



HAL
open science

A Novel in vivo Anti-amnesic Agent, Specially Designed to Express Both Acetylcholinesterase (AChE) Inhibitory, Serotonergic Subtype 4 Receptor (5-HT4R) Agonist and Serotonergic Subtype 6 Receptor (5-HT6R) Inverse Agonist Activities, With a Potential Interest Against Alzheimer's Disease

Bérénice Hatat, Samir Yahiaoui, Cédric Lecoutey, Audrey Davis, Thomas Freret, Michel Boulouard, Sylvie Claeysen, Cédric Lecoutey, Patrick Dallemagne

► **To cite this version:**

Bérénice Hatat, Samir Yahiaoui, Cédric Lecoutey, Audrey Davis, Thomas Freret, et al.. A Novel in vivo Anti-amnesic Agent, Specially Designed to Express Both Acetylcholinesterase (AChE) Inhibitory, Serotonergic Subtype 4 Receptor (5-HT4R) Agonist and Serotonergic Subtype 6 Receptor (5-HT6R) Inverse Agonist Activities, With a Potential Interest Against Alzheimer's Disease. *Frontiers in Aging Neuroscience*, 2019, 11, pp.148. 10.3389/fnagi.2019.00148 . hal-02399864

HAL Id: hal-02399864

<https://hal.science/hal-02399864v1>

Submitted on 19 Feb 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



A Novel *in vivo* Anti-amnesic Agent, Specially Designed to Express Both Acetylcholinesterase (AChE) Inhibitory, Serotonergic Subtype 4 Receptor (5-HT₄R) Agonist and Serotonergic Subtype 6 Receptor (5-HT₆R) Inverse Agonist Activities, With a Potential Interest Against Alzheimer's Disease

OPEN ACCESS

Edited by:

Romy Von Bernhardt,
Pontifical Catholic University of Chile,
Chile

Reviewed by:

Romain Lefebvre,
Ghent University, Belgium
Joachim Neumann,
Institut für Pharmakologie und
Toxikologie, Germany

*Correspondence:

Christophe Rochais
christophe.rochais@unicaen.fr
Patrick Dallemagne
patrick.dallemagne@unicaen.fr

† These authors have contributed
equally to this work

Received: 11 April 2019

Accepted: 05 June 2019

Published: 19 June 2019

Citation:

Hatat B, Yahiaoui S, Lecoutey C,
Davis A, Freret T, Boulouard M,
Claeyens S, Rochais C and
Dallemagne P (2019) A Novel *in vivo*
Anti-amnesic Agent, Specially
Designed to Express Both
Acetylcholinesterase (AChE)
Inhibitory, Serotonergic Subtype 4
Receptor (5-HT₄R) Agonist and
Serotonergic Subtype 6 Receptor
(5-HT₆R) Inverse Agonist Activities,
With a Potential Interest Against
Alzheimer's Disease.
Front. Aging Neurosci. 11:148.
doi: 10.3389/fnagi.2019.00148

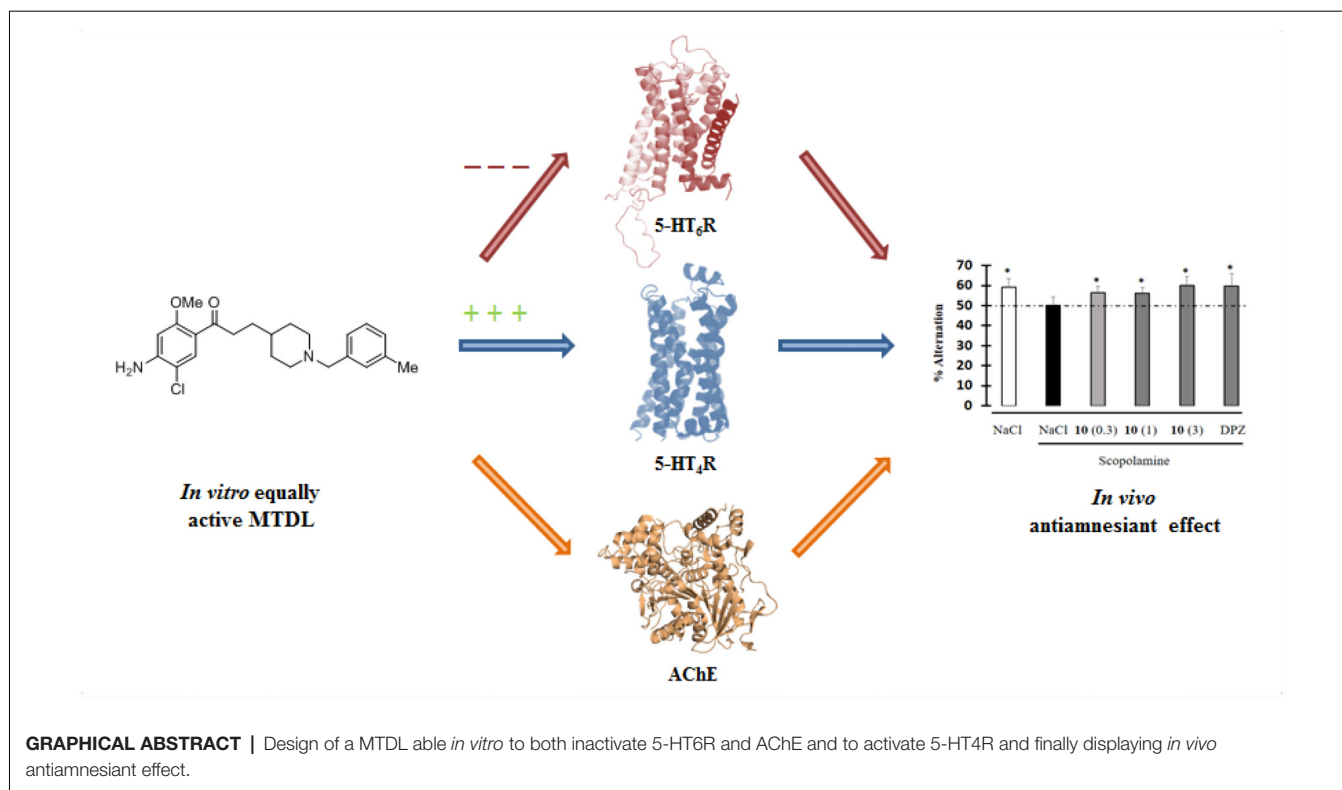
Bérénice Hatat^{1,2†}, Samir Yahiaoui^{1†}, Cédric Lecoutey¹, Audrey Davis¹, Thomas Freret³, Michel Boulouard³, Sylvie Claeyens², Christophe Rochais^{1*} and Patrick Dallemagne^{1*}

¹Normandie Université, UNICAEN, Centre d'Etudes et de Recherche sur le Médicament de Normandie (CERMN), Caen, France, ²IGF, University of Montpellier, CNRS, INSERM, Montpellier, France, ³Normandie Université, UNICAEN, INSERM, U1075, GIP CYCERON, COMETE, Caen, France

This work describes the conception, synthesis, *in vitro* and *in vivo* biological evaluation of novel Multi-Target Directed Ligands (MTDL) able to both activate 5-HT₄ receptors, block 5-HT₆ receptors and inhibit acetylcholinesterase activity (AChE), in order to exert a synergistic anti-amnesic effect, potentially useful in the treatment of Alzheimer's disease (AD). Indeed, both activation of 5-HT₄ and blockage of 5-HT₆ receptors led to an enhanced acetylcholine release, suggesting it could lead to efficiently restoring the cholinergic neurotransmission deficit observed in AD. Furthermore, 5-HT₄ receptor agonists are able to promote the non-amyloidogenic cleavage of the amyloid precursor protein (APP) and to favor the production of the neurotrophic protein sAPP α . Finally, we identified a pleiotropic compound, [1-(4-amino-5-chloro-2-methoxyphenyl)-3-(1-(3-methylbenzyl)piperidin-4-yl)propan-1-one fumaric acid salt (**10**)], which displayed *in vivo* an anti-amnesic effect in a model of scopolamine-induced deficit of working memory at a dose of 0.3 mg/kg.

Keywords: Alzheimer's disease, acetylcholinesterase, 5-HT₄ receptors, 5-HT₆ receptors, MTDL

Abbreviations: AD, Alzheimer's disease; ACh, acetylcholine; AChE, acetylcholinesterase; AChEI, acetylcholinesterase inhibitor; DPZ, donepezil; MTDL, multi-target directed ligands.



INTRODUCTION

The pathogenesis of Alzheimer's Disease (AD) is complex and related to the abnormality and dysfunction of multi-systems. Thus, to be potentially more effective, a treatment might consider more than a single target such as acetylcholinesterase (AChE) the main focus of marketed AD drugs.

Within this framework, the design of some pleiotropic ligands known as Multi-Target Directed Ligands (MTDL; Cavalli et al., 2008) appears as a promising approach to tackle the complex origin of the disease as demonstrated recently for several G Protein-Coupled Receptors (GPCRs) and enzymes (Dolles and Decker, 2017; Dolles et al., 2018). We recently described compound **1** (donecopride), which is currently a novel preclinical drug candidate exhibiting both an *in vitro* dual-binding site AChE inhibitory activity and a serotonergic subtype 4 receptor (5-HT₄R) agonist effect leading to *in vivo* procognitive and anti-amnesic effects in mice (Figure 1; Lecoutey et al., 2014; Rochais et al., 2015). Indeed, 5-HT₄R agonists are able to promote the "non-amyloidogenic" cleavage of the amyloid precursor protein (APP) by α -secretase, inducing the decrease in amyloid- β peptide (A β) production in primary neurons (Lezoualc'h, 2007; Russo et al., 2009), the release of soluble and neuroprotective sAPP α protein (Cho and Hu, 2007), and the *in vivo* improvement of memory in rodents (Lelong et al., 2003; Nirogi et al., 2018).

5-HT₄R is a GPCR. Interestingly, another serotonergic GPCR, the serotonergic subtype 6 receptor (5-HT₆R) appears as a valuable target to treat cognitive impairments in the field

of neurodegenerative disorders, notably AD (Karila et al., 2015). In fact, its blockade confers to 5-HT₆R antagonists procognitive effects (Benhamú et al., 2014). Among these 5-HT₆R antagonists, **2** (idalopirdine) was studied in phase 3 of clinical trials (Wilkinson et al., 2014), and **3** (landipirdine), a dual antagonist of the 5-HT₆ and 5-HT_{2A} receptors is currently under investigation in the field of Parkinson Disease (Figure 1; Ellis and Fell, 2017).

The procognitive activity of 5-HT₆R antagonists is probably mediated by modulation of neurotransmitters' release. Indeed, 5-HT₄R activation enhances the liberation of acetylcholine (Kilbinger and Wolf, 1992; Consolo et al., 1994), dopamine (Steward et al., 1996; Lucas et al., 2001) and serotonin (Ge and Barnes, 1996), while blockade of 5-HT₆R enhances the liberation of acetylcholine (Shirazi-Southall et al., 2002; Riemer et al., 2003; Hirst et al., 2006; Marcos et al., 2006; Zhang et al., 2007) and glutamate (Dawson et al., 2000, 2001). Consequently, 5-HT₆R antagonists can improve cognition since they limit the activation of the mTOR pathway (de Bruin and Kruse, 2015). The acute administration of 5-HT₄R agonists or 5-HT₆R antagonists leads to procognitive effects. However, recently we demonstrated that chronic 5-HT₄R activation or chronic 5-HT₆R blockade, also improved memory performances in object recognition test in mice (Quiedeville et al., 2015). These ligands are active at lower doses than those needed for an acute effect and furthermore, seem to be devoid of side effects in these conditions. We thus considered that co-modulation of these two receptors could represent a valuable strategy against memory deficits in AD (Claeyssen et al., 2015; Lalut et al., 2017).

