identified the proximal region of the 5-HT₄R C-t (amino-acids 330-346) as being a GRK5 binding motif. Within this region, the most important determinant for GRK5 binding was the D³³⁰DE³³² triplet. A similar result has been established by BRET for GRK5/Neurokinin-1 receptor association (Jorgensen et al., 2008).

We investigated the role of endogenously expressed GRK5 by using a TAT peptide, fused to the GRK5 binding motif on 5-HT₄R C-t (Inh-Pep). This peptide, but not a control TAT-peptide increased the ERK pathway in both HEK-293 cells and neurons, indicating that endogenous GRK5 significantly inhibited 5-HT₄R-operated ERK pathway. Similarly, an inhibitory role of endogenous GRK5 was also suggested by the observed increase in 5-HT₄R response following over-expression of the kinase dead GRK5 mutant (K²¹⁵R). This reveals that not only over-expressed GRK5, but also endogenously expressed GRK5 is able to inhibit 5-HT₄R-mediated ERK activation.

Our study also identified β -arr1 as a major player of the negative regulation of the 5-HT₄R-mediated Src/ERK pathway. Moreover, we demonstrate for the first time that GRK5 directly

phosphorylates β -arr1 at S⁴¹² and that GRK5 is as potent as ERK2, the first protein kinase capable of phosphorylating β -arr1 identified (Lin et al., 1999). P-S⁴¹²- β -arr1 is the major form of cytosolic β -arr1 (Lin et al., 1997). Upon β_2 -AR stimulation, the receptor interacts with p-S⁴¹²- β -arr1, a process followed by rapid de-phosphorylation of β -arr1. The de-phosphorylated form of β -arr1 is a clathrin adaptor, and thereby allowing internalization of the β_2 -AR- β -arr1 complex. In both HEK-293 and neurons, β -arr1 associated with the 5-HT₄R was only transiently phosphorylated (p-S⁴¹²- β -arr1) (1-2 min) following 5-HT exposure, a process followed by receptor internalization. In contrast, in HEK293 overexpressing GRK5, the situation was different. β -arr1 bound to the receptor remained phosphorylated up to 10 min following 5-HT exposure. Moreover, the 5-HT₄R did not internalize (Fig S5), consistent with the proposal of Lin et al. that de-phosphorylation of β -arr1 bound to β_2 -AR is necessary for its internalization (Lin et al., 1997).

P-S⁴¹²- β -arr1 was required for inhibition by GRK5 of the 5-HT₄R-operated activation of the ERK/Src pathway since: 1) transfection of β -arr1 in MEF β -arr1/2^{-/-} rescued the GRK5-mediated inhibition and 2) transfection of the S⁴¹²A- β -arr1 mutant was inefficient. We then investigated how p-S⁴¹² β -arr1 mediates its regulatory effect. The possibility that phosphorylation of β -arr1 known to block its interaction with Src may be involved has been excluded since we collected data showing that activation of Src, by 5-HT₄R, did not require β -arr1 and that over-expressing a β -arr1 mutant which inefficiently interact with Src (P⁹¹G-P¹²¹E- β -arr1) did not modified the capacity of GRK5 to inhibit the 5-HT₄R-mediated activation of the Src/ERK pathway.

The mechanisms by which Src is activated, following binding to several families of receptors, is poorly known. This is the case for β_3 -ARs or even for receptor tyrosine kinases (Bromann et al., 2004; Cao et al., 2000). Many papers are “implying” that binding of Src to the receptor is “enough” to activate Src but “how” is almost never described. Change in Src conformation *via* allosteric mechanisms is likely associated with the required de-phosphorylation of p-Tyr⁵²⁷. In this situation it is difficult to determine how this process can be inhibited by p-S⁴¹²- β -arr1. Two hypotheses can be proposed to explain the inhibitory role

of p-S⁴¹²- β -arr1 on the inhibition of Src by 5-HT₄Rs. In the first one, we can propose that once phospho- β -arr is bound to the receptor, the allosteric mechanism involved in Src activation does not longer occur. In the second one, we can propose that p-S⁴¹²- β -arr1 affects the receptor mobility within the plasma membrane. It is likely that the 5-HT₄R-Src complex needs to relocate after stimulation in a domain enabling Src activation where, for example p-Tyr phosphatases are present. P-S⁴¹²- β -arr1 may block this relocation. This assumption appears possible since endocytosis of 5-HT₄Rs was totally prevented in presence of GRK5. It is important to notice that Ser⁴¹² is localized within the R2 domain of β -arr1 that also contains LIEF binding motif for clathrin and the RXR binding motif for β 2-adaptin (AP2). (Goodman et al., 1996; Laporte et al., 2000).

Although the mechanisms by which GRK5 inhibited the 5-HT₄R-mediated activation of the G protein-independent Src/ERK pathway has been mainly dissected using HEK-293 cells we also demonstrated an effect of endogenous GRK5 in embryonic cultured neurons. Since expression of both GRK5 and β -arr1 increases considerably during development (Gurevich et al., 2004; Gurevich and Gurevich, 2004), it is likely that the negative regulation of the 5-HT₄R-mediated activation of the G protein-independent Src/ERK pathway will be higher in adult neurons.

In conclusion, GRK5, as well as a post-translational modification of β -arr1, determine the nature of the signalling pathway (G_s or ERK) predominantly engaged upon activation of 5-HT₄Rs. Such a control of signalling pathways could be critical for 5-HT₄R-dependent synaptic plasticity and memory consolidation (Kemp and Manahan-Vaughan, 2004; Kemp and Manahan-Vaughan, 2005; Marchetti et al., 2004; Micale et al., 2006).

MATERIALS AND METHODS

Cell cultures and transfection

HEK-293 cells and β -arr1,2^{-/-} MEF cells, obtained from Professor RJ Lefkowitz (Duke University Medical Center, Durham, North Carolina) were grown in Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% of dialyzed foetal calf serum and antibiotics. They were transfected by electroporation, as previously described (Claeyssen et al., 1999). Primary cultures of colliculi neurons prepared as previously described (Dumuis et al., 1988) were plated in serum-free medium in 12-well culture dishes (0.8×10^6 cells/ml, 1 ml per dish). Cultures were maintained for 8 days at 37°C in a humidified atmosphere in 5% CO₂/95% H₂O/ air and in DMEM/F12 supplemented with 10% of mixture of hormone.

Small interfering RNA transfection

The double-stranded siRNA sequence 5'-AAAGCCUUCUGCGCGGAGAAU-3' (Eurogentec, Belgium) was used to selectively target human β -arr1 at positions 439–459 relative to the initiation codon. A small RNA duplex, that has no silencing effect, was used as a control (5'-AAGUGGACCCUGUAGAUGGCG-3'). All the siRNAs used in this study have been previously described and validated (Ahn et al., 2003). A second double-stranded siRNA sequence 5'-CGC-UUA-CCC-UUU-CAC-CUU-U-3' (Eurogentec, Belgium) was used to selectively target human β -arr1. A small RNA duplex that has no silencing effect was used as a control. 5'-CGU-ACG-CGG-AAU-ACU-UCG-A-3' siRNA was used to selectively target luciferase. Early passage HEK-293 cells at 40% confluence in 6-wells plates were transfected with 300 ng of plasmid encoding WT 5-HT₄R with or without 1 μ g of plasmid encoding GRK5. siRNAs were transfected at 200 nM using the Gene Silencer transfection reagent according to manufacturer's recommendations (Gene Therapy Systems, San Diego). All assays were performed 3 days after siRNA transfection, as previously described (Barthet et al., 2007).

Immunoblotting

Proteins were separated by SDS-PAGE and transferred to nitrocellulose membranes (Hybond-C, Amersham Biosciences). Membranes were blocked for 1 h at room temperature using Tris buffered saline blocking solution containing 5% (w/v) milk powder, 0.25% v/v Tween 20. Membranes were incubated with the primary antibodies overnight at 4 °C, then washed extensively, and incubated with secondary antibodies for 1h. Immunoreactivity was detected using a Chemiluminescence Reagent Plus kit (Perkin Elmer, Courtaboeuf, France). Immunoreactive bands were quantified by densitometry using Image J and GraphPad PRISM.

Analysis of 5-HT₄R phosphorylation by mass spectrometry

HEK-293 cells transfected with the plasmid encoding HA-tagged 5-HT₄R and/or GRK constructs were grown in 100-mm culture dishes (5 dishes containing 10×10^6 cells per condition). Cells were lysed in 5 ml solubilization buffer (Hepes 20 mM, 150 mM NaCl, 1% NP40, 10% glycerol, 4 mg/ml dodecylmaltoside (DDM) supplemented with protease inhibitors and phosphatase inhibitors (NaF, 10 mM; Na⁺-vanadate, 2 mM; Na⁺-pyrophosphate, 1 mM and β-glycerophosphate, 50 mM). Receptors were immunoprecipitated on anti-HA agarose beads (Sigma Aldrich). Immunoprecipitated proteins were resolved by SDS-PAGE. After reduction and alkylation (with 10 mM DTT for 45 min at 56 °C and 55 mM iodoacetamide for 30 min at room temperature, respectively), receptors were digested in-gel by trypsin (600 ng, Gold, Promega) and tryptic peptides were extracted from the polyacrylamide, as previously described (Shevchenko et al., 1996). Trypsic digests were enriched in phosphopeptides using the PHOS-Select Iron Affinity Gel (Sigma Aldrich), as described by the manufacturer, dehydrated in a vacuum centrifuge, and solubilized in 3 μl of 0.1% formic acid, 2% acetonitrile in water. Samples were analyzed online by nano-flow HPLC-nanoelectrospray ionization using a LTQ Orbitrap mass

spectrometer (LTQ Orbitrap XL, Thermofisher Scientific) coupled with an Ultimate 3000 HPLC (Dionex). Desalting and pre-concentration of samples were performed on-line on a Pepmap[®] precolumn (0.3 mm x 10 mm). A gradient consisting of 0-40 % A in 30 min, 40-80 % B in 15 min (A = 0.1% formic acid, 2% acetonitrile in water; B = 0.1 % formic acid in acetonitrile) at 300 nl/min was used to elute peptides from the capillary (0.075 mm x 150 mm) reverse-phase column (Pepmap[®], Dionex). LC-MS/MS experiments comprised cycles of 6 events: a MS¹ scan with Orbitrap mass analysis at 15,000 resolution followed by HCD (higher energy collisional dissociation) of the five most abundant precursors. Fragment ions generated by HCD were detected in the Orbitrap analyzer at 7,500 resolution. Normalized collision energy of 45 and activation time of 30 ms were used for HCD. All Spectra were recorded under positive ion mode using the Xcalibur 2.0.7 software (Thermofisher Scientific). The mass scanning range was m/z 400-2,000 and the capillary temperature was 200°C. Source parameters were adjusted as follows: Ion spray voltage, 2.45 kV; capillary voltage, 20 V and tube lens, 140 V. Spectra were acquired with the instrument operating in the information-dependent acquisition mode throughout the HPLC gradient. Spectra were analyzed using Proteome Discover software v 1.0 (Thermofisher Scientific). MS/MS spectra were searched against the sequence of the HA-tagged 5-HT₄R by using the Mascot v 2.2 algorithm (<http://www.matrixscience.com>). All spectra for phosphorylated peptides were validated by visual inspection.

