

The PDE4 inhibitor roflumilast improves memory in rodents at  
non-emetic doses

Peer-reviewed author version

VANMIERLO, Tim; Creemers, Pim; Akkerman, Sven; van Duinen, Marlies; Sambeth, Anke; DE VRY, Jochen; Uz, Tolga; Blokland, Arjan & Prickaerts, Jos (2016) The PDE4 inhibitor roflumilast improves memory in rodents at non-emetic doses. In: BEHAVIOURAL BRAIN RESEARCH, 303, p. 26-33.

DOI: 10.1016/j.bbr.2016.01.031

Handle: <http://hdl.handle.net/1942/21610>

# 1 The PDE4 inhibitor roflumilast improves memory in rodents at non-emetic doses

2  
3 Tim Vanmierlo<sup>1,2</sup>, Pim Creemers<sup>1†</sup>, Sven Akkerman<sup>1</sup>, Marlies van Duinen<sup>1</sup>, Anke Sambeth<sup>3</sup>,  
4 Jochen De Vry<sup>1</sup>, Tolga Uz<sup>4</sup>, Arjan Blokland<sup>3</sup>, and Jos Prickaerts<sup>1\*</sup>

5  
6 <sup>1</sup> Dept. of Psychiatry and Neuropsychology, School for Mental Health and Neuroscience, Maastricht University,  
7 Maastricht, the Netherlands

8 <sup>2</sup> Dept. of Immunology and Biochemistry, BIOMED, Hasselt University, Hasselt, Belgium

9 <sup>3</sup> Dept. of Neuropsychology and Psychopharmacology, Maastricht University, Maastricht, the Netherlands

10 <sup>4</sup> Experimental Medicine CNS, Takeda Development Center Americas, Inc., Deerfield, USA.

11 <sup>†</sup> current affiliation: Dept. of Neuromodulation, Clinical, Boston Scientific Group plc, Maastricht, the Netherlands

12  
13 \*Corresponding author: Jos Prickaerts (jos.prickaerts@maastrichtuniversity.nl); Dept. Psychiatry and  
14 Neuropsychology, School of Mental Health and Neuroscience, Maastricht University, PO Box 616, 6200 MD  
15 Maastricht, the Netherlands; Tel.: +31433881168; Fax: +31433884086

## 16 **Acknowledgement**

17 Takeda (Deerfield, USA) funded the combination therapy study and participated in its design.

## 18 **Abstract**

19 Enhancement of central availability of the second messenger cAMP is a promising approach to improve  
20 cognitive function. Pharmacological inhibition of phosphodiesterase type 4 (PDE4), a group of cAMP  
21 hydrolyzing enzymes in the brain, has been shown to improve cognitive performances in rodents and  
22 monkeys. However, inhibition of PDE4 is generally associated with severe emetic side-effects.  
23 Roflumilast, an FDA-approved PDE4 inhibitor for treatment of chronic obstructive pulmonary disease  
24 (COPD), is yielding only mild emetic side effects.

25 In the present study we investigate the potential of roflumilast as a cognition enhancer and to  
26 determine the potential coinciding emetic response in comparison to rolipram, a classic PDE4 inhibitor  
27 with pronounced emetic effects.

28 Cognition enhancement was evaluated in mice and it was found that both roflumilast and rolipram  
29 enhanced memory in an object location task (0.03 mg/kg), whereas only roflumilast was effective in a  
30 spatial Y-maze (0.1 mg/kg). Emetic potential was measured using competition of PDE4 inhibition for  $\alpha$ 2-  
31 adrenergic receptor antagonism in which recovery from xylazine/ketamine-mediated anesthesia is used  
32 as a surrogate marker. While rolipram displayed emetic properties at a dose 10 times the memory-  
33 enhancing dose, roflumilast only showed increased emetic-like properties at a dose 100 times the  
34 memory-enhancing dose. Moreover, combining sub-efficacious doses of the approved cognition-  
35 enhancer donepezil and roflumilast, which did not improve memory when given alone, fully restored  
36 object recognition memory deficit in rats induced by the muscarinic receptor antagonist scopolamine.  
37 These findings suggest that roflumilast offers a more favorable window for treatment of cognitive  
38 deficits compared to rolipram.  
39

1 **Key words**

- 2 PDE4
- 3 PDE4 inhibition
- 4 Roflumilast
- 5 Rolipram
- 6 Cognition
- 7 Memory
- 8 Emesis
- 9 cAMP

10

11 **Highlights**

12

- 13 1. Roflumilast improves spatial memory equal to rolipram in rodents.
- 14 2. Roflumilast treatment evokes less emetic side effects compared to rolipram.
- 15 3. Combining sub-effficacious doses of roflumilast and donepezil is fully effective in improving spatial
- 16 memory.