Therefore, we recently reported the synthesis and the *in vivo* procognitive effect displayed by the dual compound **4** with *in vitro* 5-HT₄R agonist and 5-HT₆R antagonist effects (Figure 2; Yahiaoui et al., 2016). Based on the evidence that 5-HT₄R, 5-HT₆R and AChE are all valuable therapeutic targets in AD treatment, the present work aimed at designing, starting from our dual compound **4** and the benzyl analog of donecopride **5a** (Rochais et al., 2015), novel MTDLs associating 5-HT₄R agonist, 5-HT₆R antagonist and AChE inhibitory balanced activities (Figure 2).

EXPERIMENTAL SECTION

Chemistry

General Materials and Methods

All chemical reagents and solvents were purchased from commercial sources and used without further purification. Melting points were determined on a STUART SMP50 melting point apparatus. ¹H, ¹³C and ¹⁹F NMR spectra were recorded on a BRUKER AVANCE III 400MHz with chemical shifts expressed in parts per million (in chloroform-*d*, methanol-*d*₄ or DMSO-*d*₆) downfield from TMS as an internal standard

and coupling in Hertz. IR spectra were recorded on a Perkin-Elmer BX FT-IR apparatus using KBr pellets. High resolution mass spectra (HRMS) were obtained by electrospray on a BrukermaXis. The purities of all tested compounds were analyzed by LC-MS, with the purity all being higher than 95%. Analyses were performed using a Waters Alliance 2695 as separating module (column XBridge C18 2.5 μM/4.6 × 50 mM) using the following gradients: A (95%)/B (5%) to A (5%)/B (95%) in 4.00 min. This ratio was held during 1.50 min before return to initial conditions in 0.50 min. Initial conditions were then maintained for 2.00 min (A = H₂O, B = CH₃CN; each containing HCOOH: 0.1%). MS were obtained on a SQ detector by positive ESI.

Procedures for the Deprotection and *N*-alkylation of *tert*-butyl 4-[3-(4-amino-5-chloro-2-methoxyphenyl)-3-oxo-propyl]piperidine-1-carboxylate (**8**)

Procedure A: to a solution of compound **8** in DCM (5 mL) was added TFA (1 mL) dropwise. The reaction mixture was stirred at room temperature for 1 h and then concentrated under reduced pressure. Evaporation of the solvent provided a light-yellow oil, which was thereafter dissolved in 1,4-dioxane (30 mL). To the resulting solution, 20 equivalent of K₂CO₃

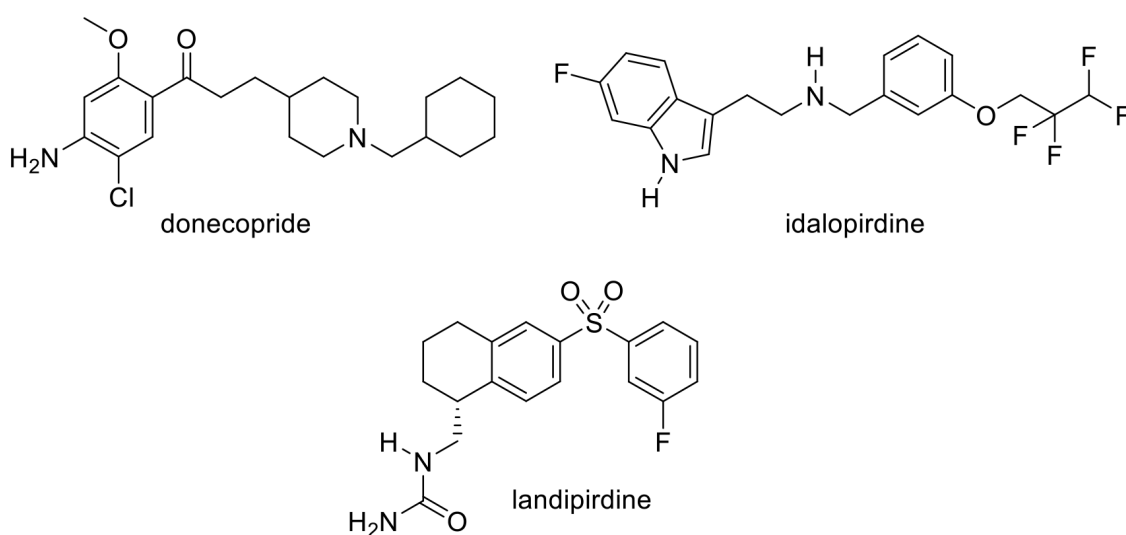


FIGURE 1 | Structure of donecopride, idalopirdine and landipirdine.

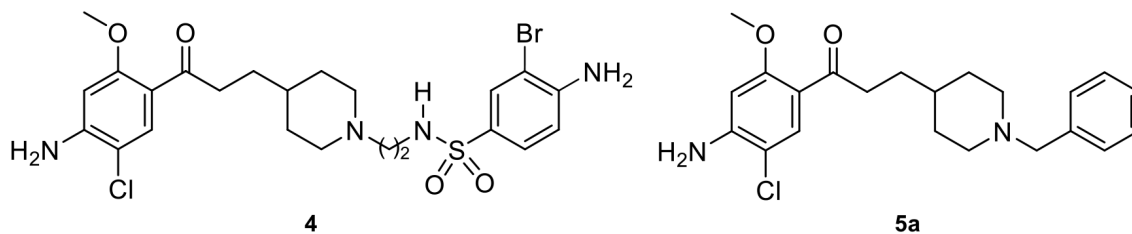


FIGURE 2 | Structure of compounds **4** and **5a**.

were added and thereafter 1.2 equivalent of commercially available benzylbromide derivative was added. The reaction mixture was then stirred at reflux until the full consumption of the starting material. The mixture was then concentrated *in vacuo*, diluted with water and extracted twice with EtOAc. The combined organic phases were washed with brine, dried over MgSO₄, filtrated and concentrated under pressure. The crude product was thereafter purified by silica column flash chromatography using the appropriate eluting system.

Procedure B: to a solution of compound **8** in DCM (5 mL/mmol) was added TFA (1 mL/mmol) dropwise. The reaction mixture was stirred at room temperature for 15 min and then concentrated under reduced pressure. Evaporation of the solvent provided a light-yellow oil, which was thereafter dissolved in DMF (10 mL/mmol). To the resulting solution, 10 equivalent of K₂CO₃ were added and thereafter 1.2 equivalent of commercially available benzylbromide derivative was added. The reaction mixture was then stirred at 110°C until the full consumption of the starting material. The mixture was then concentrated *in vacuo*, diluted with EtOAc and washed twice with brine. The organic layer was dried over MgSO₄, filtrated and concentrated under pressure. The crude product was thereafter purified by silica column flash chromatography using the appropriate eluting system.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-benzyl)piperidin-4-yl)propan-1-one (**5a**; Rochais et al., 2015)

Following procedure A. Pale yellow oil (23%); ¹H NMR (400 MHz, CDCl₃) δ 7.71 (s, 1H), 7.19 (m, 5H), 6.18 (s, 1H), 4.39 (s, 2H), 3.76 (s, 3H), 3.45 (s, 2H), 2.81 (m, 4H), 1.90 (*br t*, *J* = 10.2 Hz, 2H), 1.61 (*br d*, *J* = 9.2 Hz, 2H), 1.52 (*q*, *J* = 6.9 Hz, 2H), 1.22 (m, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 199.2, 159.5, 147.7, 137.7, 132.3, 129.5 (2C), 128.2 (2C), 127.1, 118.9, 111.3, 97.5, 63.3, 55.6, 53.7 (2C), 40.8, 35.4, 31.9 (2C), 31.4; HRMS (*m/z*) calcd for C₂₂H₂₈ClN₂O₂ [*M* + *H*]⁺ 387.183382, found 387.183120.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-chlorobenzyl)piperidin-4-yl)propan-1-one (**5b**)

Following procedure B. Pale yellow solid (33%); mp 125.4°C; ¹H NMR (400 MHz, CDCl₃) δ 7.78 (s, 1H), 7.48 (dd, *J* = 7.7, 1.6 Hz, 1H), 7.32 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.22 (dt, *J* = 7.5, 1.4 Hz, 1H), 7.16 (dt, *J* = 7.7, 1.8 Hz, 1H), 6.25 (s, 1H), 4.47 (s, 2H), 3.83 (s, 3H), 3.59 (s, 2H), 2.92–2.88 (m, 4H), 2.08–2.03 (m, 2H), 1.69–1.67 (m, 2H), 1.62–1.57 (m, 2H), 1.30–1.23 (m, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 199.3, 159.6, 147.8, 136.5, 134.3, 132.3, 130.8, 129.4, 128.0, 126.7, 119.1, 111.4, 97.7, 59.7, 55.7, 54.1 (2C), 41.1, 35.7, 32.5 (2C), 31.5; MS (*m/z*) [*M* + *H*]⁺ 421.61–423.63; HRMS (*m/z*) calcd for C₂₂H₂₇Cl₂N₂O₂ [*M* + *H*]⁺ 421.1450, found 421.1462.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-bromobenzyl)piperidin-4-yl)propan-1-one (**5c**)

Following procedure B. Pale brown solid (43%); mp 118.1°C; ¹H NMR (400 MHz, CDCl₃) δ 7.78 (s, 1H), 7.51 (dd, *J* = 7.9,

1.1 Hz, 1H), 7.48 (dd, *J* = 7.3, 1.5 Hz, 1H), 7.26 (dt, *J* = 7.5, 1.1 Hz, 1H), 7.08 (dt, *J* = 7.8, 1.7 Hz, 1H), 6.25 (s, 1H), 4.49 (s, 2H), 3.82 (s, 3H), 3.56 (s, 2H), 2.92–2.88 (m, 4H), 2.09–2.04 (m, 2H), 1.69–1.67 (m, 2H), 1.62–1.57 (m, 2H), 1.28–1.25 (m, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 199.3, 159.6, 147.8, 138.2, 132.7, 132.3, 130.8, 128.3, 127.3, 124.7, 119.0, 111.3, 97.6, 62.2, 55.7, 54.1 (2C), 41.1, 35.7, 32.5 (2C), 31.4; MS (*m/z*) [*M* + *H*]⁺ 465.59–467.59–469.59; HRMS (*m/z*) calcd for C₂₂H₂₇BrClN₂O₂ [*M* + *H*]⁺ 465.0944, found 465.0945.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-fluorobenzyl)piperidin-4-yl)propan-1-one (**5d**)

Following procedure B. Pale yellow solid (56%); mp 115°C; ¹H NMR (399.75 MHz, CDCl₃) δ 7.77 (s, 1H), 7.36 (td, *J* = 7.6, 1.8 Hz, 1H), 7.22 (m, 1H), 7.10 (td, *J* = 7.6, 1.2 Hz, 1H), 7.01 (m, 1H), 6.24 (s, 1H), 4.47 (s, 2H), 3.82 (s, 3H), 3.56 (s, 2H), 2.88 (m, 4H), 2.00 (*br t*, *J* = 10.7 Hz, 2H), 1.67 (*br d*, *J* = 9.3 Hz, 2H), 1.58 (m, 2H), 1.27 (m, 3H); ¹³C NMR (100.53 MHz, CDCl₃) δ 199.1, 161.2 (d, *J* = 244.5 Hz), 159.5, 147.7, 132.2, 131.7 (d, *J* = 4.6 Hz), 128.6 (d, *J* = 8.0 Hz), 125.0 (d, *J* = 14.7 Hz), 123.8 (d, *J* = 3.4 Hz), 118.9, 115.2 (d, *J* = 22.5 Hz), 111.2, 97.5, 63.3, 55.6 (2C), 53.6 (2C), 40.9, 35.5, 32.3, 31.3, 29.7; ¹⁹F NMR (376.10 MHz, CDCl₃) δ -117.75 (s); MS (*m/z*) [*M* + *H*]⁺ 405.56–407.55; HRMS (*m/z*) calcd for C₂₂H₂₇ClFN₂O₂ [*M* + *H*]⁺ 405.1745, found 405.1747.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-iodobenzyl)piperidin-4-yl)propan-1-one (**5e**)