β-arrestin phosphorylation assay

Phosphorylation of β-arr were performed using 500 nM purified β-arr1 or β-arr2 (Milano et al., 2002) and 50 nM purified GRK2 or GRK5 (Kim et al., 1993; Kunapuli et al., 1994), in presence or absence of 0.1 mg/ml crude soybean phosphatidylcholine. The phosphorylation medium (20 μl) including 100 μM [γ -³²P]ATP (2.0-7.5 cpm/fmol), 20 mM Tris-HCl, pH 7.5, 2 mM EDTA, and 7.5 mM MgCl₂ for 60 min at 30°C. SDS sample buffer was added to terminate the reaction and proteins were resolved by SDS-PAGE (10%). Following autoradiography, the ³²P incorporation into β-arr was determined by Cerenkov counting.

To determine the site of phosphorylation, the above reaction was performed in the absence of radiolabeled ATP. Reaction mixtures were also subjected to Western Blotting to determine β -arr1 phosphorylation on S412 by using the p-S⁴¹²- β -arr1 antibody.

Co-immunoprecipitation

Cells were transfected with WT or truncated and mutated Myc-tagged-5-HT₄R constructs generated as previously described (Claeyssen et al., 1999). Cells were seeded in 150 mm plate (10⁶ cells by plate) 48 hrs prior to the experiment. They were exposed for 5-min to 10 μ M 5-HT stimulation with 10 μ M at 37 °C in DMEM without serum. Then, the cross-linking reaction was realized during 30 min in PBS completed with 1.25 mM of dithiobissuccinimidyl propionate (DSP) (Pierce, Perbio-Brebières, France) a membrane-permeable, hydrolysable, covalent cross-linker. The cross-linking reaction was stopped with Tris 50 mM pH 7.4. After two washes in PBS, cells were incubated solubilization buffer (see above). For 30 min at 4°C, samples were centrifuged at 15000 rpm for 15 min. Solubilized proteins were incubated overnight at 4°C with 20 μ l of protein A/G-sepharose beads pre-coupled with 8 μ g of antibody. Immunoprecipitated proteins were eluted in Laemmli sample buffer, resolved by SDS-PAGE and detected by Western blotting.

In vitro protein interaction assay

Recombinant 5-HT₄R receptor was produced and purified as previously described (Baneres et al., 2005), that includes an S-tag at its N-terminus and an His-Tag (His)₆ sequence at its C-terminus. Purified receptors were incubated with either purified GRK5 (Cell signalling Technology) or purified human Src (Sigma) in the absence or presence 10 μ M 5-HT. Protein concentrations in the 5 μ M range were used. After 1 hr incubation at 15°C, the complex was loaded on a S-protein agarose column (100 μ L resin) and the flow-through fraction recovered (FT fractions). The column was washed with a first buffer containing 12.5 mM sodium borate pH 7.8, 25 mM KCl, 1% DMPC, 1% CHAPS, and 0.02% cholesteryl

hemisuccinate. Finally, the receptor immobilized on the column and associated proteins were recovered with a 12.5 mM sodium borate, 25 mM KCl, pH 7.8, 1% DMPC, 1% CHAPS, 0.02% cholesteryl hemisuccinate, 3 M MgCl₂ buffer (E fractions).

Data Analysis

All data represented correspond to the means \pm S.E.M. of at least three independent experiments performed in triplicate. Statistical analysis was carried out with the t test using GraphPad Prism 3.0 software. P-values < 0.05 were considered as statistically significant.

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FIGURE LEGENDS

Figure 1: GRK5 suppresses the 5-HT₄R mediated activation of the Src/ERK pathway

A) HEK-293 cells transiently expressing 5-HT₄R were co-transfected or not with GRK5 or the kinase-dead mutant GRK5 (K²¹⁵R) and serum starved prior to 5-HT (10μM) exposure for the indicated time. HEK-293 cells were lysed in SDS sample buffer, subjected to SDS-PAGE. ERK and Src activation were analysed by Western blotting using antibodies against phospho-Thr²⁰²/Tyr²⁰⁴-ERK1/2 (p-ERK) and phospho-Tyr⁴¹⁶-Src (p-Y⁴¹⁶-Src). Total ERK1/2 and total Src were revealed on the same blot with polyclonal antibody recognizing ERK and Src independently of their phosphorylation sites (not shown). Note that total ERK and Src were not affected in all experiments. The data are representative of a series of blots performed in the same conditions.

B) P-ERK and p-Y⁴¹⁶-Src expressed as percent of maximal 5-HT stimulation ± SEM, represented by densitometric quantification of western blot performed from four different experiments. (*) P < 0.05 or (**) P < 0.01 versus corresponding values measured in cells transfected with WT 5-HT₄R alone.

Figure 2: A Serine/Threonine cluster within the 5-HT₄R C-t is essential for inhibition, by GRK5, of receptor operated ERK signalling

A) Topology of 5-HT₄R C-t domain. The successive points of truncation are illustrated represented on the left with an arrow.

HEK-293 cells were transiently transfected with WT 5-HT₄R or the corresponding truncated or mutated receptors (Δ329, Δ346, Δ358, Δ358Ala) in combination with or without GRK5. Identical expression levels of the transfected constructs were controlled by ELISA. Cells expressing the indicated receptors were treated or not with 10 μM 5-HT for 5 min. ERK activation was analyzed by immunoblotting with p-ERK1/2 antibody.

B) HEK-293 cells were either transfected with a plasmid encoding Myc-tagged WT 5-HT₄R or Myc-tagged Δ 346 alone or co-transfected with GRK5. They were challenged with 10 μ M 5-HT for 5 min. Total lysates were analyzed by sequential immunoblotting, using p-Y⁴¹⁶-Src, p-ERK1/2 antibodies.

Figure 3: Analysis of 5-HT-dependent phosphorylation of 5-HT₄R by tandem mass spectrometry

HEK-293 cells co-transfected with HA-tagged 5-HT₄R and GRK5 constructs were treated with 5-HT (10 μ M, 10 min). Immunoprecipitated receptors were digested with trypsin and peptides were analysed by nano-LC FT MS/MS. MS/MS spectra resulting from Higher-energy Collisional Dissociation (HCD) fragmentation of the non-phosphorylated, monophosphorylated and bi-phosphorylated versions of the R³³⁶-R³⁵⁹ peptide are depicted in A, B and C respectively. The three peptides have respective mascot scores of 66, 65 and 59. In C, the bracket indicates that one residue of the S³⁴⁷TTT³⁵⁰ motif is phosphorylated. Its exact position could not be determined by MS/MS.

Figure 4: A direct interaction between GRK5 and 5-HT₄R is necessary for ERK pathway regulation

A) Recombinant purified His-tag 5-HT₄R receptors obtained as previously described (Baneres et al., 2005) were incubated with purified full-length GRK5 (Cell signalling Technology) in the presence or absence of 5-HT (10 μ M). The western blot analysis with the antibody against GRK5 or anti-His-tag (receptor) showed the fractions eluted from the S-agarose column. Fraction FT: in flow-through fractions the unbound proteins were detected. Fraction E: the receptor immobilized on the column and its tightly associated proteins were recovered in this fraction E (see Materials and Methods).

His-Tag-BLT1, which did not interact with GRK5, is used as control (right part). – and + indicate the absence or the presence of the agonists, 5-HT for 5-HT₄R at 10 μ M and LTB₄ at

10 μ M for BLT1R, respectively. The control has been carried out only in the presence of the agonist LTB₄.

B) HEK-293 cells were either transfected with a plasmid encoding Myc-tagged WT 5-HT₄R or different Myc-tagged mutants, co-transfected with GRK5. DDE³³⁰⁻³³² indicated by blue circles in Fig 2A, represent the putative binding site of GRK5. Cells co-expressing the indicated receptors and GRK5 were challenged with 10 μ M 5-HT for 5 min. Receptors were immunoprecipitated using polyclonal-anti-Myc antibody. Co-precipitated GRK5 was analyzed by Western blotting by using the antibody against GRK5 a gift from Dr. R.J. Lefkowitz (Duke University Medical Center, Durham, NC, US). Immunoprecipitated proteins were analyzed by Western blotting using the monoclonal anti-Myc antibody. On the left part, inputs represent 5% of the total protein amount used in immunoprecipitation.

Quantification of GRK5 bound to the receptor was performed by densitometry using the NIH Image Software. Data are means \pm SEM of results obtained in four independent experiments. (**) $P < 0.01$ versus corresponding values measured in experiments performed from cells expressing WT 5-HT₄Rs.

C) The 5-HT₄R C-t peptide (Inh-Pep) reduced the association of GRK5 with the receptor. The sequence (330 to 346) located on 5-HT₄R-C-t (see fig. 2A) (DDERYKRPPILGQTVPC) fused to the transduction domain of TAT protein (YGRKKRRQRRR) was used as inhibitor peptide. HEK-293 cells co-transfected with Myc-tagged-WT 5-HT₄R and GRK5 were treated with either 10 μ M of TAT-Inh-Pep or TAT-Ctrl (Ctrl-Pep) (the C-t residues of 5-HT_{2c}-C-t VNPSSVVSERISSV fused with TAT protein (YGRKKRRQRRR) for 1 h with 10 μ M 5-HT for 5 min. Receptors were immunoprecipitated using the polyclonal anti-Myc antibody. Immunoprecipitated receptor was detected with the monoclonal anti-Myc antibody. Co-precipitated GRK5 was analyzed by Western blotting using the anti-GRK5 antibody. Intensities of the bands in immunoblots were measured by densitometry analysis using Image J software. Data are means \pm SEM of results obtained in four independent experiments. (**) $P < 0.01$ versus corresponding values obtained from cells treated with the control peptide (Ctrl-Pep).

D) The 5-HT₄R C-t peptide (Inh-Pep) increased the 5-HT₄R induced ERK signalling. HEK-293 cells were pre-incubated for 1 h with either 10 μ M TAT-peptides (Inh-Pep) or a control peptide (see C) before the 5-min challenge (10 μ M 5-HT). Cells were then lysed in SDS sample buffer and subjected to SDS-PAGE. ERK activation was analyzed by Western blot using the polyclonal antibody against phospho-Thr²⁰²/Tyr²⁰⁴-ERK1/2. Illustrated data are representative of four blots performed in different sets of cultured cells. The histogram is the means \pm of densitometric quantification of four western blots using Image J software.

Figure 5: Role of β -arrestins in the inhibition, by GRK5, of the 5-HT₄R-activated Src/ERK pathway

A) Activated WT 5-HT₄R and Δ 346 mutant differentially interact with endogenous β -arr1. HEK-293 cells co-transfected with either Myc-tagged Δ 346 or Myc-tagged WT 5-HT₄R and GRK5 were challenged with 10 μ M 5-HT for 5 min. Receptors were immunoprecipitated using the polyclonal anti-Myc antibody. Co-precipitated β -arr 1/2 were analyzed by Western blotting by using the anti- β -arr A1CT antibody which equally recognizes β -arr1 and 2, a gift from Dr. R.J. Lefkowitz (Duke University Medical Center, Durham, NC, US).