17 **1. Introduction**

18 Phosphodiesterase type 4 inhibitors (PDE4-Is) are a group of drugs that prevent hydrolyzing of the  
19 intracellular second messenger cyclic adenosine monophosphate (cAMP), thereby prolonging the cAMP-  
20 induced downstream signaling [1]. cAMP activates protein kinase A (PKA), resulting in the  
21 phosphorylation of the transcription factor cAMP response element binding protein (P-CREB). P-CREB  
22 induces expression of CREB responsive genes involved in a wide range of biological functions, such as  
23 synaptic plasticity, memory and cognition [2-6], but also inflammation and bronchodilation [7-11].

24

25 PDE4 is expressed in the hippocampus and cortex [12, 13] and was also found to remain present in the  
26 aged and Alzheimer brain [14, 15]. It can therefore be considered as a promising target for  
27 enhancement of cognitive functions. Acute treatment with a PDE4-I clearly improved cognitive functions  
28 in healthy and pharmacologically impaired rodents which was particularly investigated using the classic  
29 PDE4-I rolipram (e.g. [3, 16]; for reviews see [17-19]). Chronic treatment with rolipram is also beneficial  
30 for brain plasticity and cognitive function as was found in age-impaired mice and transgenic mice  
31 models of Alzheimer’s disease (e.g. [20, 21]; for reviews see [17, 18]). Moreover, acute treatment with  
32 rolipram [22] or the PDE4-I D159687 [23] improved cognition including executive function/planning in  
33 monkeys. In humans, only a few PDE4-Is have been tested up to clinical phase II studies. For instance,  
34 MK-0952 was tested on cognitive impairment in mild to moderate Alzheimer’s disease  
35 (ClinicalTrials.gov, NCT00362014). However, its announced results [24] have not been disclosed.  
36 Currently, HT-0712 is being tested on age-associated memory impairment (ClinicalTrials.gov,  
37 NCT02013310).

38

39 The development of PDE4-Is as therapeutic drugs has been hampered by the dose-limiting emetic side  
40 effects (nausea and even vomiting) in humans [25-27], as was particularly evident with rolipram.  
41 Whether MK-0952 and HT-0712 have emetic effects is not yet known. Currently, PDE4-Is are being  
42 developed that show a strong reduction in emetic side effects. Roflumilast is such an example and its

1 effect on nausea is mostly mild or moderate in intensity and occurs in only 5% of the subjects [28]. In  
2 2011 the selective PDE4-I roflumilast was approved by the FDA as an anti-inflammatory drug under the  
3 name of Daliresp or Daxas, indicated as a treatment to reduce the risk of chronic obstructive pulmonary  
4 disease (COPD) exacerbations in patients with severe COPD associated with chronic bronchitis and a  
5 history of exacerbations [29, 30].

6  
7 PDE4 is a family of proteins encoded by four different genes (PDE4A-D). In addition, each gene has  
8 multiple splice variants (e.g. PDE4D1–PDE4D11) [19]. Rolipram and roflumilast show no PDE4 subtype  
9 selectivity, with the exception of PDE4C, which is inhibited at a slightly lower potency [31]. It has been  
10 demonstrated that PDE4D splice variants are a very selective target for memory enhancement [5, 10].  
11 Therefore, PDE4-Is and in particular selective PDE4D-Is provide a promising target for cognition  
12 enhancement. However, in particular PDE4D inhibition has been attributed to induce emesis [32, 33].  
13 This is likely due to inhibition of PDE4D in the area postrema and nucleus of the solitary tract, which are  
14 responsible for the emetic reflex, as well as in the gut. Thus, it remains a challenge to reduce the emetic  
15 effect of possible PDE4-Is that enhance cognition. One approach to achieve this is by designing small-  
16 molecule negative allosteric modulators of PDE4D, e.g. D159687, that do not completely inhibit  
17 enzymatic activity ( $I_{max} \sim 80\text{--}90\%$ ) [10, 34]. Another approach is to design selective full ( $I_{max} 100\%$ )  
18 PDE4D inhibitors, such as Gebr7b, that nevertheless show a partial reduction in emetic potential [35]  
19 (and recently reviewed in [36]).