Following procedure B. Pale yellow solid (44%); mp 106°C; ¹H NMR (400 MHz, CDCl₃) δ 7.81 (dd, *J* = 7.8, 1.1 Hz, 1H), 7.78 (s, 1H), 7.44 (d, *J* = 7.4 Hz, 1H), 7.30 (dt, *J* = 7.4, 1.1 Hz, 1H), 6.92 (dt, *J* = 7.6, 1.7 Hz, 1H), 6.25 (s, 1H), 4.48 (s, 2H), 3.83 (s, 3H), 3.50 (s, 2H), 2.92–2.88 (m, 4H), 2.11–2.06 (m, 2H), 1.69–1.67 (m, 2H), 1.62–1.57 (m, 2H), 1.31–1.25 (m, 3H) ¹³C NMR (100 MHz, CDCl₃) δ 199.2, 159.6, 147.8, 141.0, 139.4, 132.3, 130.4, 128.7, 128.1, 119.0, 111.3, 100.7, 97.7, 67.0, 55.8, 54.0 (2C), 41.1, 35.7, 32.4 (2C), 31.4; MS (*m/z*) [*M* + *H*]⁺ 513.59–515.61; HRMS (*m/z*) calcd for C₂₂H₂₇ClIN₂O₂ [*M* + *H*]⁺ 513.0806, found 513.0824.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-methylbenzyl)piperidin-4-yl)propan-1-one (**5f**)

Following procedure B. Yellow-pale solid (45%); mp 119°C; ¹H NMR (400 MHz, CDCl₃) δ 7.78 (s, 1H), 7.37 (m, 1H), 7.13 (m, 1H), 6.25 (s, 1H), 4.44 (*br s*, 2H), 3.84 (s, 3H), 3.41 (s, 2H), 2.91–2.83 (m, 4H), 2.35 (s, 3H), 1.95 (*br t*, *J* = 11.6 Hz, 2H), 1.67–1.53 (m, 4H), 1.28–1.18 (m, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 199.3, 159.5, 137.4, 137.1, 132.2, 130.1, 129.7, 126.8, 125.4, 119.0, 111.2, 97.6, 61.1, 55.6, 54.1, 41.0, 35.8, 32.5, 31.4, 19.3; MS (*m/z*) [*M* + *H*]⁺ 401.65–403.64; HRMS (*m/z*) calcd for C₂₃H₃₀ClN₂O₂ [*M* + *H*]⁺ 401.1996, found 401.1994.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-benzyloxybenzyl)piperidin-4-yl)propan-1-one (**5g**)

Following procedure B. Yellow oil (16%); ¹H NMR (400 MHz, CDCl₃) δ 7.78 (s, 1H), 7.46–7.44 (m, 2H), 7.40–7.37 (m, 3H),

7.32 (m, 1H), 7.21 (dt, $J = 7.9, 1.6$ Hz, 1H), 6.96–6.91 (m, 2H), 6.24 (s, 1H), 5.08 (s, 2H), 4.47 (s, 2H), 3.82 (s, 3H), 3.62 (s, 2H), 2.95–2.87 (m, 4H), 2.05–2.00 (m, 2H), 1.68–1.66 (m, 2H), 1.61–1.56 (m, 2H), 1.31–1.26 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.3, 159.6, 157.1, 147.8, 137.5, 132.3, 130.9, 128.6 (2C), 128.0, 127.8, 127.3 (3C), 120.7, 119.1, 112.0, 111.3, 97.7, 70.2, 56.7, 55.7, 54.0 (2C), 41.1, 35.7, 32.5 (2C), 31.5; MS (m/z) [$\text{M} + \text{H}$] $^+$ 493.65–495.66; HRMS (m/z) calcd for $\text{C}_{29}\text{H}_{34}\text{ClN}_2\text{O}_3$ [$\text{M} + \text{H}$] $^+$ 493.2258, found 493.2254.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-hydroxybenzyl)piperidin-4-yl)propan-1-one (5h)

Following procedure B. Yellow-brown oil (12%); ^1H NMR (400 MHz, CDCl_3) δ 7.78 (s, 1H), 7.15 (dt, $J = 8.0, 1.3$ Hz, 1H), 6.95 (d, $J = 7.3$ Hz, 1H), 6.80 (d, $J = 8.1$ Hz, 1H), 6.76 (dt, $J = 7.4, 1.1$ Hz, 1H), 6.25 (s, 1H), 4.45 (s, 2H), 3.84 (s, 3H), 3.68 (s, 2H), 3.00–2.97 (m, 2H), 2.90 (t, $J = 7.8$ Hz, 2H), 2.10–2.07 (m, 2H), 1.76–1.73 (m, 2H), 1.63–1.58 (m, 2H), 1.33–1.25 (m, 4H); ^{13}C NMR (100 MHz, CDCl_3) δ 198.9, 159.6, 158.3, 147.8, 132.4, 128.7, 128.6, 122.0, 119.1, 119.0, 116.2, 109.9, 97.7, 61.8, 55.8, 53.4 (2C), 40.8, 35.3, 32.2 (2C), 31.1; MS (m/z) [$\text{M} + \text{H}$] $^+$ 403.60–405.58; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{28}\text{ClN}_2\text{O}_3$ [$\text{M} + \text{H}$] $^+$ 403.1788, found 403.1788.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(3-bromobenzyl)piperidin-4-yl)propan-1-one (5i)

Following procedure A. Yellow-pale oil (34%); ^1H NMR (400 MHz, CDCl_3) δ 7.78 (s, 1H), 7.47 (*br t*, $J = 1.6$ Hz, 1H), 7.36 (*br dt*, $J = 1.6, 7.6$ Hz, 1H), 7.23 (*br dt*, $J = 1.6, 7.6$ Hz, 1H), 7.16 (t, $J = 7.6$ Hz, 1H), 6.25 (s, 1H), 4.44 (s, 2H), 3.84 (s, 3H), 3.44 (s, 2H), 2.89 (*br t*, $J = 7.8$ Hz, 2H), 2.84 (*br d*, $J = 10.8$ Hz, 2H), 1.93 (*br t*, $J = 11.0$ Hz, 2H), 1.74–1.64 (m, 2H), 1.59 (*br q*, $J = 6.9$ Hz, 2H), 1.34–1.19 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.2, 159.6, 147.8, 141.3, 132.4, 132.1, 130.1, 129.8, 127.9, 122.5, 119.2, 111.4, 97.7, 63.0, 55.8, 54.0, 41.0, 35.7, 32.4, 31.4; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{27}\text{BrClN}_2\text{O}_2$ [$\text{M} + \text{H}$] $^+$ 465.093894, found 465.093548.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(3-fluorobenzyl)piperidin-4-yl)propan-1-one (5j)

Following procedure B. White solid (48%); mp 95°C; ^1H NMR (400 MHz, CDCl_3) δ 7.78 (s, 1H), 7.25 (m, 1H), 7.06 (m, 2H), 6.92 (m, 1H), 6.25 (s, 1H), 4.44 (s, 2H), 3.84 (s, 3H), 3.46 (s, 2H), 2.87 (m, 4H), 1.94 (*br t*, $J = 11.1$ Hz, 2H), 1.66 (m, 2H), 1.58 (m, 2H), 1.27 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.1, 162.9 (d, $J = 243.7$ Hz), 147.7, 141.5 (d, $J = 6.7$ Hz), 132.2, 129.5 (d, $J = 8.1$ Hz), 124.6 (d, $J = 2.9$ Hz), 118.9, 115.8 (d, $J = 21.1$ Hz), 113.7 (d, $J = 20.8$ Hz), 111.3, 97.6, 62.9, 55.6, 53.9, 40.9, 35.5, 32.3, 31.3; ^{19}F NMR (376.1 MHz, CDCl_3) δ -113.97 (s); MS (m/z) [$\text{M} + \text{H}$] $^+$ 405.58–407.57; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{27}\text{ClFN}_2\text{O}_2$ [$\text{M} + \text{H}$] $^+$ 405.1745, found 405.1745.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(3-methylbenzyl)piperidin-4-yl)propan-1-one (5k)

Following procedure A. Yellow-pale oil (41%); ^1H NMR (400 MHz, CDCl_3) δ 7.78 (s, 1H), 7.19 (t, $J = 7.4$ Hz, 1H), 7.13 (*br s*, 1H), 7.09 (*br d*, $J = 7.6$ Hz, 1H), 7.06 (*br d*, $J = 7.2$ Hz, 1H), 6.25 (s, 1H), 4.44 (s, 2H), 3.83 (s, 3H), 3.45 (s, 2H), 2.96–2.80

(m, 4H), 2.34 (s, 3H), 1.93 (*br t*, $J = 10.4$ Hz, 2H), 1.73–1.52 (m, 4H), 1.36–1.17 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.3, 159.6, 147.8, 138.3, 137.9, 132.4, 130.2, 128.1, 127.8, 126.6, 119.2, 111.4, 97.7, 63.7, 55.8, 54.0, 41.0, 35.7, 32.3, 31.5, 21.5; HRMS (m/z) calcd for $\text{C}_{23}\text{H}_{30}\text{ClN}_2\text{O}_2$ [$\text{M} + \text{H}$] $^+$ 401.1994, found 401.1992.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(3-methoxybenzyl)piperidin-4-yl)propan-1-one (5l)

Following procedure A. Colorless oil (27%); ^1H NMR (400 MHz, CDCl_3) δ 7.78 (s, 1H), 7.22 (t, $J = 8.0$ Hz, 1H), 6.93–6.85 (m, 2H), 6.79 (ddd, $J = 0.8, 2.4, 8.0$ Hz, 1H), 6.25 (s, 1H), 4.44 (s, 2H), 3.83 (s, 3H), 3.81 (s, 3H), 3.47 (s, 2H), 2.95–2.81 (m, 4H), 1.94 (*br t*, $J = 10.2$ Hz, 2H), 1.75–1.52 (m, 4H), 1.36–1.17 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.3, 159.7, 159.6, 147.7, 140.2, 132.4, 129.2, 121.8, 119.2, 114.9, 112.5, 111.4, 97.7, 63.5, 55.8, 55.4, 54.0, 41.0, 35.7, 32.4, 31.5; HRMS (m/z) calcd for $\text{C}_{23}\text{H}_{30}\text{ClN}_2\text{O}_3$ [$\text{M} + \text{H}$] $^+$ 417.193947, found 417.193907.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(3-aminobenzyl)piperidin-4-yl)propan-1-one (5m)

Following procedure A. Hygroscopic solid (36%); ^1H NMR (400 MHz, CD_3OD) δ 7.66 (s, 1H), 7.17 (t, $J = 7.8$ Hz, 1H), 6.87–6.70 (m, 3H), 6.69 (s, 2H), 6.44 (s, 1H), 4.11 (s, 2H), 3.85 (s, 3H), 3.43 (*br d*, $J = 12.4$ Hz, 2H), 3.05–2.76 (m, 4H), 1.95 (*br d*, $J = 14.0$ Hz, 2H), 1.73–1.28 (m, 5H).