B) Down-regulation of β -arr1 expression, by siRNA, enhances inhibition by GRK5 of the 5-HT₄R-activated Src/ERK pathway. HEK-293 cells expressing Myc-tagged-WT were transfected with either control or β -arr1 specific siRNAs. 72 hrs after transfection, cells were stimulated 5 or 30 min before lysis. P-ERK and β -arr contents were analyzed by sequential Western blotting with p-ERK, and β -arr antibodies.

C) Quantification of ERK1/2 phosphorylation (top) and β -arr1 (bottom) was performed by densitometry using the Image J software. Data are means \pm SEM of results obtained in four independent experiments. (**) $P < 0.01$ versus corresponding values measured in cells transfected with control siRNA.

Figure 6: GRK5 fails to inhibit 5-HT₄R-mediated Src/ERK pathway in MEF β -arr1^{-/-}/ β -arr2^{-/-}

MEF β -arr1^{-/-}/ β -arr2^{-/-} cells were transiently co-transfected with WT 5-HT₄R in the presence or absence of GRK5, in combination with β -arr1, β -arr1 S⁴¹²A mutant or β -arr2. Expression levels of the transfected WT 5-HT₄R construct controlled by ELISA were very similar for all the combinations. Serum starved β -arr1^{-/-}/ β -arr2^{-/-} MEF cells expressing the receptors were treated or not with 10 μ M BIMU8 (a 5-HT₄ selective agonist) for 5 min. Total lysates were analyzed by immunoblotting with the p-ERK1/2 antibody for all transfected MEF β -arr1^{-/-}/ β -arr2^{-/-} cells. The histograms represented p-ERK1/2 quantified by densitometry from four western blotting, data represent mean \pm SEM. (*) P < 0.05, (**) P < 0.01 versus corresponding values measured in cells transfected with both GRK5 and β -arr1 as control.

Figure 7: Inhibition, by GRK5, of 5-HT₄R-operated ERK signalling pathway involves p-S⁴¹²- β -arr1

A) Cells co-transfected with Myc-tagged 5-HT₄R co-expressed with β -arr1-YFP and with or without GRK5 were incubated with 10 μ M 5-HT for 5 min. Receptors were immunoprecipitated using anti-Myc-tagged antibody. Co-precipitated proteins (GRK5 and β -arr1) were analyzed by Western blotting by using the antibodies against GRK5 or against GFP for β -arr1-YFP. The immunoprecipitated receptor was revealed by using the anti-Myc antibody. On the left part, inputs represent 5% of the total protein amount used in immunoprecipitation lysates (receptor; GRK5; total β -arr1). On the right, only proteins co-immunoprecipitated with WT were visualized (GRK5, total β -arr1-YFP).

B) Cells co-transfected with β -arr-YFP, GRK5 with or without Myc-tagged 5-HT₄R were incubated with 10 μ M 5-HT for 5 min. β -arr1-YFP was immunoprecipitated using anti-GFP antibody. Co-precipitated proteins (GRK5 and 5-HT₄R) were analyzed by Western blotting by using the antibodies against GRK5 or Myc-tagged.

C) HEK-293 cells expressing 5-HT₄R, β -arrestin1-YFP in the absence or the presence of

GRK5 or the kinase deficient GRK5 (K²¹⁵R) were exposed to 10 μ M 5-HT for 5 min. 5-HT₄R was immunoprecipitated using anti-Myc antibody. Co-precipitated proteins (GRK5, K²¹⁵R-GRK5, total β -arr1-YFP and phosphorylated β -arr1 (p-S⁴¹²- β -arr1) were analyzed by Western blotting. As in A, the corresponding blot of total lysate probed with antibody to p-ERK1/2 shows the correlation between the recruitment of p-S⁴¹²- β -arr1 and the inhibition of p-ERK. P-S⁴¹²- β -arr1 was revealed by using the monoclonal anti-p-S⁴¹²- β -arr1 antibody (Cell Signalling, Ozyme, France).

D) P-S⁴¹²- β -arr1 is rapidly dephosphorylated upon receptor binding in the absence of GRK5 but is stabilized on the receptor by GRK5. HEK-293 cells transiently expressing WT 5-HT₄R and β -arr1-YFP in the absence or the presence of GRK5 were exposed to 5-HT 10 μ M for 1, 2, 5 or 10 min. 5-HT₄R was immunoprecipitated as above and co-precipitated p-S⁴¹²- β -arr1 was analyzed by Western blotting.

E) Cells co-transfected with Myc-tagged 5-HT₄R, β -arr-YFP, with or without GRK5 and dominant negative of MEK1 (MEK1(K⁹⁷A)), were incubated in the absence or presence of 10 μ M 5-HT for 5 min. 5-HT₄R was immunoprecipitated using anti-Myc antibody. Co-precipitated proteins (total β -arr1-YFP, p-S⁴¹²- β -arr1 and GRK5) were analyzed by Western blotting. The histogram represented total β -arr1-YFP, p-S⁴¹²- β -arr1 quantified by densitometry from four western blotting, data represent mean \pm SEM. (**) P < 0.01 versus corresponding values measured in cells transfected in absence of GRK5 as control.

Figure 8: GRK5 phosphorylates β -arr1 *in vitro*

A) Phosphorylation reactions were performed at 30°C for 60 min with 500 nM β -arr1 and 50 nM GRK. The proteins labelled with [³²Pi] phosphate were analyzed by SDS-PAGE and autoradiography. The stoichiometry of phosphorylation was determined by excising the arrestin bands and counting in a scintillation counter. Quantified data from three separate experiments (expressed as mean \pm S.D.) are depicted.

Proteins were separated by SDS-PAGE, transferred to nitrocellulose and immunoblotted

with an anti p-S⁴¹²- β -arr1 antibody.

B) Same experiment as in A except that phosphorylation reactions were performed with either 500 nM WT β -arr1 or 500 nM β -arr1S412D mutant and 50 nM GRK5. The proteins labelled with [³²Pi] phosphate were analyzed by SDS-PAGE and autoradiography.

C) Time course of β -arr1 phosphorylation in the presence of GRK5 or ERK2. Reactions were performed at 30°C for the indicated periods (0-60 min) with 500 nM β -arr1 and 50 nM of GRK5 or 50 nM of ERK2. The western blot analysis with the anti p-S⁴¹²- β -arr1 antibody revealed the level of p-S⁴¹²- β -arr1 produced after phosphorylation with either GRK5 or ERK2. The amounts of p-S⁴¹²- β -arr1 were quantified by densitometry from three different experiments.

Figure 9: GRK5 affects activation of Src but not its direct interaction with 5-HT₄R

A) Src directly interacts with the recombinant 5-HT₄R. The recombinant purified His-tag 5-HT₄R receptor was incubated with purified full-length Src in the presence or absence of 5-HT; His-Tag BLT1, which did not interact with Src is used as control (right part). The western blot analysis with an anti-Src antibody or anti-His-tag (receptor) showed the fractions eluted from the S-agarose column. Fraction FT: or flow-through fraction contains unbound Src. Fraction E: contains Src, highly retained on the receptor and released with the receptor. – and + indicate the absence or the presence of the agonists, 5-HT for 5-HT₄R at 10 μ M and LTB₄ at 10 μ M for BLT1R, respectively.

B) Cells co-transfected with Myc-tagged 5-HT₄R in the presence of Flag-tagged β -arr1 or mutant P⁹¹G-P¹²¹E with Src and with or without GRK5, were incubated with 10 μ M 5-HT for 5 min. Immunoprecipitated 5-HT₄R as well as co-precipitated proteins (GRK5, p-Y⁴¹⁶-Src and total Src) were analyzed by Western blotting with the corresponding antibodies against GRK5, flag β -arr1 or mutant p-S⁴¹²- β -arr1, p-Y⁴¹⁶-Src, total Src and Myc for 5-HT₄R. The histogram represents total Flag-tagged β -arr1 versus p-S⁴¹²- β -arr1 co-immunoprecipitated with 5-HT₄R and total mutant P⁹¹G-P¹²¹E Flag-tagged β -arr1 versus

p-S⁴¹²mutant- β -arr1 quantified by densitometry from four western blotting, data represent mean \pm SEM. (**) $P < 0.01$ and versus corresponding values measured in cells transfected in absence of GRK5 as control.

C) MEF β -arr1^{-/-}/arr2^{-/-} cells were transiently transfected with WT 5-HT₄R, in combination. MEF β -arr1^{-/-}/arr2^{-/-} cells expressing the receptors were treated or not with 10 μ M BIMU8 (a 5-HT₄ selective agonist) for 5 min. Total lysates were analyzed by immunoblotting with the p-ERK1/2 antibody. Immunoprecipitated 5-HT₄Rs as well as co-precipitated proteins (p-Y⁴¹⁶-Src and total Src) were analyzed by Western blotting with the corresponding antibodies against p-Y⁴¹⁶-Src, total Src and Myc for 5-HT₄R.

Figure 10: GRK5 mediated specific inhibition of ERK1/2 pathway also occurs in neurons

A) Endogenous GRK5 expression levels in HEK-293 cells and in colliculi neurons in primary culture.

B) Inhibitory effect of the TAT-5-HT₄R C-t peptide (Inh-Pep) on GRK5-induced ERK regulation in neurons. As in Fig 4, (Inh-Pep) and TAT-peptide control (Ctrl-Pep) were pre-incubated for 1 h before the 5-min exposure to 10 μ M BIMU8. Neurons were lysed in SDS sample buffer, subjected to SDS-PAGE. ERK activation (p-ERK) in the presence of the Inh-Pep was detected by western blot using p-ERK antibody. This western blotting is representative of four blots performed in the same conditions. The histogram represented the results quantified by densitometry from four western blotting, data represent mean \pm SEM.

C) Colliculi neurons endogenously expressing 5-HT₄R were transfected with GRK5 or empty vector using lipofectamine as indicated in materials and methods, then stimulated with vehicle or BIMU8 (a selective 5-HT₄R agonist). Total neuron lysates were analyzed by immunoblotting with the anti GRK5 or anti p-ERK antibodies. In parallel, neurons issued

from the same culture were used for cAMP production measurement. The histogram on the right shows quantification of the ERK phosphorylation and bottom histograms indicate cAMP level in neurons. Data are means \pm SEM of results obtained in four independent experiments. (**) $P < 0.01$ versus corresponding values measured in transfected neurons with empty vector.