20  
21 Because of the reduced emetic properties of roflumilast in humans we explored in the present  
22 preclinical study whether roflumilast has the potential to test as a translational cognition enhancer (e.g.  
23 ClinicalTrials.gov, NCT01433666). First we determined whether roflumilast improves memory in mice,  
24 using the object location test (OLT) and the spatial Y-maze, which are based on the natural tendency of  
25 rodents to explore displaced objects and novel spatial environment [37, 38]. As rodents are unable to  
26 vomit, we investigated the emetic properties using the xylazine/ketamine-induced anesthesia test.  
27 PDE4-Is mimic the pharmacological actions of  $\alpha 2$ -adrenoceptor antagonists, which has been described  
28 as the mechanism by which in particular PDE4D-Is induce emesis [32, 33]. Since  $\alpha 2$ -adrenoceptor  
29 antagonists are also known to reverse xylazine/ketamine-induced anesthesia, the latter effect can be  
30 used as a surrogate measure of emesis in rodents [32, 33]. Next, the mice were used for a  
31 pharmacokinetic study to verify central availability and biological activity of the PDE4-Is. Finally, we  
32 tested the potential beneficial interaction between the acetylcholinesterase inhibitor (AChE-I) donepezil,  
33 which is used as a cognition enhancer for the treatment of Alzheimer’s disease [39], and roflumilast on  
34 the scopolamine induced memory deficit in rats using the object recognition task (ORT).

## 35 **2. Materials and Methods**

### 36 **2.1 Animals**

37 All experimental procedures were approved by the local ethical committee of the Maastricht University  
38 for animal experiments and met the governmental guidelines and EU guidelines for the care and use of  
39 laboratory animals. Twenty-four seven months-old male C57BL/6NCrI mice (Charles River, L’Arbresle,  
40 France) were used for the OLT, spatial Y-maze, and xylazine/ketamine induced  $\alpha 2$ -adrenergic receptor-

1 mediated anesthesia test. Average body weight was 27.6 grams at the beginning of the study. Twenty-  
2 four male Wistar rats were supplied by Charles River (Sulzfeld, Germany) and tested between 3-4  
3 months of age in the ORT. Average body weight at the beginning of the study was 345 g. All animals  
4 were housed individually in standard individually ventilated cages on sawdust bedding in an air-  
5 conditioned room (about 21°C). They were kept on a 12/12-h reversed light/dark cycle (lights on from  
6 19.00 to 7.00 h) and had free access to food and water. Animals were housed in the same room as  
7 where they were tested. A radio, which was playing softly, provided background noise in the room. All  
8 testing was done between 9.00 and 18.00 h. All behavioral experiments were performed in a  
9 randomized blinded setup. The sample size was calculated based on a power analysis using historical  
10 data on rolipram treatment in the object recognition/location task [16, 35, 38]. For the murine studies,  
11 all mice were subject chronologically to the object location task, the spatial Y-maze, and  
12 xylazine/ketamine test with a one-week-interval between the tasks.

13

## 14 **2.2 Treatments**

### 15 *2.2.1 Object location and spatial Y-maze in mice*

16 Drugs were prepared daily. For testing in mice, both roflumilast (a kind gift of BioCrea, Radebeul,  
17 Germany; MW 403.21) and rolipram (Sigma-Aldrich St. Louis, USA; MW 275.34) were dissolved in  
18 dimethylsulfoxide (DMSO) and kept at 4°C; this stock solution was used for further dilutions in 0.5%  
19 methylcellulose. Roflumilast and rolipram were used in form of its free base. All injected solutions  
20 consisted of 0.5% methylcellulose with a fixed DMSO percentage (1.2%) (vehicle). Doses of 0.01, 0.03  
21 and 0.1 mg/kg of rolipram or roflumilast or vehicle were administered subcutaneously (s.c.). Based on  
22 previous findings, PDE4-I administration was performed 3 h after the learning trial as this has an  
23 optimum effect on object memory performance [40]. Injection volume was 5 µl/g.