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(3-nitrobenzyl)piperidin-4-yl)propan-1-one (5n)

Following procedure A. Yellow oil (80%); ^1H NMR (400 MHz, CDCl_3) δ 8.18 (*br t*, $J = 1.6$ Hz, 1H), 8.09 (*br d*, $J = 8.0$ Hz, 1H), 7.78 (s, 1H), 7.66 (*br d*, $J = 7.6$ Hz, 1H), 7.47 (t, $J = 8.0$ Hz, 1H), 6.26 (s, 1H), 4.45 (s, 2H), 3.84 (s, 3H), 3.55 (s, 2H), 2.90 (*br t*, $J = 7.8$ Hz, 2H), 2.83 (*br d*, $J = 11.6$ Hz, 2H), 1.99 (*br t*, $J = 10.2$ Hz, 2H), 1.78–1.64 (m, 2H), 1.60 (*br q*, $J = 6.8$ Hz, 2H), 1.35–1.19 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.2, 159.6, 148.4, 147.8, 141.4, 135.2, 132.4, 129.2, 123.9, 122.2, 119.1, 114.4, 97.7, 62.6, 55.8, 54.1, 41.0, 35.6, 32.4, 31.4; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{27}\text{ClN}_3\text{O}_4$ [$\text{M} + \text{H}$] $^+$ 432.168460, found 432.168262.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(4-fluorobenzyl)piperidin-4-yl)propan-1-one (5o)

Following procedure B. Yellow pale solid (32%); mp 128°C; ^1H NMR (400 MHz, CDCl_3) δ 7.78 (s, 1H), 7.26 (m, 2H), 7.06 (m, 2H), 6.98 (m, 2H), 6.25 (s, 1H), 4.48 (s, 2H), 3.83 (s, 3H), 3.43 (s, 2H), 2.86 (m, 4H), 1.91 (*br t*, $J = 10.6$ Hz, 2H), 1.66 (*br d*, $J = 8.8$ Hz, 2H), 1.58 (m, 2H), 1.25 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.1, 161.9 (d, $J = 243.0$ Hz), 159.5, 147.7, 134.3 (d, $J = 3.0$ Hz), 132.2, 130.7 (d, $J = 7.9$ Hz, 2C), 118.9, 114.9 (d, $J = 21.1$ Hz, 2C), 111.2, 97.5, 62.7, 55.6, 53.8, 40.9, 35.6, 32.3, 31.3; ^{19}F NMR (376.1 MHz, CDCl_3) δ -113.97 (s); MS (m/z) [$\text{M} + \text{H}$] $^+$ 405.62–407.62; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{27}\text{ClFN}_2\text{O}_2$ [$\text{M} + \text{H}$] $^+$ 405.1745, found 405.1740.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(4-hydroxybenzyl)piperidin-4-yl)propan-1-one (5p)

Following procedure B. Yellow oil (13%); ^1H NMR (400 MHz, CD_3OD) δ 7.64 (s, 1H), 7.14–7.12 (m, 2H), 6.74 (m, 2H), 6.43

(s, 1H), 3.84 (s, 3H), 3.44 (s, 2H), 2.93–2.87 (m, 4H), 2.04–1.99 (m, 2H), 1.72–1.70 (m, 2H), 1.57–1.51 (m, 2H), 1.32–1.22 (m, 4H); ^{13}C NMR (100 MHz, CD_3OD) δ 201.0, 161.6, 158.1, 151.7, 132.9, 132.4 (2C), 128.2, 117.9, 116.0 (2C), 111.6, 98.1, 63.7, 56.1, 54.4 (2C), 41.7, 36.6, 32.6 (3C); MS (m/z) [$\text{M} + \text{H}$] $^+$ 403.65–405.66; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{28}\text{ClN}_2\text{O}_3$ [$\text{M} + \text{H}$] $^+$ 403.1788, found 403.1786.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(4-methylbenzyl)piperidin-4-yl)propan-1-one (5q)

Following procedure B. White solid (20%); mp 97.0°C; ^1H NMR (400 MHz, CDCl_3) δ 7.77 (s, 1H), 7.20 (d, $J = 7.9$ Hz, 2H), 7.11 (d, $J = 7.9$ Hz, 2H), 6.24 (s, 1H), 4.49 (br s, 2H), 3.81 (s, 3H), 3.47 (s, 2H), 2.90–2.86 (m, 4H), 2.33 (s, 3H), 1.96–1.91 (m, 2H), 1.68–1.65 (m, 2H), 1.60–1.55 (m, 2H), 1.33–1.23 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.2, 159.6, 147.8, 136.7, 135.0, 132.3, 129.5 (2C), 128.9 (2C), 118.9, 111.3, 97.6, 63.2, 55.7, 53.8, 53.5, 41.0, 35.6, 32.2 (2C), 31.4, 21.2; MS (m/z) [$\text{M} + \text{H}$] $^+$ 401.66–403.65; HRMS (m/z) calcd for $\text{C}_{23}\text{H}_{30}\text{ClN}_2\text{O}_2$ [$\text{M} + \text{H}$] $^+$ 401.1996, found 401.1996.

N-(3-((4-(3-(4-Amino-5-chloro-2-methoxyphenyl)-3-oxopropyl)piperidin-1-yl)methyl)-4-bromophenyl)acetamide (5r)

Following procedure A. Yellow-pale oil (70%); ^1H NMR (400 MHz, CDCl_3) δ 7.77 (s, 1H), 7.96 (br s, 1H), 7.52 (dd, $J = 2.4$, 8.8 Hz, 1H), 7.47–7.39 (m, 2H), 6.25 (s, 1H), 4.50 (s, 2H), 3.82 (s, 3H), 3.50 (s, 2H), 3.01–2.77 (m, 4H), 2.16 (s, 3H), 2.05 (br t, $J = 10.8$ Hz, 2H), 1.72–1.61 (m, 2H), 1.57 (br q, $J = 6.8$ Hz, 2H), 1.35–1.18 (m, 3H). ^{13}C NMR (100 MHz, CDCl_3) δ 199.4, 168.7, 159.7, 147.9, 138.8, 137.5, 133.0, 132.3, 121.6, 120.0, 118.9, 118.8, 111.3, 97.7, 62.0, 55.8, 54.1, 41.1, 35.7, 32.5, 31.4, 24.7; HRMS (m/z) calcd for $\text{C}_{24}\text{H}_{30}\text{BrClN}_3\text{O}_3$ [$\text{M} + \text{H}$] $^+$ 522.115358, found 522.114977.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(2-fluoro-5-nitrobenzyl)piperidin-4-yl)propan-1-one (5s)

Following procedure B. Yellow solid (35%); mp 133.4°C; ^1H NMR (400 MHz, CDCl_3) δ 8.36 (dd, $J = 6.1$ Hz, $J = 2.8$ Hz, 1H), 8.13 (ddd, $J = 8.9$, 4.3 Hz, $J = 3.0$ Hz, 1H), 7.78 (s, 1H), 7.15 (t_{app} , $J = 8.8$ Hz, 1H), 6.25 (s, 1H), 4.45 (s, 2H), 3.84 (s, 3H), 3.59 (s, 2H), 2.91–2.84 (m, 4H), 2.08–2.02 (m, 2H), 1.70–1.68 (m, 2H), 1.62–1.57 (m, 2H), 1.29–1.25 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 199.1, 164.8 (d, $J = 256.4$ Hz), 159.6, 147.8, 144.4 (d, $J = 1.9$ Hz), 132.4, 127.8 (d, $J = 16.2$ Hz), 127.2 (d, $J = 6.9$ Hz), 124.6 (d, $J = 10.2$ Hz), 119.1, 116.3 (d, $J = 25.1$ Hz), 111.4, 97.7, 55.8, 55.1, 53.9 (2C), 40.9, 35.4, 32.3 (2C), 31.3; MS (m/z) [$\text{M} + \text{H}$] $^+$ 450.51–452.50; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{26}\text{ClFN}_3\text{O}_4$ [$\text{M} + \text{H}$] $^+$ 450.1596, found 450.1594.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(5-amino-2-fluorobenzyl)piperidin-4-yl)propan-1-one (5t)

Following procedure B. Yellow-brown oil (11%); ^1H NMR (400 MHz, CDCl_3) δ 7.64 (s, 1H), 6.83 (dd, $J = 9.5$ Hz, $J = 8.8$ Hz, 1H), 6.72 (dd, $J = 6.2$, 2.8 Hz, 1H), 6.65 (ddd, $J = 8.7$, 4.1, 2.8 Hz, 1H), 6.44 (s, 1H), 3.85 (s, 3H), 3.55 (d, $J = 1.2$ Hz, 2H), 2.98–2.95 (m, 2H), 2.91–2.87 (m, 2H), 2.16–2.11 (m, 2H), 1.73–1.71 (m, 2H), 1.59–1.52 (m, 2H),

1.33–1.26 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 200.1, 161.7, 156.3 (d, $J = 234.0$ Hz), 151.7, 144.8, 132.9, 124.1 (d, $J = 16.4$ Hz), 119.7 (d, $J = 3.3$ Hz), 117.9, 117.3 (d, $J = 7.7$ Hz), 116.4 (d, $J = 23.8$ Hz), 111.6, 98.1, 56.3 (d, $J = 1.3$ Hz), 56.1, 54.4 (2C), 41.6, 36.4, 32.6 (3C); MS (m/z) [$\text{M} + \text{H}$] $^+$ 420.60–422.60; HRMS (m/z) calcd for $\text{C}_{22}\text{H}_{28}\text{ClFN}_3\text{O}_2$ [$\text{M} + \text{H}$] $^+$ 420.1854, found 420.1857.

1-(4-Amino-5-chloro-2-methoxyphenyl)-3-(1-(3-methylbenzyl)piperidin-4-yl)propan-1-one fumaric acid salt (10)

To a solution of 85 mg of compound **5k** (0.212 mmol) in 3 mL of *i*PrOH was added 25 mg of fumaric acid (0.212 mmol, 1 equivalent). The solution was refluxed for 2 h. The mixture was then concentrated *in vacuo*. The residue is triturated in Et_2O and then filtrated. Sixty milligram of desired compound were obtained as a beige solid (55%). Yellow solid; mp 185.4°C; ^1H NMR (400 MHz, CD_3OD) δ 7.56 (s, 1H), 7.28–7.16 (m, 4H), 6.60 (s, 2H), 6.35 (s, 1H), 4.11 (s, 2H), 3.75 (s, 3H), 3.32 (br d, $J = 12.4$ Hz, 2H), 2.88–2.81 (m, 4H), 2.28 (s, 3H), 1.86 (br d, $J = 13.9$ Hz, 2H), 1.55–1.52 (m, 3H), 1.38–1.32 (m, 2H); ^{13}C NMR (100 MHz, CD_3OD) δ 198.7, 169.8 (2C), 160.3, 150.4, 139.0, 134.8 (2C), 131.5, 130.4, 129.3, 128.8, 127.9, 116.3, 110.3, 96.6, 60.2, 54.7 (2C), 52.1, 48.2, 39.8, 33.1, 30.1, 28.9, 20.0 (2C). HRMS (m/z) calcd for $\text{C}_{23}\text{H}_{30}\text{ClN}_2\text{O}_2$ [$\text{M} + \text{H}$] $^+$ 401.1994, found 401.1996.

In vitro Biological Studies

Pharmacological Characterization of Drugs on Human 5-HT₄R

For competition studies, 2.5 μg of proteins (5-HT_{4(b)} membrane preparations, HTS110M, Eurofins. Eurofins' 5-HT_{4(b)} membrane preparations are crude membrane preparations made from their proprietary stable recombinant cell lines to ensure high-level of GPCR surface expression) were incubated in duplicate at 25°C for 60 min in the absence or the presence of 10^{-6} or 10^{-8}M of each drug (**9** was used as a reference standard) and 0.2 nM [^3H]-GR113808 (NET 1152, Perkin Elmer) in 25 mM Tris buffer (pH 7.4, 25°C). At the end of the incubation, homogenates were filtered through Whatman GF/C filters (Alpha Biotec) presoaked with 0.5% polyethylenimine using a Brandel cell harvester. Filters were subsequently washed three times with 1 mL of ice-cold 25 mM Tris buffer (pH 7.4, 4°C). Non-specific binding was evaluated in parallel in the presence of 30 μM serotonin.

For some of these compounds, affinity constants were calculated from five-point inhibition curves using the GraphPad Prism 6 software and expressed as $\text{K}_i \pm \text{SD}$.

Pharmacological Characterization of Drugs on Human 5-HT₆R

Drugs were evaluated through their possibility to compete for the binding of [^3H]-LSD on membranes of HEK-293 cells transiently expressing the human 5-HT₆ receptors (ref. RBHS6M, Perkin Elmer). In brief, 4 μg of proteins were incubated at 37°C for 60 min in duplicate in the absence or the presence of 10^{-6} or 10^{-8}M of each drug (**2** was used as a reference

standard) and 2.5 nM [³H]-LSD (ref. NET638250UC, Perkin Elmer), in 25 mM Tris-HCl buffer (pH 7.4) supplemented with 0.5 mM EDTA. At the end of the incubation, the homogenates were then filtered through Whatman GF/C filters and washed five times with ice-cold 25 mM Tris-HCl buffer. Non-specific binding was evaluated in the presence of 100 μM serotonin. Radioactivity associated to proteins was then quantified and expressed as the percentage of inhibition of the drugs under study.