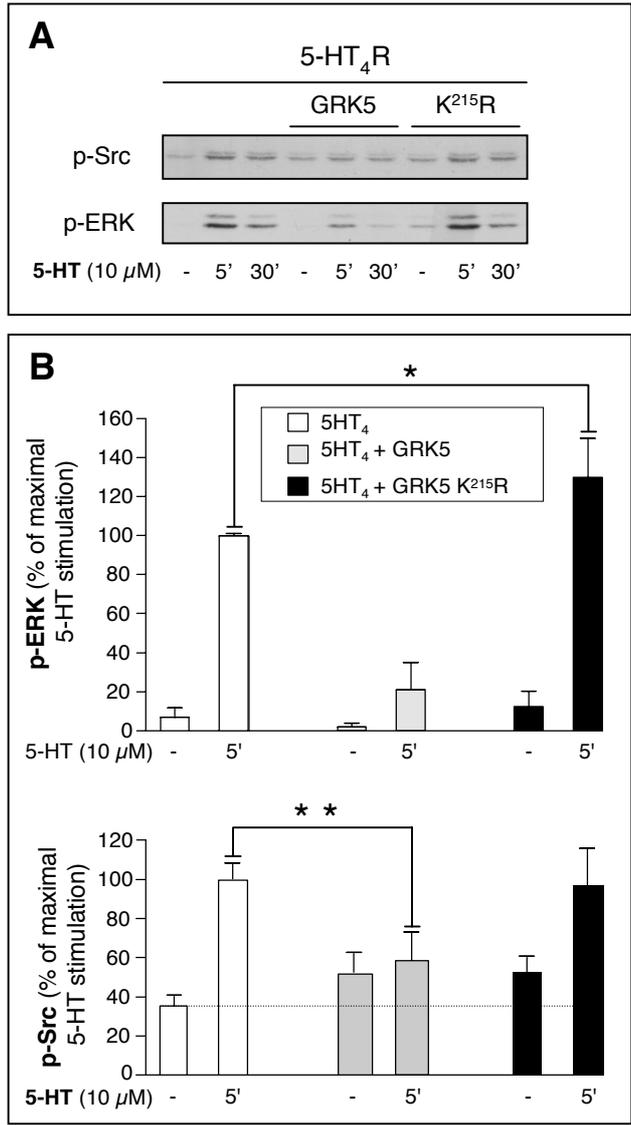


Figure 1

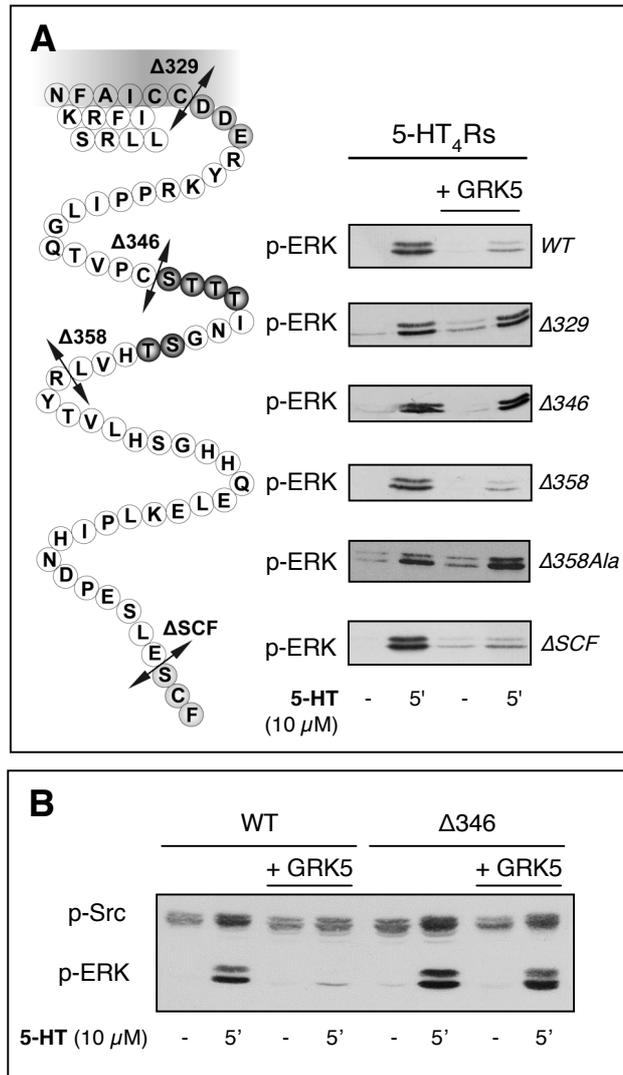


Figure 2

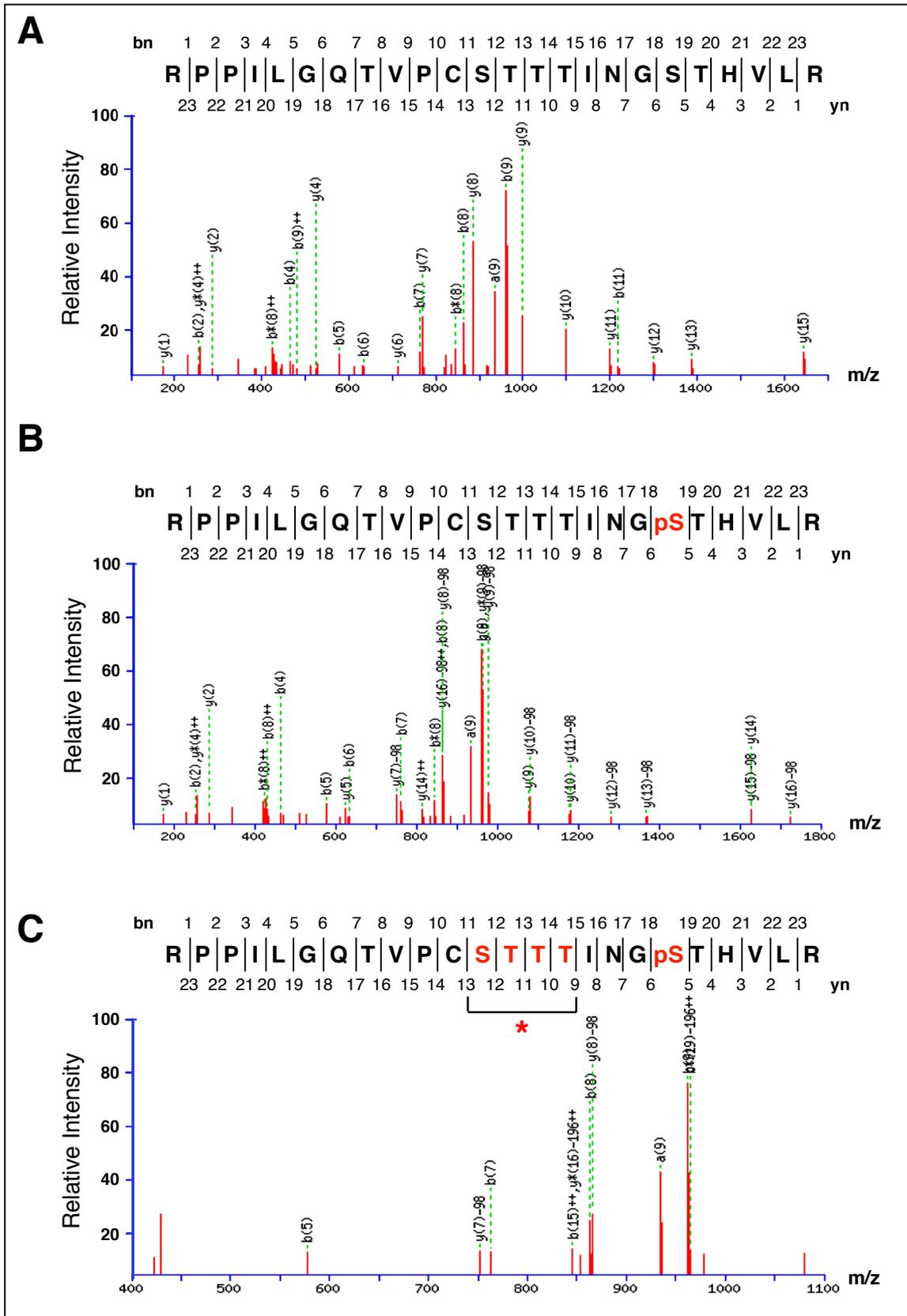


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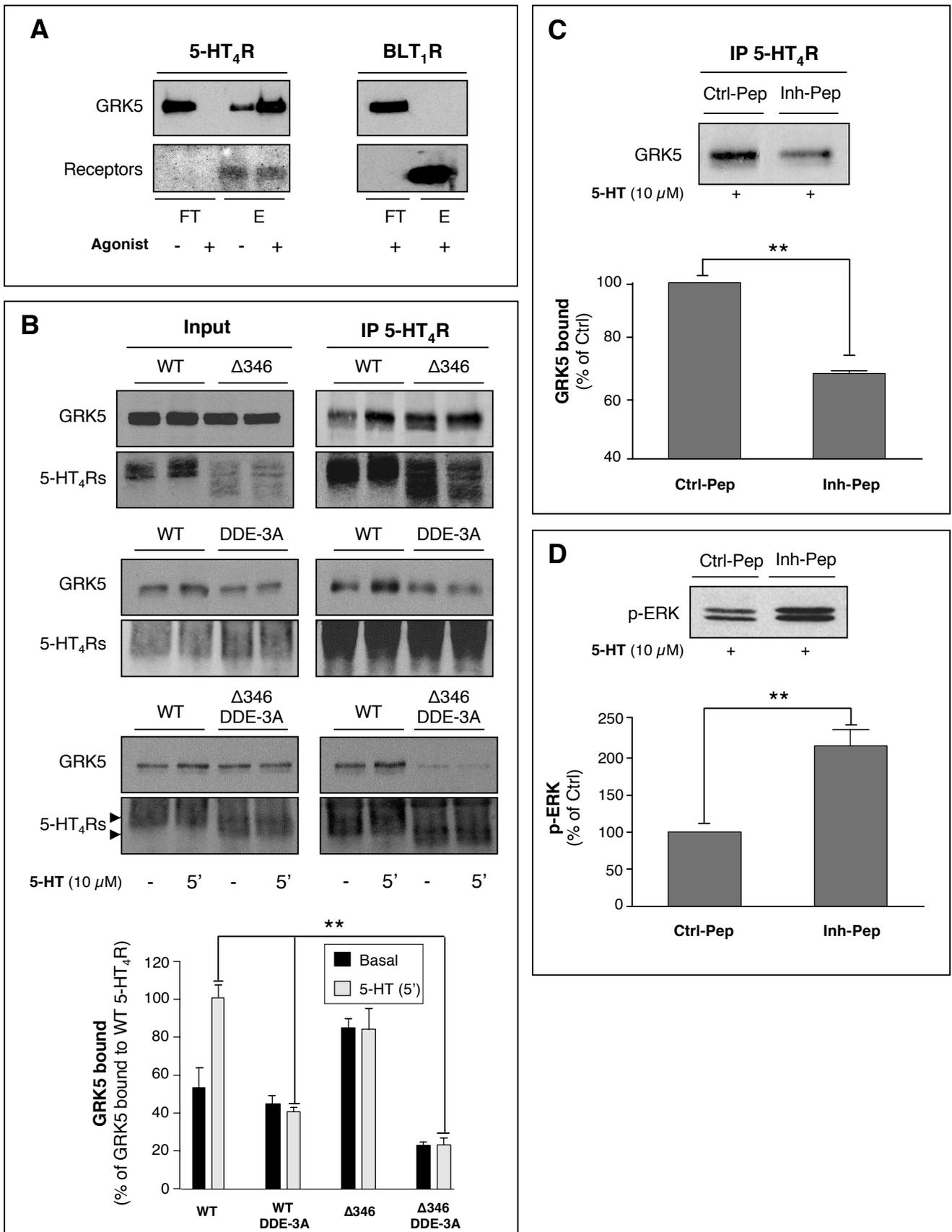