24

### 25 *2.2.2 Object recognition in rats*

26 For testing in rats, roflumilast (kindly provided by Takeda, Konstanz, Germany; MW 403.21) was  
27 dissolved in 98% methylcellulose solution (0.5% methylcellulose) and 2% Tween 80. Roflumilast in doses  
28 of 0 (vehicle), 0.0001, 0.0003, 0.001, 0.003, 0.01 and 0.03 mg/kg was administered intraperitoneally (i.p.).  
29 Scopolamine (scopolamine hydrobromide; Sigma-Aldrich St. Louis, USA) and donepezil (donepezil  
30 hydrochloride; a kind gift from Solvay, Weesp, the Netherlands) were both dissolved in saline (0.9%  
31 NaCl). Scopolamine was administered i.p. at a dose of 0.1 mg/kg, which has been shown to reliably  
32 impair object recognition memory [41]. Donepezil was dissolved in saline and administered orally (p.o.)  
33 at a dose of 0.1 mg/kg, which has been shown to be a sub-efficacious dose, not having an effect on  
34 object recognition memory [41]. All compounds were administered 30 min before the learning trial and  
35 injection volumes were 1 ml/kg.

36

### 37 *2.2.3 Xylazine/ketamine test in mice*

38 All solutions were prepared daily. The anesthetic solution consisted of xylazine (CEVA Santé Animale,  
39 Naaldwijk, the Netherlands) (10 mg/kg) and ketamine (Eurovet Animal Health, Bladel, the Netherlands)  
40 (60 mg/kg). Injections were given i.p. and injection volume was 1.1 µl/g. Doses of 0.03, 0.3 and 3.0  
41 mg/kg roflumilast, 0.03 and 3.0 mg/kg rolipram, or vehicle, were administered 15 min after anesthesia  
42 induction. Injection volume was 5 µl/g (s.c.).

## 1 **2.3 Behavioral analyses**

### 2 *2.3.1 Object location in mice*

3 The OLT was performed as described elsewhere [42]. The apparatus consisted of a circular arena, 40 cm  
4 in diameter. Half of the 40 cm high transparent polyvinyl chloride wall was covered from the outside  
5 with white paper. Two objects were placed symmetrically about 10 cm away from the wall on the  
6 separation line, between the transparent and the covered side of the arena. Four different sets of  
7 objects were available: (1) a cone made of brass (maximal diameter 6 cm and total height 3.8 cm), (2) a  
8 transparent glass bottle (diameter 2.7 cm, height 8.5 cm) filled with sand and water, (3) a massive metal  
9 cube (2.5 cm × 5 cm × 7.5 cm) with two holes (diameter 1.5 cm), and (4) a massive aluminium cube with  
10 a tapering top (4.5 cm × 4.5 cm × 8.5 cm). Objects and locations were presented to the animals in a  
11 balanced manner to avoid object or place biases. A testing session comprised two trials of 4 min. Before  
12 each trial, mice were placed in an empty Makrolon cage (incubation cage) for 4 min, to prime their  
13 attention. During the first learning trial (T1) two identical objects were placed symmetrically about 10  
14 cm away from the wall on the separation line between the transparent and covered side of the arena.  
15 After the first exploration period, the mouse was put back in its home cage. Mice then received their  
16 treatment 3 h post T1. Subsequently, after the normal forgetting inter-trial interval of 24 h, the mouse  
17 was placed in the apparatus for the second trial of 4 min (T2). Two identical objects as in T1 were used;  
18 one object was placed in the previously used position, whereas the other was placed in a novel position  
19 which could be either a fixed distance towards the front or a fixed distance towards the back of the  
20 arena. The times spent exploring each object during T1 and T2 were recorded manually using a personal  
21 computer by an experimenter unaware of the conditions being tested. Exploration was defined in the  
22 following manner: directing the nose to the object at a distance of no more than 2 cm and/or touching  
23 the object with the nose. Sitting on the object was not considered as exploratory behavior. To avoid  
24 olfactory cues, the objects were thoroughly cleaned with 70% ethanol after each trial. The testing order  
25 of conditions was determined randomly. T1 was always on Monday and Thursday in order to have a  
26 sufficient wash-out period between compound sessions. Prior to compound testing, animals were  
27 handled daily and adapted to the procedures in two days, i.e. they were allowed to explore the  
28 apparatus twice for 3 min each day. All four objects used in this study were presented in these two  
29 subsequent days. Thereafter, animals were adapted to the compound administration by one s.c. vehicle  
30 injection.