For some of these compounds, affinity constants were calculated from five-point inhibition curves using the GraphPad Prism 6 software and expressed as $K_i \pm SD$.

Determination of cAMP Production

COS-7 cells were grown in Dulbecco's modified Eagle medium (DMEM) supplemented with 10% dialyzed fetal calf serum (dFCS) and antibiotics. Cells were transiently transfected by electroporation with plasmids encoding HA-tagged 5-HT₄R (100 ng/10⁶ cells) or HA-tagged 5-HT₆R (70 ng/10⁶ cells or 300 ng/10⁶ cells), then seeded in 96-well plates (16,000 cells/well).

5-HT₄R-induced cAMP production: 24 h after transfection, cells were exposed to the indicated concentrations of 5-HT₄R ligands in the presence of 0.1 mM of the phosphodiesterase inhibitor RO-20-1724, at 37°C in 100 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). After 10 min, cells were then lysed by addition of the same volume of Triton-X100 (0.1%).

Blockade of the 5-HT₆R-induced cAMP production: 24 h after transfection, cells were exposed to the indicated concentrations of 5-HT₆R ligands at 37°C in 50 μL of HBS. After 7 min, 5-HT (5.10⁻⁷M final concentration) in the presence of RO-20-1724 (0.1 mM final concentration), in 50 μL HBS, was added to the wells. After 10 min at 37°C, cells were then lysed by addition of 100 μL of Triton-X100 (0.1%).

Reversion of the basal 5-HT₆R-induced cAMP production: the 5-HT₆R expression was augmented by transfection of higher quantities of cDNA (300 ng/10⁶ cells) to increase the basal cAMP production linked to the constitutive activity of the receptor. Twenty-four hours after transfection, cells were exposed to 10⁻⁴M of 5-HT₆R ligands in the presence of RO-20-1724 (0.1 mM final concentration), at 37°C in 100 μL of HBS. This experiment is performed in the absence of 5-HT. After 10 min at 37°C, cells were then lysed by addition of 100 μL of Triton-X100 (0.1%).

Quantification of cAMP production was performed by HTRF[®] by using the cAMP Dynamic kit (Cisbio Bioassays) according to the manufacturer's instructions.

In vitro Tests of AChE Biological Activity

Inhibitory capacity of compounds on AChE biological activity was evaluated through the use of the spectrometric method of Ellman et al. (1961). Acetylthiocholine iodide and 5,5-dithiobis-(2-nitrobenzoic) acid (DTNB) were purchased from Sigma Aldrich. AChE from human erythrocytes (buffered aqueous solution, ≥500 units/mg protein (BCA), Sigma Aldrich) was diluted in 20 mM HEPES buffer pH 8, 0.1% Triton X-100 such as to have enzyme solution with 0.25 unit/mL enzyme activity. In the procedure, 100 μL of 0.3 mM DTNB

dissolved in phosphate buffer pH 7.4 was added into the 96-well plate followed by 50 μL of test compound solution and 50 μL of enzyme (0.05 U final). After 5 min of preincubation at 25°C, the reaction was then initiated by the injection of 50 μL of 10 mM acetylthiocholine iodide solution. The hydrolysis of acetylthiocholine was monitored by the formation of yellow 5-thio-2-nitrobenzoate anion as the result of the reaction of DTNB with thiocholine, released by the enzymatic hydrolysis of acetylthiocholine, at a wavelength of 412 nm using a 96-well microplate plate reader (BioTek, Synergy 2). Test compounds were dissolved in analytical grade DMSO. Donepezil (DPZ) was used as a reference standard. The rate of absorbance increase at 412 nm was followed every minute for 10 min. Assays were performed with a blank containing all components except acetylthiocholine, in order to account for non-enzymatic reaction. The reaction slopes were compared and the percent inhibition due to the presence of test compounds was calculated by the following expression: $100 - (v_i/v_0 \times 100)$ where v_i is the rate calculated in the presence of inhibitor and v_0 is the enzyme activity.

First screening of AChE activity was carried out at a 10⁻⁶M concentration of compounds under study. For the compounds with significant inhibition (≥50%), IC₅₀ values were determined graphically by plotting the % inhibition vs. the logarithm of six inhibitor concentrations in the assay solution using the GraphPad Prism 6 software.

In vivo Biological Studies

Animals

Adult male NMRI mice (3 months old, weighing 35–40 g) from Janvier labs (Le Genest-Saint-Isle, France) were used to perform experiments. Mice were housed by ten in standard polycarbonate cages in standard controlled conditions (22 ± 2°C, 55 ± 10% humidity) with a reversed 12 h light/dark cycle (light on at 7 pm). Food and water were available *ad libitum* in the home cage. All experiments were conducted (between 9 am and 3 pm) during the active-dark-phase of the cycle, were approved by the ethics committee of Normandy (CENOMEXA, n°5161) and were in agreement with the European Directives and French law on animal experimentation (personal authorization n° 14–17 for MB and 14–60 for TF).

CNS-Activity and Acute Toxicity Test

Behavioral and neurological changes induced by graded doses (1, 10, 100 mg/kg) of the tested derivatives were evaluated in mice, in groups of four, by a standardized observation technique at different times (30 min, 3 and 24 h) after intraperitoneal administration (Morpuigo, 1971). Major changes of behavioral data (for example, hypo- or hyperactivity, ataxia, tremors, convulsion, etc...) were noted in comparison to the control group. The approximate DL₅₀ of the compounds were also calculated through the quantification of mortality after 24 h. Amphetamine (2 mg/kg), chlorpromazine (10 mg/kg) were used as a stimulant and depressive references, respectively.

Locomotor Activity

Locomotion of mice was measured using an actimeter (Imetronic[®]) through infrared detection. Eight individual removable polycarbonate cages (21 cm length, 7 cm wide and 12 cm high), where each mouse was placed, are disposed in the actimeter. Locomotor activity was measured by recording the number of interruption of beams of the red light over a period of 30 min through an attached recording system to the actimeter. Compound **10** was tested at 1, 3 and 10 mg/kg. Amphetamine (2 mg/kg), chlorpromazine (3 mg/kg) were used as a stimulant and depressive references, respectively (Freret et al., 2012).

Spatial Working Memory

Anti-amnesic activity of tested compounds was evaluated by reversal of scopolamine (0.5 mg/kg)-induced deficit on spontaneous alternation behavior in the Y maze test (Hooper et al., 1996). The Y maze made of gray plastic consisted of three equally spaced arms (21 cm long, 7 cm wide with walls 15-cm high). The mouse was placed at the end of one of the arms and allowed to move freely through the maze during a 5 min session while the sequence of arm entries was recorded by an observer. An arm entry was scored when all four feet crossed into the arm. An alternation was defined as entries into all three arms on a consecutive occasion. The number of possible alternation is thus the total number of arm entries minus two; the percentage of alternation was calculated as (actual alternation/ possible alternation) × 100. Compound **10** was tested at 0.3, 1 and 3 mg/kg. DPZ (1 mg/kg) was tested as a clinical reference.

Pharmacological Treatments

Amphetamine, (+)- α -Methylphenethylamine hemisulfate, chlorpromazine hydrochloride, imipramine hydrochloride and scopolamine hydrobromide were purchased from Sigma (France). All those pharmacological compounds were

dissolved in NaCl 0.9% as the vehicle were administered IP 30 min before tests, except scopolamine which was subcutaneously administered 20 min before spontaneous alternation test.

Statistical Analysis

Results were expressed as mean \pm SD and were analyzed by one-way analysis of variance (ANOVA), with Statview[®] software. In case of significance, a SNK (Student-Newman-Keuls) *post hoc* test was realized. Additionally, for the spontaneous alternation test, the percentage of alternation was compared to a theoretical 50% value (random alternation) by an univariate *t*-test. Differences were considered as statistically significant if the *p*-value was strictly under 0.05.

RESULTS

Chemistry

The targeted compounds **5a–t** were obtained starting from 4-amino-5-chloro-2-methoxybenzoic acid (**6**) as reported for the synthesis of **5a** (Scheme 1; Rochais et al., 2015). The synthesis of a β -ketoester (**7**) was achieved in 62% yield using the carbonyldiimidazole (CDI) activation of the carboxylic acid group of **6**. A nucleophilic substitution, using *N*-Boc 4-(iodomethyl) piperidine at room temperature to avoid the risk of a double substitution, allowed the installation of the methylpiperidine moiety. The latter was immediately followed by a saponification–decarboxylation sequence using hydroalcoholic potassium hydroxide. The reaction yielded **8** in a 86% yield. Finally, the TFA-*N*-deprotection of **8**, immediately followed by another nucleophilic substitution with various benzyl bromides yielded compounds **5a–t**. The fumaric acid salt **10** was synthesized starting from **5k** and using fumaric acid in *i*PrOH.

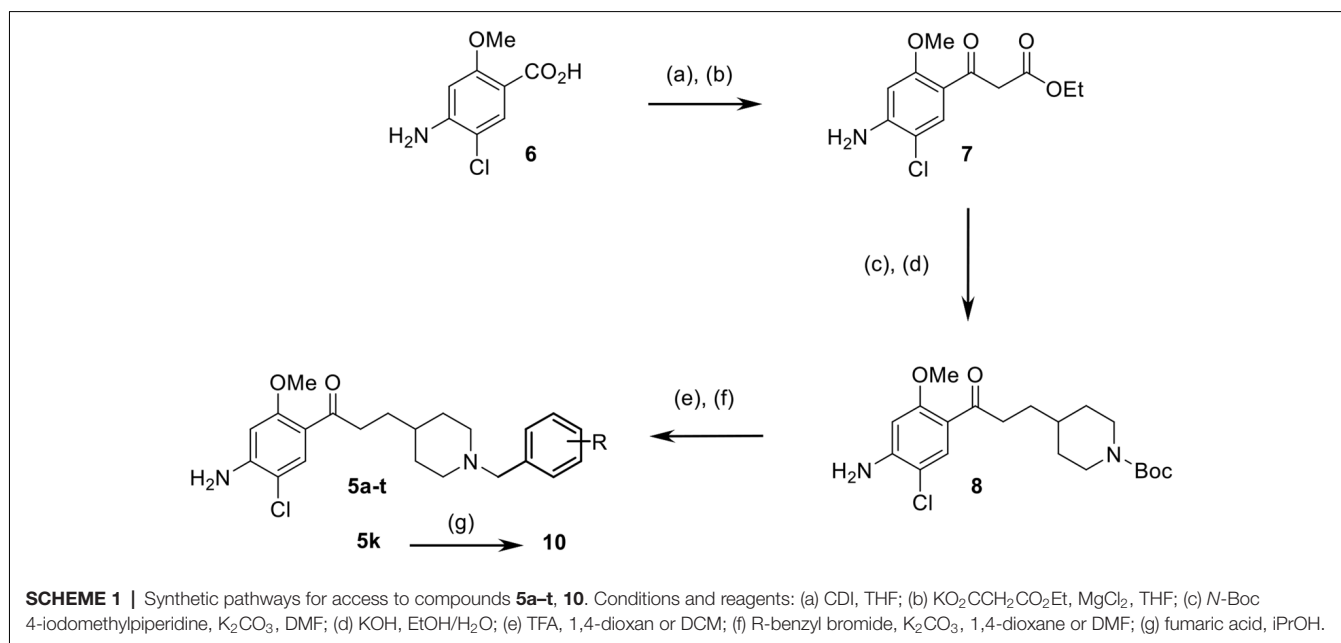


TABLE 1 | (*h*)AChE inhibitory activity, (*h*)5-HT₆R and (*h*)5-HT₄R affinity for DPZ, **2**, **9** and compounds **5a–t** (% inhibition at 10⁻⁶M, 10⁻⁸M and 10⁻⁸ M, respectively).