Figure 4

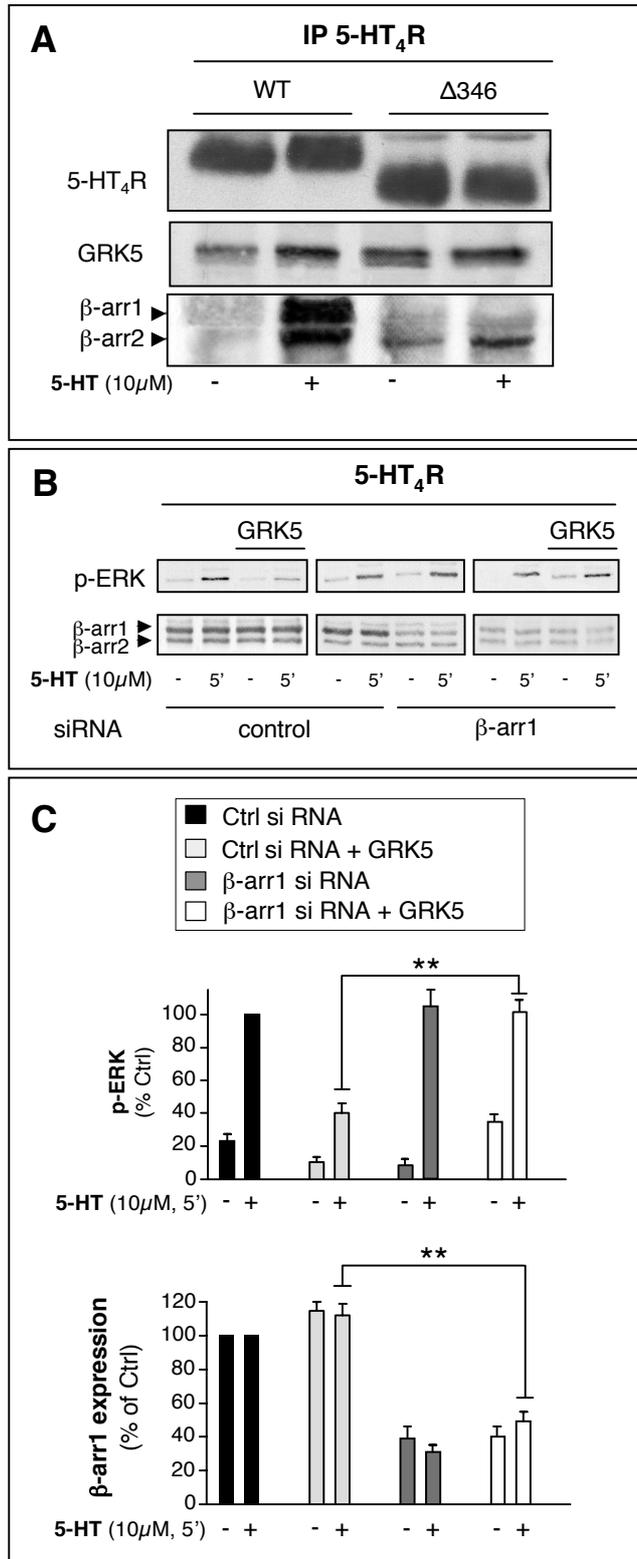


Figure 5

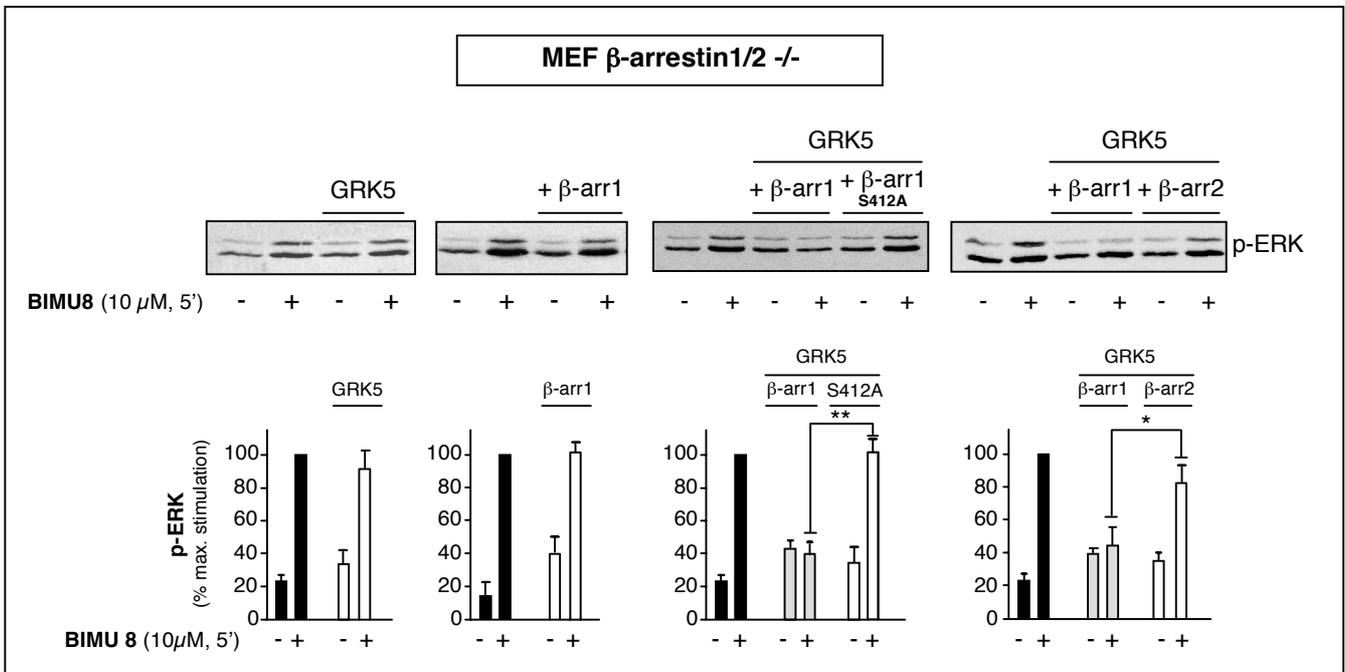


Figure 6

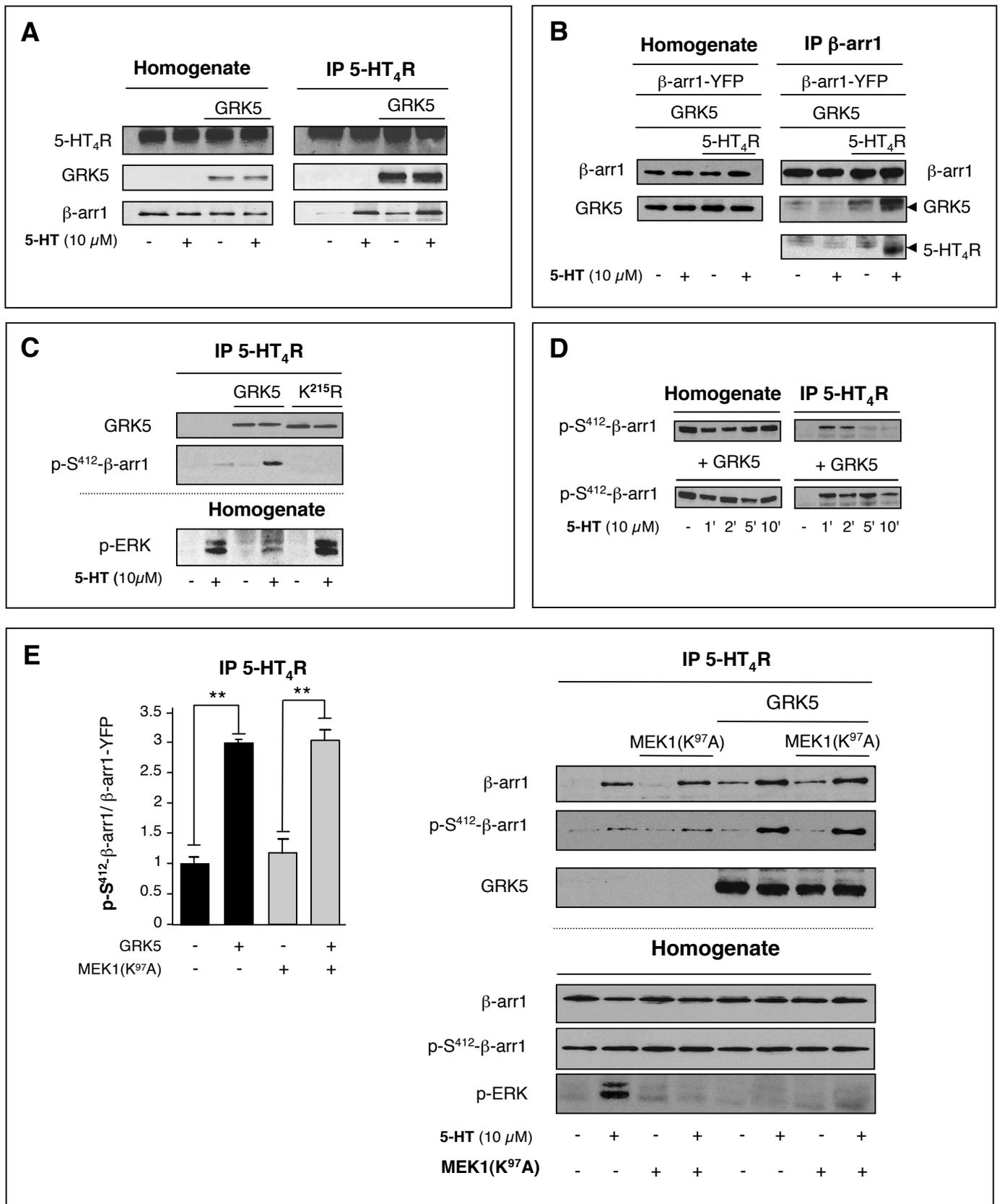


Figure 7

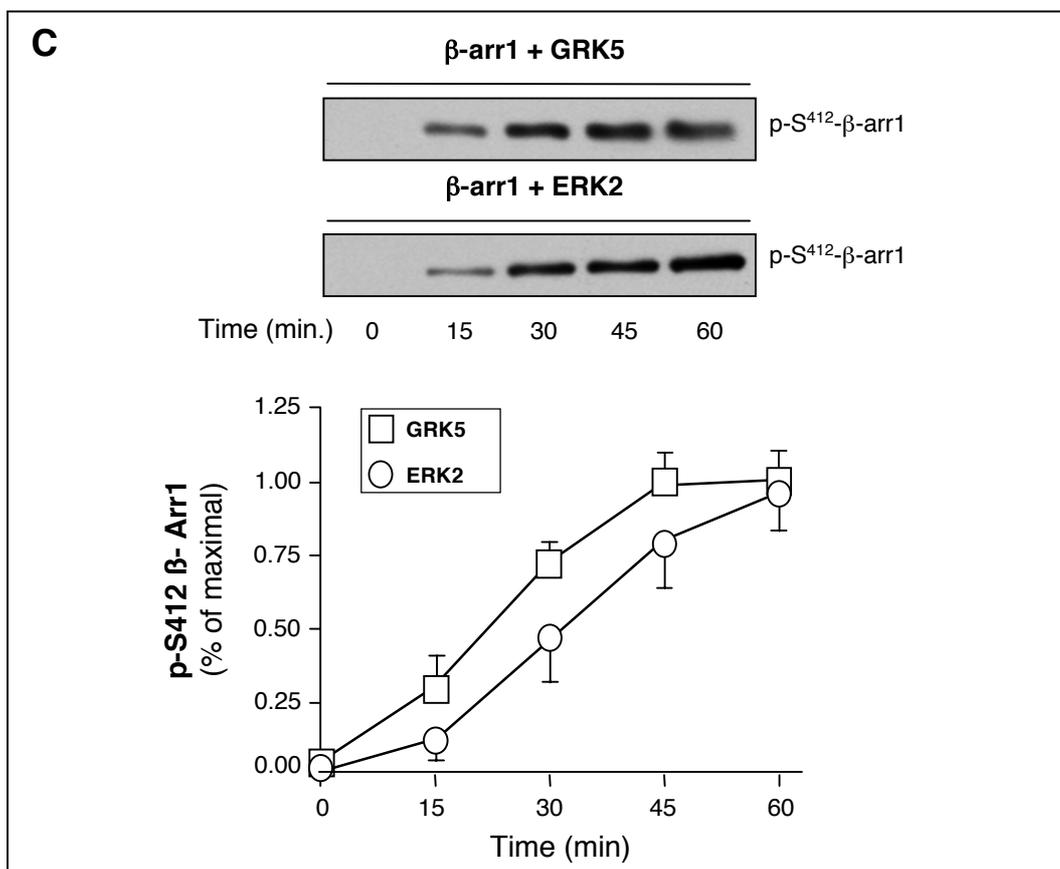
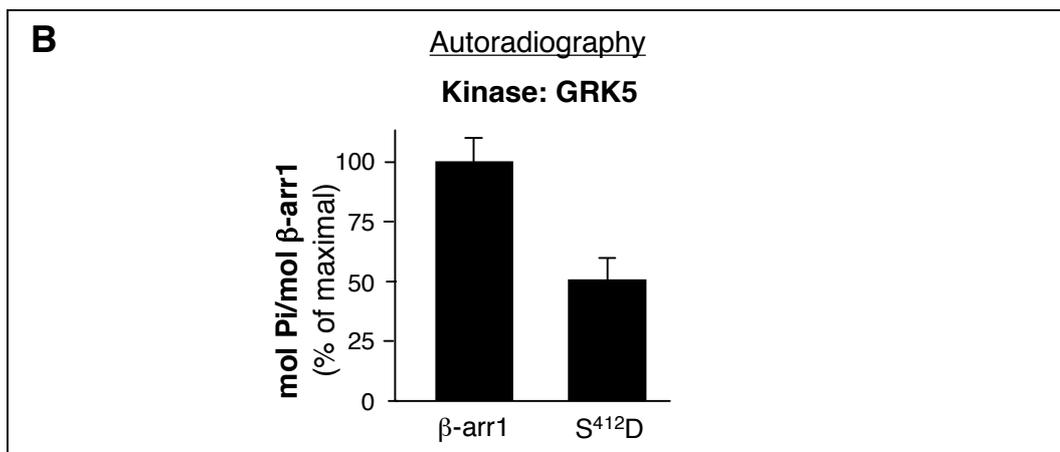
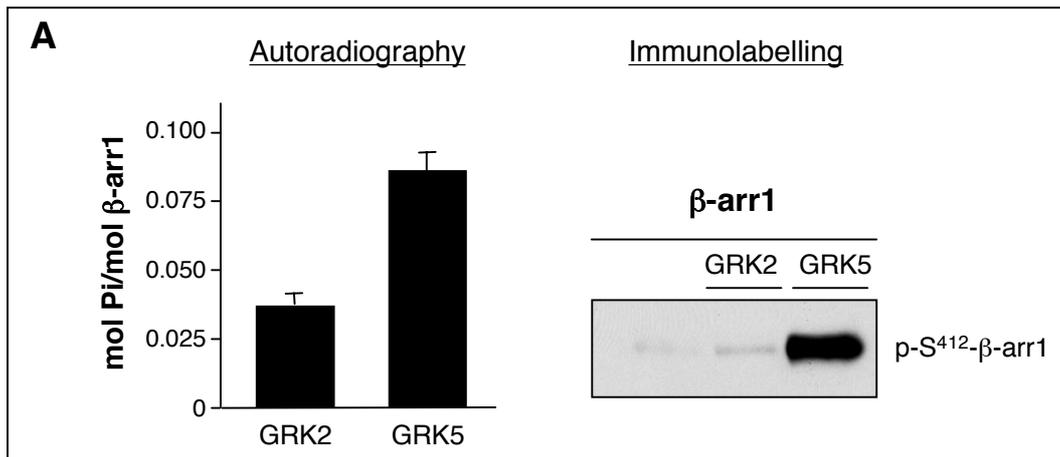