Cmpd	R	<i>(h)</i> AChE		<i>(h)</i> 5-HT ₆ R		<i>(h)</i> 5-HT ₄ R	
		%10 ⁻⁶ M	%10 ⁻⁶ M	%10 ⁻⁸ M	%10 ⁻⁶ M	%10 ⁻⁸ M	
DPZ	-	97	-	-	-	-	-
2	-	-	106	88	-	-	-
9	-	-	-	-	100	42	-
5a	H	98	29	0	102	41	-
5b	2-Cl	91	92	27	94	16	-
5c	2-Br	80	65	34	96	17	-
5d	2-F	96	68	21	94	10	-
5e	2-I	37	81	25	96	1	-
5f	2-Me	87	85	24	98	9	-
5g	2-OBn	33	18	0	70	7	-
5h	2-OH	94	24	0	98	10	-
5i	3-Br	44	77	7	94	5	-
5j	3-F	97	59	9	98	12	-
5k	3-Me	89	80	9	98	25	-
5l	3-OMe	35	78	6	94	9	-
5m	3-NH ₂	93	74	31	100	35	-
5n	3-NO ₂	64	51	0	90	3	-
5o	4-F	92	58	13	102	19	-
5p	4-OH	98	24	0	100	23	-
5q	4-Me	87	21	21	100	24	-
5r	2-Br;5-NHCOMe	13	35	7	96	6	-
5s	2-F;5-NO ₂	63	18	5	62	4	-
5t	2-F;5-NH ₂	79	65	3	98	18	-

In vitro Results

The biological evaluation of the synthesized compounds as potential inhibitors of human AChE was performed using the Ellman assay (Ellman et al., 1961), as well as their affinity for human 5-HT₆R and 5-HT₄R using a radioligand displacement assay (Table 1). In these tests, DPZ was used as a reference AChE inhibitor (AChEI), **2** as a 5-HT₆R ligand and **9** (RS67333; Eglen et al., 1995) as a 5-HT₄R ligand.

The results of these *in vitro* evaluations are reported in a 3-fold-entry figure (Figure 3).

Among the 20 tested compounds, 12 novel derivatives appear as moderate to potent AChEIs with %inhibition at 10⁻⁶M ≥ 80%. Their IC₅₀ values ranged from 450 (**5q**) to 6 nM (**5p**; Table 2). Some of these AChEI showed an additional affinity towards 5-HT₆R with %inhibition at 10⁻⁶M > 70% (**5b**, **f**, **k**, **m**) and *K_i* ranging from 1,150 to 110 nM. Three derivatives (**5e**, **i**, **l**) displayed affinity for 5-HT₆R, while being devoid of inhibitory effect towards AChE. Finally, among the four dual compounds, **5k** and **5m** further exhibited an affinity towards 5-HT₄R with %inhibition at 10⁻⁸M ≥ 25% and *K_i* of 168 and 43 nM respectively. Three other compounds (**5o–q**) displayed good affinity towards 5-HT₄R but are devoid of such an affinity towards 5-HT₆R.

By virtue of its well-balanced *in vitro* activities towards the three targets, **5k** was selected for further investigation. According to the concept of MTDL and the synergy theoretically displayed by the association of activities into a sole compound, **5k** has been preferred to more potent compounds (e.g., **5m**) but with unbalanced levels of activity towards the three targets. This derivative has then been used as its fumaric

acid salt **10**. The *in vitro* activities of **10** are depicted in Table 3.

The pharmacological profile of **10** was established towards (*h*)5-HT₄R and (*h*)5-HT₆R, respectively. It acts as a partial agonist towards (*h*)5-HT₄R, in a similar manner as RS67333 (**9**), and as an inverse agonist towards (*h*)5-HT₆R, in a similar manner as SB271046, used as a control 5-HT₆R antagonist, and idalopirdine (**2**; Figure 4 and Table 3). Indeed, in our hands, these three compounds decreased cAMP production below the basal, in the absence of agonist (Figure 4C).

In vivo Results

Whatever the dose tested (1, 10 and 100 mg/kg), preliminary toxicological and pharmacological screening of **10** (Table 4) did not show any deleterious signs, suggesting thus a LD₅₀ quite higher than 100 mg/kg.

None of the tested doses of **10** (1, 3 and 10 mg/kg) did neither modify spontaneous locomotor activity (Figure 5).

Moreover, an anti-amnesic effect was observed in the scopolamine-induced spontaneous alternation deficit test, after IP administration of **10** at doses starting from 0.3 mg/kg (Figure 6). The degree of effect was similar to that of the dual-targeted compound donecopride in the same dose range (Rochais et al., 2015).

DISCUSSION

Trying to establish SAR for MTDL is always quite challenging taking into consideration that the structural requirements can be divergent between the expected interactions with the different targets. Considering the three present targets, the SAR appeared similar between AChE and 5-HT₄R, but partially different from those observed for 5-HT₆R.

Indeed, with regard to AChE and 5-HT₄R activities, the best substituent of the piperidine moiety of compounds **5** is the unsubstituted benzyl group (**5a**). According to our previous work (Yahiaoui et al., 2016), the nature of the substitution of a phenyl group distant from the piperidine moiety could influence in a great manner the affinity of the ligands towards both 5-HT receptors. For the two targets, poly or bulky substituents (Br, I, OBn, OMe, NO₂), appear detrimental to the activities (**5c**, **g**, **i**, **l**, **n**) while a smaller one (OH, NH₂, F, Me) seems likely to relatively maintain the activity (**5h**, **p**, **m**, **d**, **j**, **o**), especially when present in para position (**5p**).

Conversely, the 5-HT₆R affinity appears linked to the substitution of the benzyl group within the studied scaffold, since the unsubstituted derivative **5a** was devoid of such an activity. Further, small substituents (OH, F) do not favor, this time, the affinity (**5d**, **h**, **j**, **o**, **p**), whatever their position on the phenyl ring, while bulkier ones (Cl, Br, I, Me, OMe) promote it, especially in *ortho* or *meta* positions (**5b**, **c**, **e**, **f**, **i**, **k**, **l**).

These contradictory requirements explain that **5k** with a methyl group in *meta* position displayed balanced activities towards the three targets and was chosen for further investigation under its fumarate form (**10**). Indeed, according to the MTDL concept (Cavalli et al., 2008),

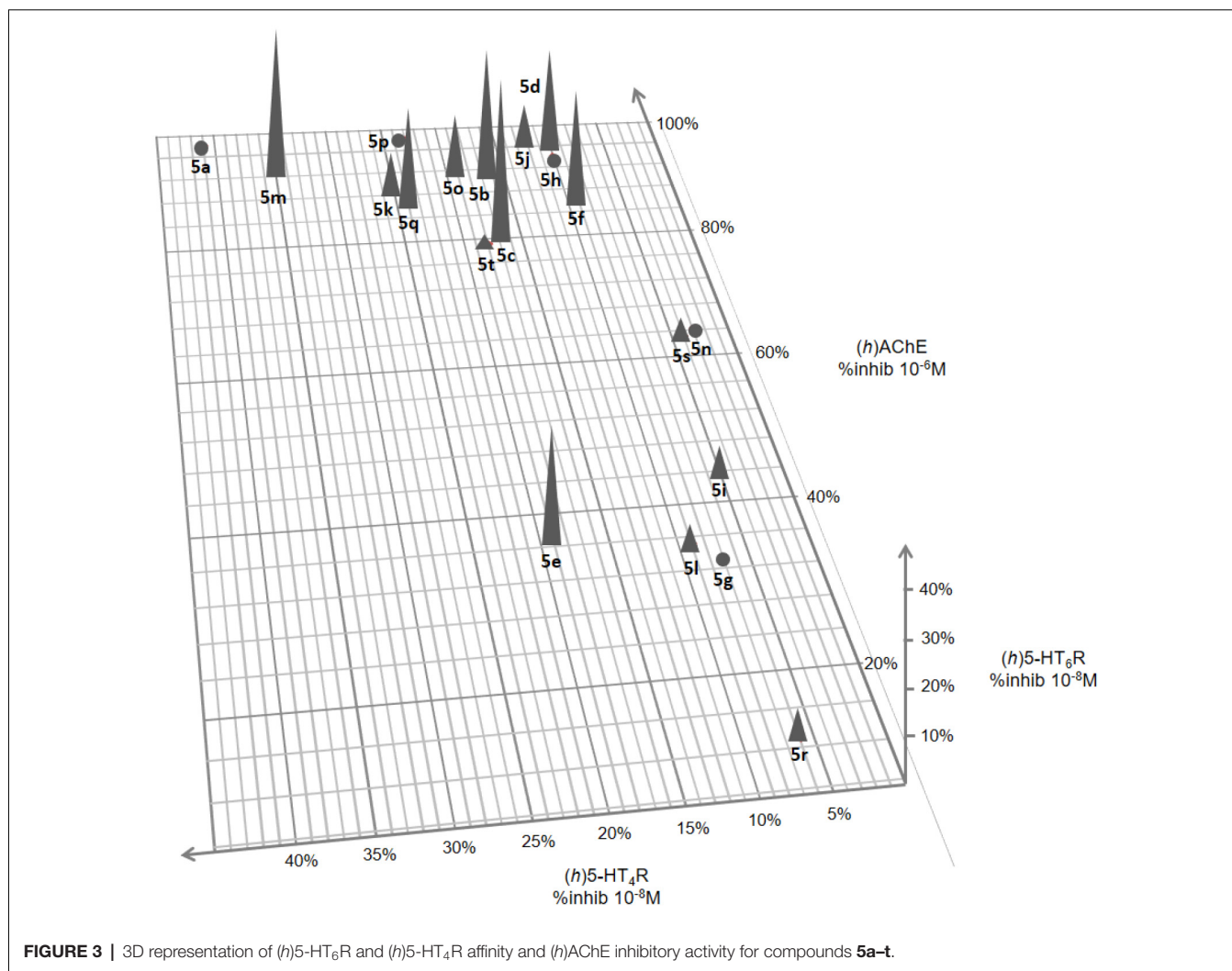


TABLE 2 | (h)AChE inhibitory activity (IC₅₀) and (h)5-HT₆R and (h)5-HT₄R affinity (K_i) for DPZ, 2, 9, 5b–f, h–m, o–q, t and the fumarate 10.

Cmpd	R	(h)AChE	(h)5-HT ₆ R	(h)5-HT ₄ R
		IC ₅₀ (nM) n = 2	K _i (nM) n = 3	K _i (nM) n = 3
DPZ	-	7 ± 1.5	ND	ND
2	-	ND	6.9 ± 1.2	ND
9	-	ND	ND	5.1 ± 0.5 (Irving et al., 2010)
5b	2-Cl	156 ± 71	110 ± 19	ND
5c	2-Br	317 ± 115	ND	ND
5d	2-F	101.6 ± 65.4	ND	ND
5e	2-I	ND	186 ± 71	ND
5f	2-Me	225.2 ± 57.3	270 ± 14	ND
5h	2-OH	57.4 ± 9.4	ND	ND
5i	3-Br	ND	169 ± 44	ND
5j	3-F	91 ± 53.8	ND	ND
5k	3-Me	161 ± 43	230 ± 49	168 ± 15
5l	3-OMe	ND	265 ± 64	ND
5m	3-NH ₂	41 ± 5	1150 ± 559	42.5 ± 2.6
5o	4-F	78.4 ± 12.1	ND	ND
5p	4-OH	6.0 ± 0.4%	ND	ND
5q	4-Me	450.5 ± 89.5	ND	ND
5t	2-F;5-NH ₂	152.7 ± 19.9	ND	ND
10	3-Me, fumarate salt	33.7 ± 1.7	219 ± 42	210 ± 43

ND, not determined.

TABLE 3 | (*h*)5-HT₆R and (*h*)5-HT_{4(a)}R pharmacological profile of compounds **2**, **9** and **10**.

	<i>(h)</i> 5-HT ₆ R			<i>(h)</i> 5-HT _{4(a)} R		
	Log(IC ₅₀)	% control antagonist response	Profile	Log(EC ₅₀)	% control agonist response	Profile
2	-6.2 ± 0.2 <i>n</i> = 2	101.2 ± 3.2 <i>n</i> = 2	Inverse agonist	-	-	-
9	-	-	-	-8.8 ± 0.2 <i>n</i> = 2	48.7 ± 5.2 <i>n</i> = 3*	Partial agonist
10	-5.0 ± 0.1 <i>n</i> = 2	93.4 ± 1.8 <i>n</i> = 2	Inverse agonist	-7.7 ± 0.0 <i>n</i> = 2	59.8 ± 2.5 <i>n</i> = 2	Partial agonist

SB271046 was used as a control 5-HT₆R antagonist and 5-HT as control 5-HT₄R agonist. *Result reported from Lecoutey et al. (2014).

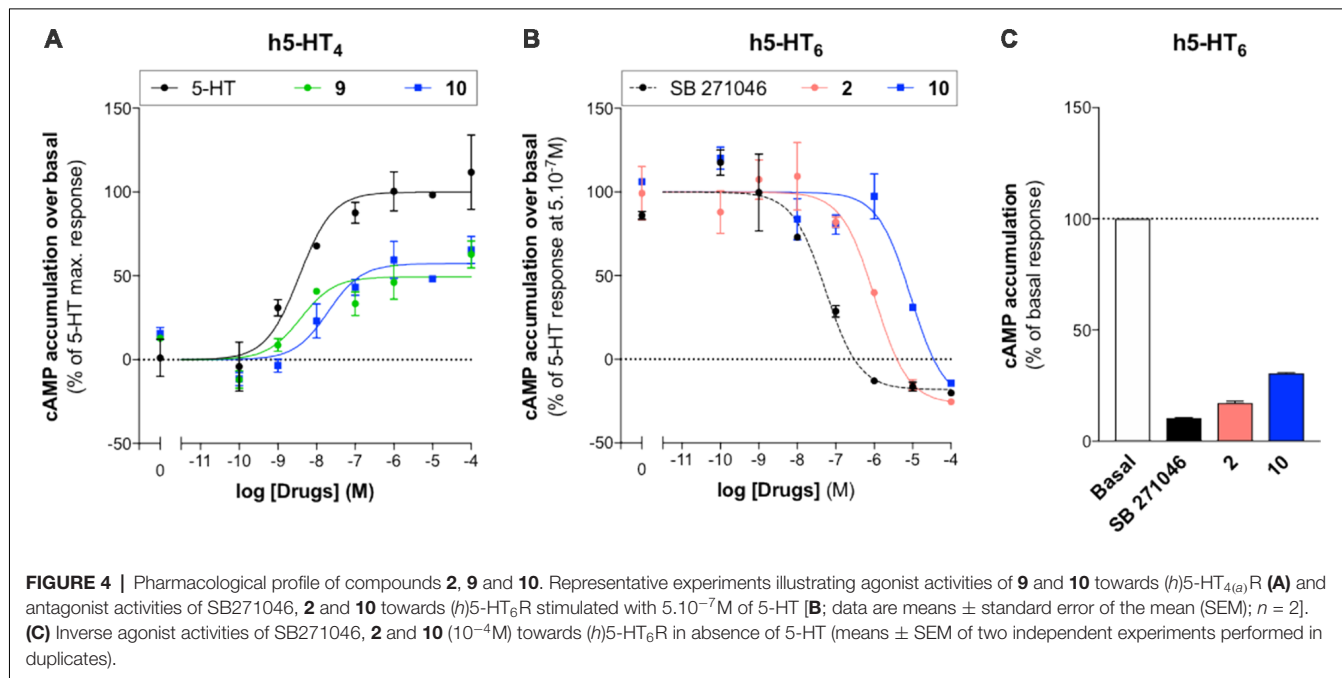


TABLE 4 | Pharmacological and toxicological properties of **10**.

Compound	Doses (mg/kg)	LD ₅₀ (mg/kg)	Symptoms (subtoxic doses)
10	1–10–100	>100	No symptoms
Amphetamine	2		Hyperactivity Exophthalmy Irritability
Chlorpromazine	10		Hypoactivity Ataxia Sleep

pleiotropic ligand could present moderate *in vitro* activities toward their targets that could, however, lead to potent and promising *in vivo* activities explained by their synergistic effect (Prati et al., 2015).

Of interest, compound **10**, idalopirdine and SB271046 were able to reverse the constitutive activity of the 5-HT₆ receptor, thus demonstrating an inverse agonist profile. Such a property is of high interest regarding this receptor as it is known to possess a high constitutive activity in the brain, exerting a tonic activity (Duhr et al., 2014; Deraredj Nadim et al., 2016). Regarding the 5-HT₄R, **10** demonstrated a partial agonist activity similar to the one of **9**, which had proven its efficiency to prevent amyloid production in a mouse

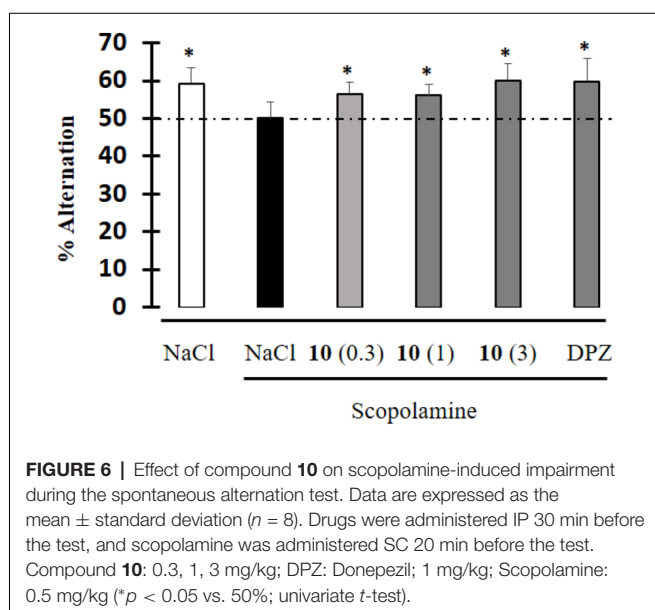
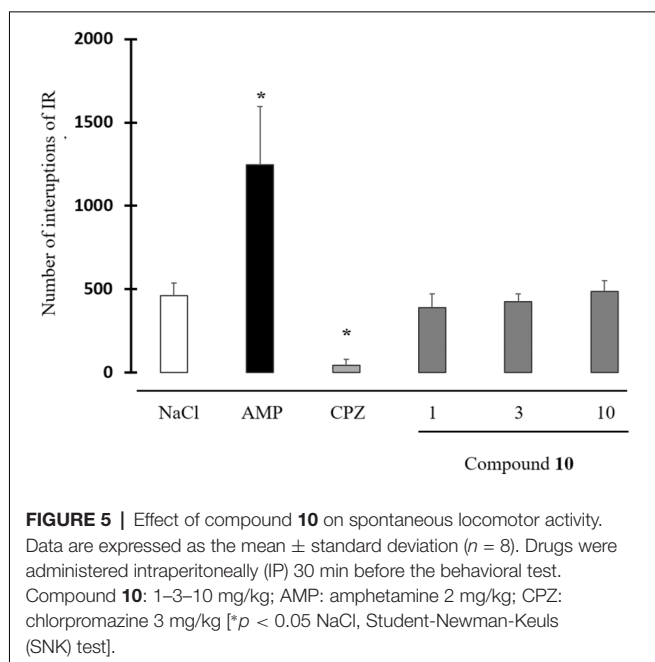
model of AD (Hashimoto et al., 2012; Giannoni et al., 2013; Baranger et al., 2017).

The main result of the behavioral study concerns the anti-amnesic effect of **10** in a model of scopolamine-induced deficit of working memory from the dose of 0.3 mg/kg.

Although no pharmacokinetic data are available for compound **10** yet, this result indicates that it reaches the general circulation and crosses the blood-brain barrier upon IP administration. The anti-amnesic effect of compound **10** suggests that the co-modulation of the three targets could be a therapeutic strategy of interest in the field of memory impairments. The anti-amnesic properties of the compound **10**, together with the absence of any deleterious signs during the pharmacological screening (even when tested at high dose: 100 mg/kg), are arguing in favor of **10** as a new promising drug, with excellent general tolerance.

CONCLUSION

We have synthesized a variety of compounds possessing both *in vitro* and *in vivo* activities towards three therapeutic targets (5-HT₄R/5-HT₆R, AChE) in the potential treatment



of AD. The use of these innovative MTDL which may exhibit a greater benefit than single-targeted drugs towards the neuropathological hallmarks of the disease and the associated behavioral deficits will require further studies in animal

REFERENCES

Baranger, K., Giannoni, P., Girard, S. D., Girot, S., Gaven, F., Stephan, D., et al. (2017). Chronic treatments with a 5-HT₄ receptor agonist decrease amyloid pathology in the entorhinal cortex and learning and memory deficits in the 5xFAD mouse model of Alzheimer's disease. *Neuropharmacology* 126, 128–141. doi: 10.1016/j.neuropharm.2017.08.031

models and potential future clinical trials to demonstrate their efficacy.

ASSOCIATED CONTENT

Analytical data of final compounds. This material is available free of charge *via* the Internet at <http://pubs.acs.org>.

DATA AVAILABILITY

All datasets generated for this study are included in the manuscript and/or the **Supplementary Files**.

ETHICS STATEMENT

All experiments were conducted in agreement with the European Directives and French law on animal experimentation (personal authorization n° 14-17 for MB and 14-60 for TF).

AUTHOR CONTRIBUTIONS

The manuscript was written through contributions of SC, TF, MB, CR and PD. All authors have given approval to the final version of the manuscript.

FUNDING

This work was supported by funding from the Fondation Vaincre Alzheimer (#FR-15072) and the Fondation Plan Alzheimer (AAP2015 Project TRIAD 016). The authors gratefully acknowledge the Conseil Régional de Normandie, as well as the European Community (FEDER) for their contribution to the CERMN's analytical platform. European COST action CA15135 (Multi-Target Paradigm for Innovative Ligand Identification in the Drug Discovery Process, MuTaLig) supports this article.

ACKNOWLEDGMENTS

We would like to thank Steve Dubel for final proofreading of the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fnagi.2019.00148/full#supplementary-material>

Benhamú, B., Martín-Fontecha, M., Vázquez-Villa, H., Pardo, L., and López-Rodríguez, M. L. (2014). Serotonin 5-HT₆ receptor antagonists for the treatment of cognitive deficiency in Alzheimer's disease. *J. Med. Chem.* 57, 7160–7181. doi: 10.1021/jm5003952

Cavalli, A., Bolognesi, M. L., Minarini, A., Rosini, M., Tumiatti, V., Recanatini, M., et al. (2008). Multi-target-directed ligands to combat neurodegenerative diseases. *J. Med. Chem.* 51, 347–372. doi: 10.1021/jm7009364