Figure 8

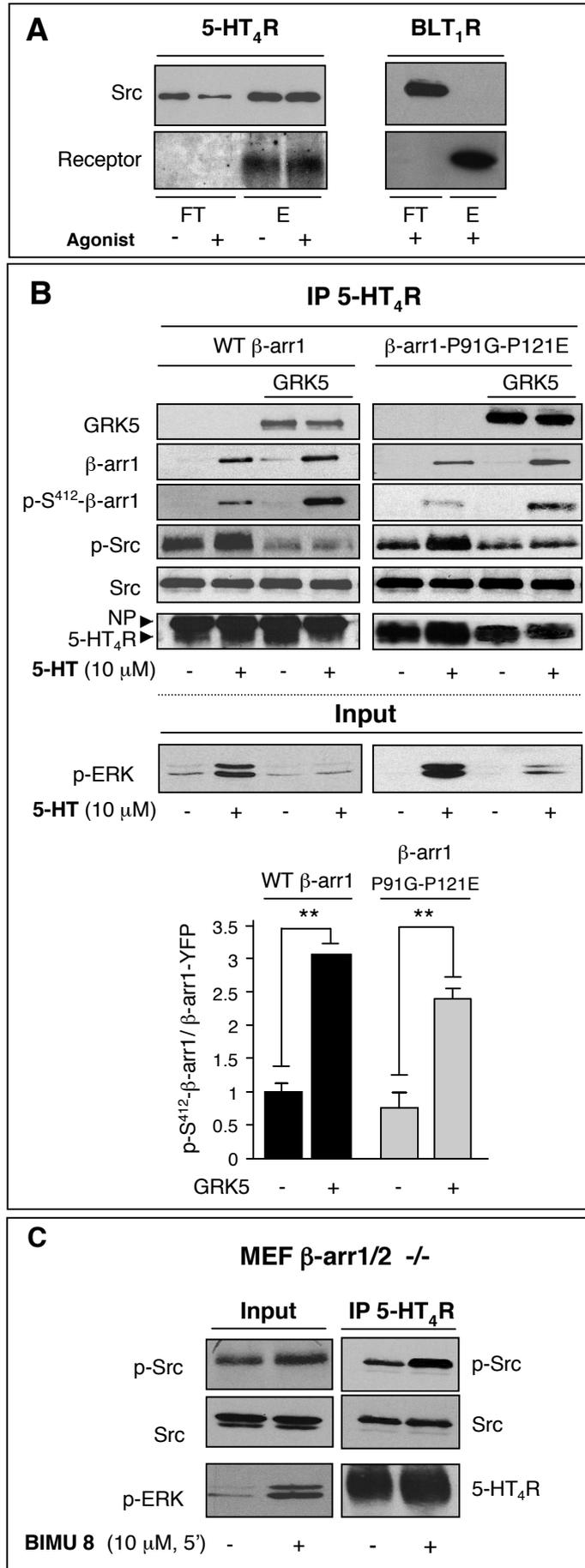


Figure 9

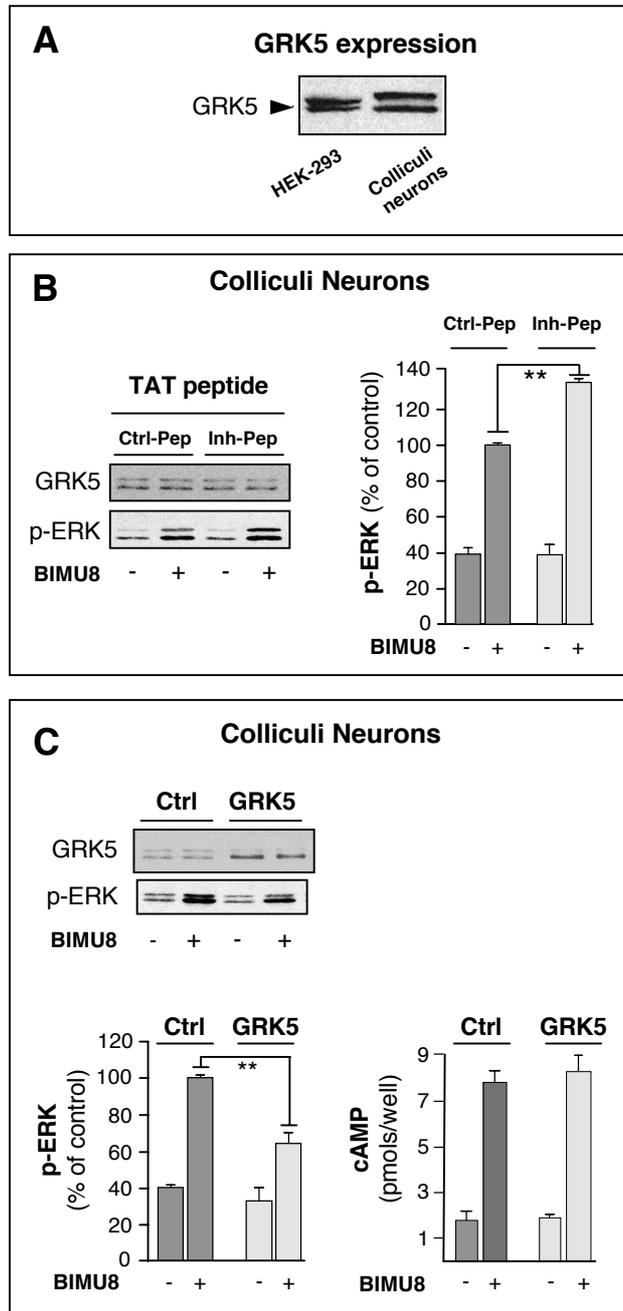


Figure 10

β -ARRESTIN1 PHOSPHORYLATION BY GRK5 REGULATES G PROTEIN-INDEPENDENT 5-HT₄ RECEPTOR SIGNALLING

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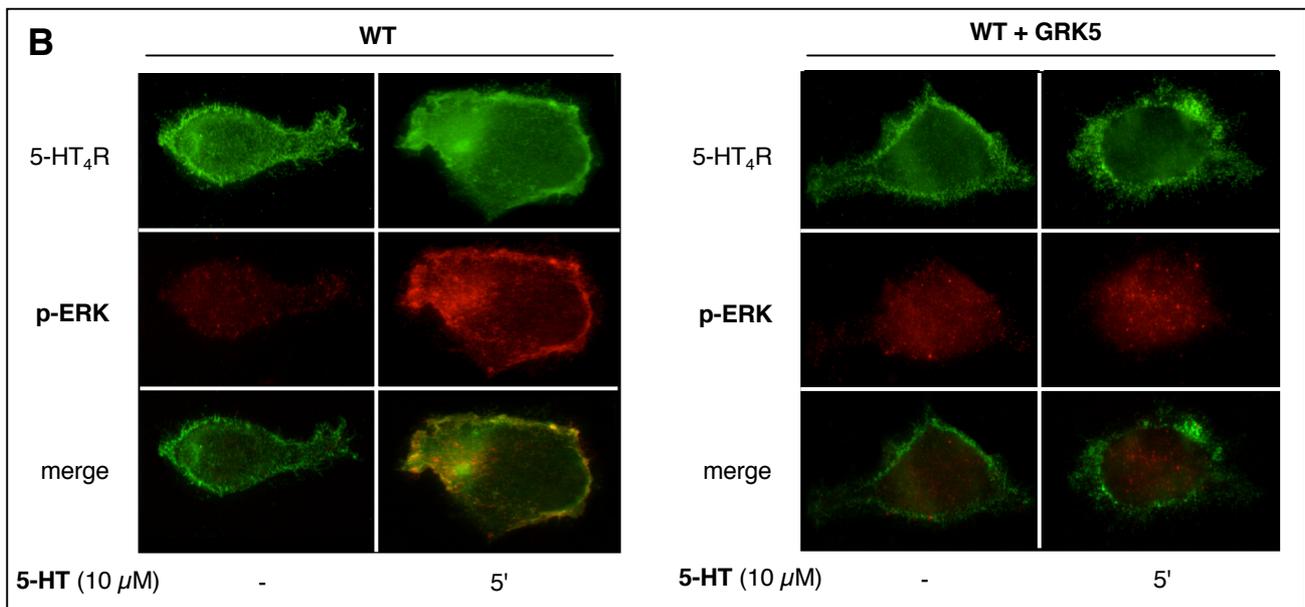
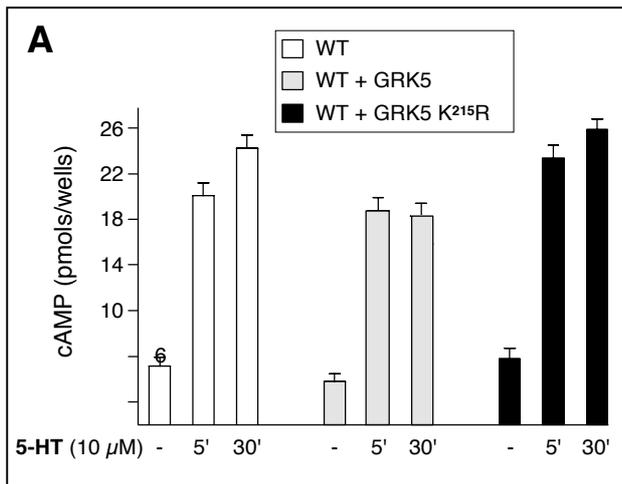
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SUPPLEMENTARY METHODS



Supplementary Figure S1: Effect of GRK5 on 5-HT₄R-mediated cAMP formation and ERK activation

A) HEK-293 cells were either transfected with a plasmid encoding Myc-tagged 5-HT₄R alone or co-transfected with GRK5 or the kinase-dead mutant GRK5 (K²¹⁵R). They were challenged with 10 μ M 5-HT for 5 min. cAMP accumulation was measured as indicated in Material and Methods for each condition and expressed in pmol/well. The data represent the mean \pm S.E.M. of values obtained in three independent experiments performed in triplicate.

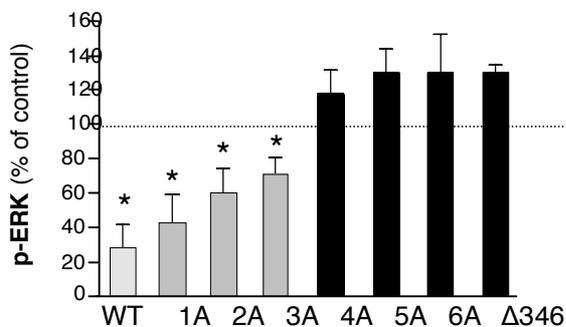
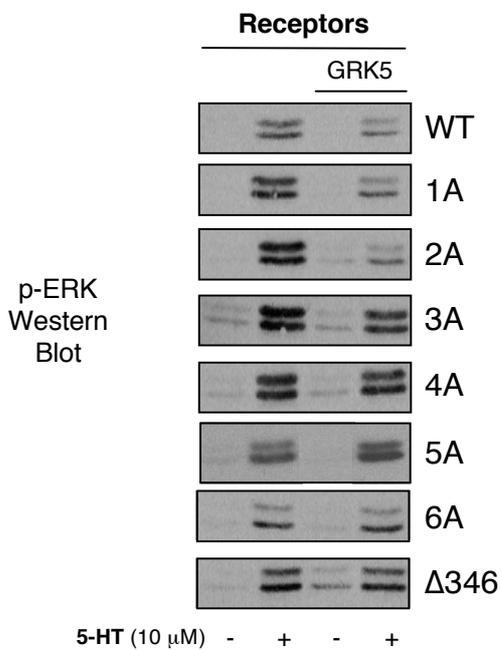
B) HEK-293 cells transfected with Rho-tagged 5-HT₄R were seeded onto cover slips. At 24 h post-transfection, cells were serum starved overnight. They were incubated for 90 min with anti Rho-tag antibody at 4°C before a 5 min-stimulation with 5-HT 10 μ M. After fixation and permeabilization, cells were incubated with primary antibody against p-ERK1/2 and with fluorochrome-labelled secondary antibody. Fluorescence microscopy was then used to visualize the distribution of antibody-labelled receptors (green channel) and the appearance of phosphorylated form of ERK (p-ERK1/2) (red channel). Representative images from several independent experiments are shown.