- Cho, S., and Hu, Y. (2007). Activation of 5-HT₄ receptors inhibits secretion of β -amyloid peptides and increases neuronal survival. *Exp. Neurol.* 203, 274–278. doi: 10.1016/j.expneurol.2006.07.021
- Claeysen, S., Bockaert, J., and Giannoni, P. (2015). Serotonin: a new hope in Alzheimer's disease? *ACS Chem. Neurosci.* 6, 940–943. doi: 10.1021/acschemneuro.5b00135
- Consolo, S., Arnaboldi, S., Giorgi, S., Russi, G., and Ladinsky, H. (1994). 5-HT₄ receptor stimulation facilitates acetylcholine release in rat frontal cortex. *Neuroreport* 5, 1230–1232. doi: 10.1097/00001756-199406020-00018
- Dawson, L. A., Nguyen, H. Q., and Li, P. (2000). *In vivo* effects of the 5-HT₆ antagonist SB-271046 on striatal and frontal cortex extracellular concentrations of noradrenaline, dopamine, 5-HT, glutamate and aspartate. *Br. J. Pharmacol.* 130, 23–26. doi: 10.1038/sj.bjp.0703288
- Dawson, L., Nguyen, H., and Li, P. (2001). The 5-HT(6) receptor antagonist SB-271046 selectively enhances excitatory neurotransmission in the rat frontal cortex and hippocampus. *Neuropsychopharmacology* 25, 662–668. doi: 10.1016/s0893-133x(01)00265-2
- de Bruin, N. M., and Kruse, C. G. (2015). 5-HT₆ receptor antagonists: potential efficacy for the treatment of cognitive impairment in schizophrenia. *Curr. Pharm. Des.* 21, 3739–3759. doi: 10.2174/1381612821666150605112105
- Deraredj Nadim, W., Chaumont-Dubel, S., Madouri, F., Cobret, L., De Tauszia, M. L., Zajdel, P., et al. (2016). Physical interaction between neurofibromin and serotonin 5-HT₆ receptor promotes receptor constitutive activity. *Proc. Natl. Acad. Sci. U S A* 113, 12310–12315. doi: 10.1073/pnas.1600914113
- Dolles, D., and Decker, M. (2017). “Dual-acting compounds acting as receptor ligands and enzyme inhibitors,” in *Design of Hybrid Molecules for Drug Development*, ed. M. Decker (Oxford: Elsevier), 137–165.
- Dolles, D., Hoffmann, M., Gunesch, S., Marinelli, O., Möller, J., Santoni, G., et al. (2018). Structure-activity relationships and computational investigations into the development of potent and balanced dual-acting butyrylcholinesterase inhibitors and human cannabinoid receptor 2 ligands with pro-cognitive *in vivo* profiles. *J. Med. Chem.* 61, 1646–1663. doi: 10.1021/acs.jmedchem.7b01760
- Duhr, F., Délérès, P., Raynaud, F., Séveno, M., Morisset-Lopez, S., Mannoury la Cour, C., et al. (2014). Cdk5 induces constitutive activation of 5-HT₆ receptors to promote neurite growth. *Nat. Chem. Biol.* 10, 590–597. doi: 10.1038/nchembio.1547
- Eglen, R. M., Bonhaus, D. W., Johnson, L. G., Leung, E., and Clark, R. D. (1995). Pharmacological characterization of two novel and potent 5-HT₄ receptor agonists, RS67333 and RS67506, *in vitro* and *in vivo*. *Br. J. Pharmacol.* 115, 1387–1392. doi: 10.1111/j.1476-5381.1995.tb16628.x
- Ellis, J. M., and Fell, M. J. (2017). Current approaches to the treatment of Parkinson's disease. *Bioorg. Med. Chem. Lett.* 27, 4247–4255. doi: 10.1016/j.bmcl.2017.07.075
- Ellman, G. L., Courtney, K. D., Andres, V. Jr., and Featherstone, R. M. (1961). A new and rapid colorimetric determination of acetylcholinesterase activity. *Biochem. Pharmacol.* 7, 88–95. doi: 10.1016/0006-2952(61)90145-9
- Freret, T., Bouet, V., Quiedeville, A., Nee, G., Dallemagne, P., Rochais, C., et al. (2012). Synergistic effect of acetylcholinesterase inhibition (donepezil) and 5-HT(4) receptor activation (RS67333) on object recognition in mice. *Behav. Brain Res.* 230, 304–308. doi: 10.1016/j.bbr.2012.02.012
- Ge, J., and Barnes, N. M. (1996). 5-HT₄ receptor-mediated modulation of 5-HT release in the rat hippocampus *in vivo*. *Br. J. Pharmacol.* 117, 1475–1480. doi: 10.1111/j.1476-5381.1996.tb15309.x
- Giannoni, P., Gaven, F., De Bundel, D., Baranger, K., Marchetti-Gauthier, E., Roman, F., et al. (2013). Early administration of RS 67333, a specific 5-HT₄ receptor agonist, prevents amyloidogenesis and behavioral deficits in the 5XFAD mouse model of Alzheimer's disease. *Front. Aging Neurosci.* 5:96. doi: 10.3389/fnagi.2013.00096
- Hashimoto, G., Sakurai, M., Teich, A. F., Saeed, F., Aziz, F., and Arancio, O. (2012). 5-HT₄ receptor stimulation leads to soluble A β PP α production through MMP-9 upregulation. *J. Alzheimers Dis.* 32, 437–445. doi: 10.3233/jad-2012-111235
- Hirst, W. D., Stean, T. O., Rogers, D. C., Sunter, D., Pugh, P., Moss, S. F., et al. (2006). SB-399885 is a potent, selective 5-HT₆ receptor antagonist with cognitive enhancing properties in aged rat water maze and novel object recognition models. *Eur. J. Pharmacol.* 553, 109–119. doi: 10.1016/j.ejphar.2006.09.049
- Hooper, N., Fraser, C., and Stone, T. W. (1996). Effect of purines analogues on spontaneous alternation in mice. *Psychopharmacology* 123, 250–257. doi: 10.1007/bf02246579
- Irving, H. R., Tochon-Danguy, N., Chinkwo, K. A., Li, J. G., Grabbe, C., Shapiro, M., et al. (2010). Investigations into the binding affinities of different human 5-HT₄ receptor splice variants. *Pharmacology* 85, 224–233. doi: 10.1159/000280418
- Karila, D., Freret, T., Bouet, V., Boulouard, M., Dallemagne, P., and Rochais, C. (2015). Therapeutic potential of 5-HT₆ receptor agonists. *J. Med. Chem.* 58, 7901–7912. doi: 10.1021/acs.jmedchem.5b00179
- Kilbinger, H., and Wolf, D. (1992). Effects of 5-HT₄ receptor stimulation on basal and electrically evoked release of acetylcholine from guinea-pig myenteric plexus. *Naunyn Schmiedebergs Arch. Pharmacol.* 345, 270–275. doi: 10.1007/bf00168686
- Lalut, J., Karila, D., Dallemagne, P., and Rochais, C. (2017). Modulating 5-HT₄ and 5-HT₆ receptors in Alzheimer's disease treatment. *Future Med. Chem.* 9, 781–795. doi: 10.4155/fmc-2017-0031
- Lecoutey, C., Hédou, D., Freret, T., Giannoni, P., Gaven, F., Since, M., et al. (2014). Design of donecopride, a dual serotonin subtype 4 receptor agonist/acetylcholinesterase inhibitor with potential interest for Alzheimer's disease treatment. *Proc. Natl. Acad. Sci. U S A* 111, E3825–E3830. doi: 10.1073/pnas.1410315111
- Lelong, V., Lhonneur, L., Dauphin, F., and Boulouard, M. (2003). BIMU 1 and RS 67333, two 5-HT₄ receptor agonists, modulate spontaneous alternation deficits induced by scopolamine in the mouse. *Naunyn Schmiedebergs Arch. Pharmacol.* 367, 621–628. doi: 10.1007/s00210-003-0743-2
- Lezoualc'h, F. (2007). 5-HT₄ receptor and Alzheimer's disease: the amyloid connection. *Exp. Neurol.* 205, 325–329. doi: 10.1016/j.expneurol.2007.02.001
- Lucas, G., Di Matteo, V., De Deurwaerdère, P., Porras, G., Martín-Ruiz, R., Artigas, F., et al. (2001). Neurochemical and electrophysiological evidence that 5-HT₄ receptors exert a state-dependent facilitatory control *in vivo* on nigrostriatal, but not mesoaccumbal, dopaminergic function. *Eur. J. Neurosci.* 13, 889–898. doi: 10.1046/j.0953-816x.2000.01453.x
- Marcos, B., Gil-Bea, F. J., Hirst, W. D., Garcia-Alloza, M., and Ramirez, M. J. (2006). Lack of localization of 5-HT₆ receptors on cholinergic neurons: implication of multiple neurotransmitter systems in 5-HT₆ receptor-mediated acetylcholine release. *Eur. J. Neurosci.* 24, 1299–1306. doi: 10.1111/j.1460-9568.2006.05003.x
- Morpugo, C. (1971). A new design for the screening of CNS-active drugs in mice. *Arzneimittelforschung* 11, 1727–1734.
- Nirogi, R., Mohammed, A. R., Shinde, A. K., Gagginapally, S. R., Kancharla, D. M., Middekadi, V. R., et al. (2018). Synthesis, structure-activity relationships, and preclinical evaluation of heteroaromatic amides and 1,3,4-oxadiazole derivatives as 5-HT₄ receptor partial agonists. *J. Med. Chem.* 61, 4993–5008. doi: 10.1021/acs.jmedchem.8b00457
- Prati, F., De Simone, A., Bisignano, P., Armirotti, A., Summa, M., Pizzirani, D., et al. (2015). Multitarget drug discovery for Alzheimer's disease: triazinones as BACE-1 and GSK-3 β inhibitors. *Angew. Chem. Int. Ed Engl.* 54, 1578–1582. doi: 10.1002/anie.201410456
- Quiedeville, A., Boulouard, M., Hamidouche, K., Da Silva Costa-Aze, V., Nee, G., Rochais, C., et al. (2015). Chronic activation of 5-HT₄ receptors or blockade of 5-HT₆ receptors improve memory performances. *Behav. Brain Res.* 293, 10–17. doi: 10.1016/j.bbr.2015.07.020
- Riemer, C., Borroni, E., Levet-Trafit, B., Martin, J. R., Poli, S., Porter, R. H. P., et al. (2003). Influence of the 5-HT₆ receptor on acetylcholine release in the cortex: pharmacological characterization of 4-(2-bromo-6-pyrrolidin-1-ylpyridine-4-sulfonyl)phenylamine, a potent and selective 5-HT₆ receptor antagonist. *J. Med. Chem.* 46, 1273–1276. doi: 10.1021/jm021085c
- Rochais, C., Lecoutey, C., Gaven, F., Giannoni, P., Hamidouche, K., Hedou, D., et al. (2015). Multi target-directed ligands (MTDLs) with acetylcholinesterase (AChE) inhibitory and serotonergic subtype 4 receptor (5-HT₄R) agonist activities as potential agents against Alzheimer's disease: the design of donecopride. *J. Med. Chem.* 58, 3172–3187. doi: 10.1021/acs.jmedchem.5b00115

- Russo, O., Cachard-chastel, M., Giner, M., Soulier, J., Berthouze, M., Richard, T., et al. (2009). Design, synthesis, and biological evaluation of new 5-HT₄ receptor agonists: application as amyloid cascade modulators and potential therapeutic utility in Alzheimer's disease design. *J. Med. Chem.* 52, 2214–2225. doi: 10.1021/jm801327q
- Shirazi-Southall, S., Rodriguez, D. E., and Nomikos, G. G. (2002). Effects of typical and atypical antipsychotics and receptor selective compounds on acetylcholine efflux in the hippocampus of the rat. *Neuropsychopharmacology* 26, 583–594. doi: 10.1016/s0893-133x(01)00400-6
- Steward, L. J., Ge, J., Stowe, R. L., Brown, D. C., Bruton, R. K., Stokes, P. R. A., et al. (1996). Ability of 5-HT₄ receptor ligands to modulate rat striatal dopamine release *in vitro* and *in vivo*. *Br. J. Pharmacol.* 117, 55–62. doi: 10.1111/j.1476-5381.1996.tb15154.x
- Wilkinson, D., Windfeld, K., and Colding-Jørgensen, E. (2014). Safety and efficacy of idalopirdine, a 5-HT₆ receptor antagonist, in patients with moderate Alzheimer's disease (LADDER): a randomised, double-blind, placebo-controlled phase 2 trial. *Lancet Neurol.* 13, 1092–1099. doi: 10.1016/s1474-4422(14)70198-x
- Yahiaoui, S., Hamidouche, K., Ballandonne, C., Davis, A., De Oliveira Santos, J. S., Freret, T., et al. (2016). Design, synthesis, and pharmacological evaluation of multitarget-directed ligands with both serotonergic subtype 4 receptor (5-HT₄) partial agonist and 5-HT₆ antagonist activities, as potential treatment of Alzheimer's disease. *Eur. J. Med. Chem.* 121, 283–293. doi: 10.1016/j.ejmech.2016.05.048
- Zhang, M. Y., Hughes, Z. A., Kerns, E. H., Lin, Q., and Beyer, C. E. (2007). Development of a liquid chromatography/tandem mass spectrometry method for the quantitation of acetylcholine and related neurotransmitters in brain microdialysis samples. *J. Pharm. Biomed. Anal.* 44, 586–593. doi: 10.1016/j.jpba.2007.02.024
- Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2019 Hatat, Yahiaoui, Lecoutey, Davis, Freret, Boulouard, Claeysen, Rochais and Dallemagne. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.