The upper panels show the distribution of Rho-tagged 5-HT₄R before or after addition of 10 μ M 5-HT to the culture medium at 37 °C in the absence of co-expressed GRK5. The left column shows the distribution of the receptor and the absence of p-ERK1/2 before activation. An increase in phosphorylation state of ERK1/2 at the plasma membrane is visualized after a 5-min treatment with 5-HT. Merged images were magnified to show co-localization of 5-HT₄R with p-ERK1/2 at the plasma membrane after stimulation.

The lower panels show the same experiment in the presence of co-expressed GRK5. Absence in phosphorylated ERK1/2 at the plasma membrane is visualized before and after the 5-min 5-HT treatment. 5-HT₄R does not seem to better internalize in the presence of GRK5.

The lower panels show the same experiment in the presence of co-expressed GRK5. Absence in phosphorylated ERK1/2 at the plasma membrane is visualized before and after the 5-min 5-HT treatment. 5-HT₄R does not seem to better internalize in the presence of GRK5.

346 **358**
 | |
 STTTINGSTHVL WT
 ATTTINGSTHVL 1A
 AATTINGSTHVL 2A
 AAATINGSTHVL 3A
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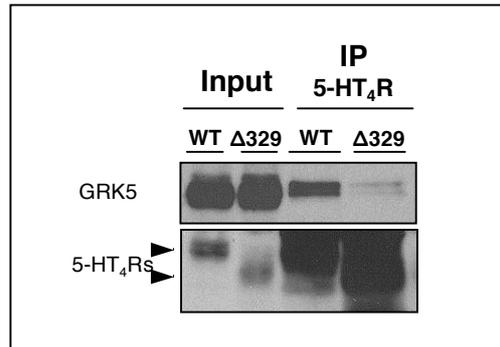


Supplementary Figure S2: Inhibition of 5-HT₄R-mediated ERK activation by GRK5 requires some specific Serine/Threonine residues within the Ser/Thr cluster 347 to 355

In the top is represented the amino acid sequence of the S/T cluster between amino acid 346 to 358. Each serine or threonine is progressively replaced by an alanine. The corresponding progressive mutated receptors are named 1A, 2A, 3A, 4A, 5A and 6A.

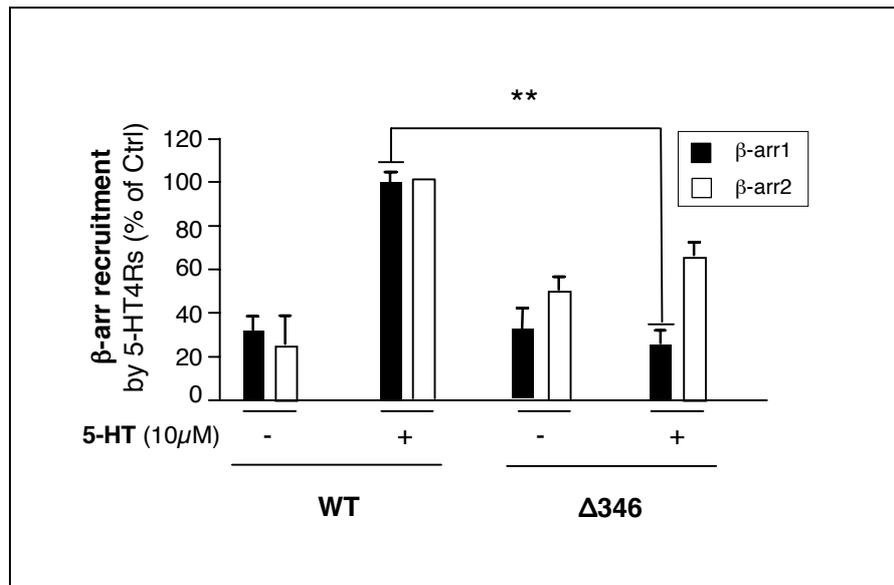
HEK-293 cells expressed the progressive mutated 5-HT₄Rs, in combination with or without GRK5. Identical expression levels of the transfected constructs were controlled by ELISA. Serum starved HEK-293 cells expressing the indicated receptors were treated or not with 10 μM 5 HT for 5 min. Total lysates were analyzed by immunoblotting with antibody to p-ERK1/2.

Quantification of ERK1/2 phosphorylation was performed by densitometry using the ImageJ software. Data are means ± SEM of results obtained in four independent experiments.



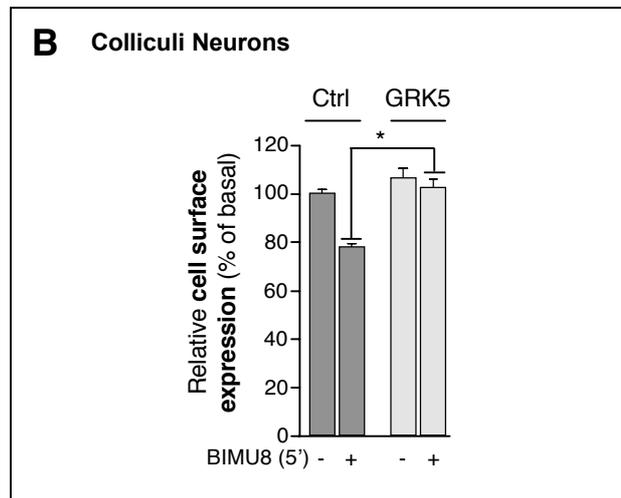
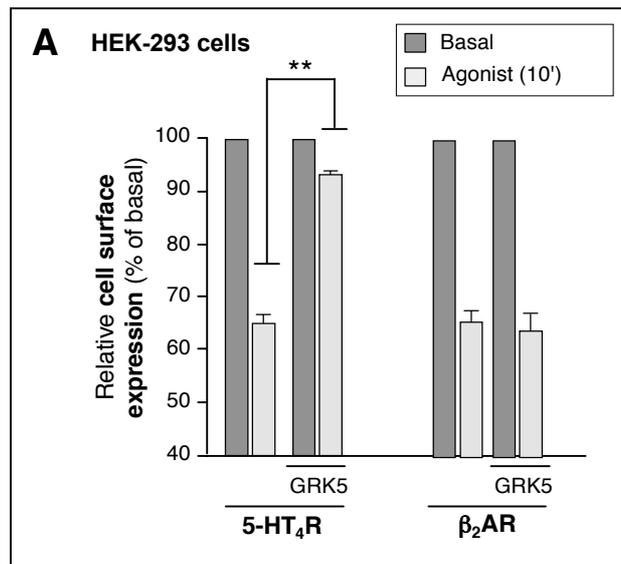
Supplementary Figure S3: Loss of interaction between GRK5 and 5-HT₄R mutants devoid of its C-terminal domain

HEK-293 cells were either transfected with a plasmid encoding the Myc-tagged WT 5-HT₄R or the Myc-tagged mutant totally devoid of its C-terminal domain (Δ329) in the presence GRK5. Receptors were immunoprecipitated using polyclonal-anti-Myc antibody. Co-precipitated GRK5 was analyzed by Western blotting by using the antibody against GRK5. Immunoprecipitated proteins were analyzed by Western blotting using the monoclonal anti-Myc antibody. On the left part, inputs represent 5% of the total protein amount used in immunoprecipitation.



Supplementary Figure S4: Requirement of β -arrestins in the inhibition, by GRK5, of the 5-HT₄R-activated Src/ERK pathway

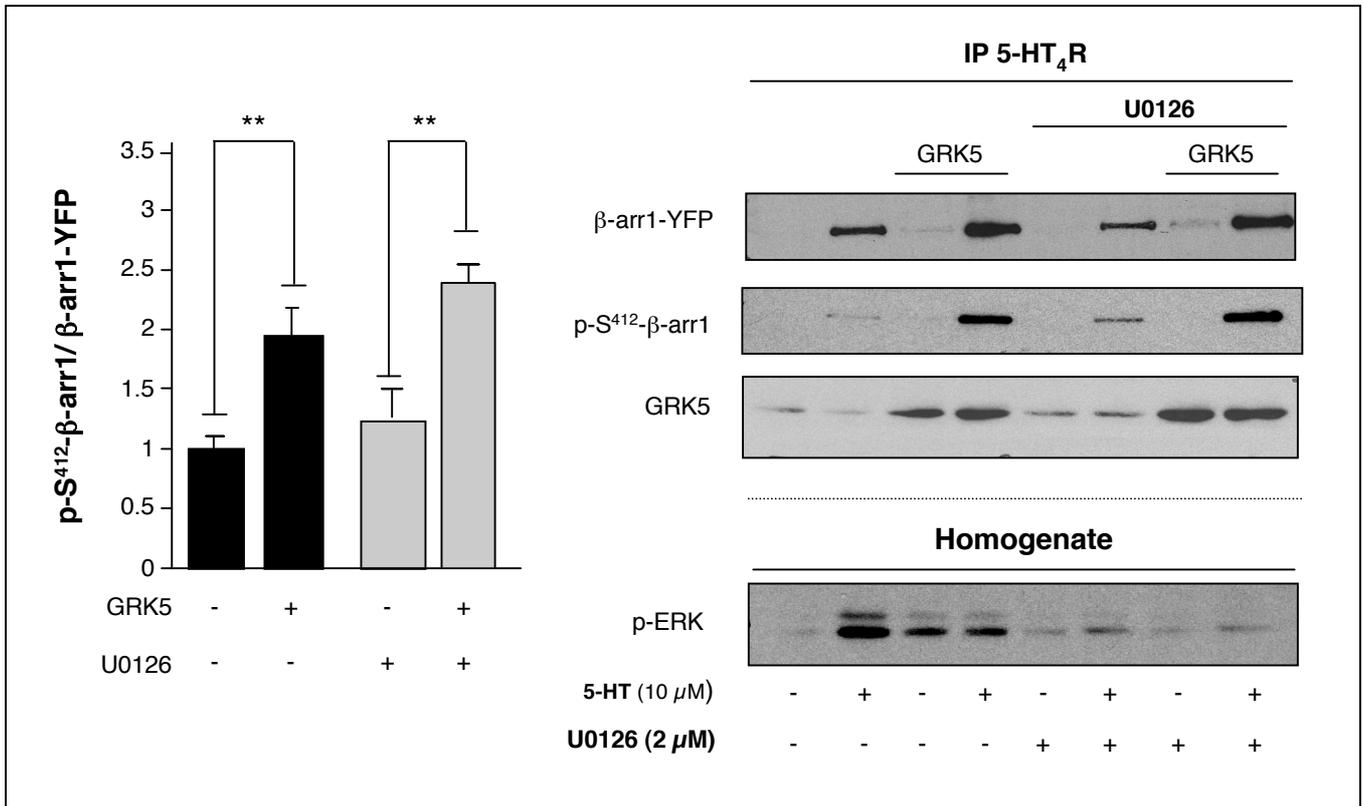
Co-precipitated β -arr1/2 with WT 5-HT₄R or Δ 346 mutant were analyzed by Western blotting (reported in Fig 5A) by using the anti- β -arr A1CT antibody which equally recognizes β -arr1 and 2. Quantifications of β -arr1 and β -arr2 were performed by densitometry using the Image J software. Data are means \pm SEM of results obtained in four independent experiments. (**) $P < 0.01$ versus corresponding values of β -arr1 measured in cells transfected with WT 5-HT₄R.



Supplementary Figure S5: Effect of GRK5, on 5-HT₄R-mediated receptor endocytosis in HEK-293 cells and in neurons

A) HEK-293 cells transiently transfected with Myc-tagged-WT 5-HT₄R or Myc-tagged-β₂-AR in the presence or absence or without GRK5 were pre-treated with 10 μM 5-HT or 10 μM isoproterenol for 10 min at 37°C. Cells were then fixed and the amount of receptors on the cell surface was quantified by ELISA. Results shown are the means ± SEM of four separate experiments performed in triplicate. ** P < 0.01.

B) Colliculi neurons transfected with Myc-5-HT₄R, in combination with GRK5 or empty vector were pre-treated with 10 μM BIMU8 for 5 min at 37°C. Neurons were then fixed and the amount of receptor on the cell surface was quantified by ELISA. Results shown are the means ± SE of four separate experiments performed in triplicate. * P < 0.05.



Supplementary Figure S6: Inhibition of MEK1 does not affect 5-HT₄R-operated ERK signalling inhibited by GRK5

Cells co-transfected with Myc-tagged 5-HT₄R, β-arr-YFP, with or without GRK5 and were pre-treated for 1 h with 2 μM U0126 (a MEK1 inhibitor) before incubation, in the absence or presence of 10 μM 5-HT for 5 min. 5-HT₄R was immunoprecipitated using anti-Myc antibody. Co-precipitated proteins (total β-arr1-YFP, p-S⁴¹²-β-arr1 and GRK5) were analyzed by Western blotting. The histogram represented total β-arr1-YFP, p-S⁴¹²-β-arr1 quantified by densitometry from four western blotting, data represent mean ± SEM. (**) P < 0.01 versus corresponding values measured in cells transfected in absence of GRK5 as control.

SUPPLEMENTARY METHODS

Determination of cAMP production

HEK-293 cells were transfected with the appropriate cDNA and seeded into 24-well plates (50 000 cells/well). 24 h after transfection, cells were exposed to the indicated concentrations of 5-HT, in the presence of 0.1 mM L-ascorbic acid and 0.1 mM phosphodiesterase inhibitor RO-20-1724, at 37°C in 250 µl of HBS (20 mM HEPES, 150 mM NaCl, 4.2 mM KCl, 0.9 mM CaCl₂, 0.5 mM MgCl₂, 0.1% glucose, 0.1% BSA). Cells were then lysed by addition of the same volume of Triton-X100 (0.1%). Quantification of cAMP production was performed by Homogenous Time Resolved Fluorescence™ (HTRF) using the cAMP Dynamic kit (CIS Bio International, Bagnols sur Cèze, France) according to the manufacturer's instructions.

Cell surface ELISA (Enzyme-Linked Immunosorbent Assay)

HEK-293 cells transfected with Myc-tagged-WT 5-HT₄R or Myc-tagged-5-HT₄R-mutants with or without GRK5 construct were grown on polyornithine-coated 96 wells plates in DMEM medium with 10% of foetal calf serum. Twenty-four hours after transfection, cells were stimulated or not with agonist in 37°C serum-starved medium, washed and fixed with 4% paraformaldehyde for 15 min at room temperature and blocked with PBS + 1% foetal calf serum. Cells were then incubated with anti-Myc antibody (A-14: Santa Cruz) at 0.2 µg.ml⁻¹ for one hour in the same buffer. They were then incubated with anti-rabbit/HRP (horseradish peroxidase) conjugate (Amersham Pharmacia Biotech) at 1 µg.ml⁻¹ for 30 min. After extensive washes, chromogenic substrate was added (Supersignal® ELISA femto maximum sensitivity (Pierce)). Chemiluminescence was detected and quantified by a Wallac Victor2 luminescence counter.