31 The time spent exploring the two identical objects in T1 was indicated as “a1” and “a2”,  
32 respectively. The time spent exploring the familiar and the new location in T2 was indicated as “a” and  
33 “b”, respectively. The following variables were calculated:  $e1 = a1 + a2$ ;  $e2 = a + b$  and  $d2 = (b - a)/e2$ .  $e1$   
34 and  $e2$  are measures of the total exploration time of both objects during T1 and T2, respectively.  $d2$  is a  
35 relative measure of discrimination, corrected for exploration activity ( $e2$ ). This  $d2$  index can range from -  
36 1 to 1, with 1 indicating complete preference for the novel location/object and 0 signifying no  
37 preference for either location/object. Animals with an  $e1$  or  $e2$  lower than 7.5 seconds were excluded  
38 since this does not allow to reliably measure memory performance [43].

### 39 *2.3.2 Spatial Y-maze in mice*

40 After completion of the OLT test, the Y-maze spatial memory test was performed using a Y-maze  
41 consisting of three equal arms, with each arm being separated from the others at a 120° angle [44, 45].

1 Each arm was 40 cm long, 17 cm high, 4 cm wide at the bottom and 13 cm wide at the top. In the task,  
2 one arm was made inaccessible due to a removable blockade placed in front of the arm during trial one.  
3 The blocked arm was randomly alternated among the different trials. In between trials, the maze was  
4 cleaned thoroughly with a 70% ethanol solution to reduce olfactory biases. A mouse was placed in one  
5 of the open arms (termed the 'start arm', which was randomized over groups) and allowed to explore  
6 the two open arms of the maze for 5 min. One arm visit required that both hind paws of the animal had  
7 to be placed completely inside the arm. Mice received treatment at 3 h after the first learning trial. After  
8 a 24 h interval, the mouse was placed back into its corresponding start arm, but now the blockade had  
9 been removed, providing access to the previously blocked arm (termed the 'novel arm'). Spatial memory  
10 was assessed by the amount of time spent in the novel arm, which had to be significantly more than  
11 33.33%, corrected for the latency to move from the start arm to another arm and the amount of time  
12 the animal spent in the center of the maze. The times spent exploring each arm was recorded using  
13 Ethovision (Noldus, the Netherlands). Also, the total distance the mouse had travelled in the Y-maze was  
14 measured, to rule out any effects caused by differences in activity level.

15

### 16 *2.3.3 Xylazine/ketamine induced $\alpha$ 2-adrenergic receptor-mediated anesthesia test in mice*

17 Given the emetic properties of PDE4-Is, the ability of roflumilast to shorten xylazine/ketamine induced  
18  $\alpha$ 2-adrenergic receptor-mediated anesthesia was measured one week after completion of the Y-maze  
19 test. Since mice are a non-vomiting species, the xylazine/ketamine anesthesia test, a well-established  
20 surrogate marker for emesis in mice, was applied [32]. The earlier the treated mice recover their righting  
21 reflex upon anesthesia the more competition there is on the  $\alpha$ 2-adrenergic receptor. Xylazine (CEVA  
22 Santé Animale, Naaldwijk, the Netherlands) (10 mg/kg) and ketamine (Eurovet Animal Health, Bladel,  
23 the Netherlands) (60 mg/kg) was given intraperitoneal (i.p.) to induce anesthesia (injection volume: 1.1  
24  $\mu$ l/g) [35]. Rolipram, roflumilast or vehicle were administered 15 min after induction of anesthesia and  
25 the mouse was placed in a dorsal position awaiting recovery. The time-delay to the recovery towards  
26 the righting reflex (four paws on the floor) was used as an endpoint to measure the time to regain their  
27 righting reflex. Animals regaining their righting reflex before the treatment injection or not displaying a  
28 righting reflex within 2 h were excluded from analysis.

### 29 *2.3.4 Object recognition in rats*

30 Rats were tested in the ORT which was performed as described elsewhere [38, 43]. The apparatus  
31 consisted of a circular arena, 83 cm in diameter. The back half of the 40 cm high wall was made of gray  
32 polyvinyl chloride (PVC) and the front was made of transparent PVC. Two objects were placed in  
33 symmetrical positions at the mid-line between the gray and transparent halves of the arena, about 10  
34 cm away from the wall. Four sets of 3 identical objects were used: 1) a standard 1 L brown transparent  
35 glass bottle (diameter 10 cm, height 22 cm) filled with water, 2) a metal cube (10.0 x 5.0 x 7.5 cm) with  
36 two holes (diameter 1.9 cm), 3) a cone consisting of a gray polyvinyl chloride base (maximal diameter 18  
37 cm) with a collar on top made of brass (total height 16 cm), and 4) an aluminum cube with a tapering  
38 top (13.0 x 8.0 x 8.0 cm). Objects were presented to the animals in a balanced manner to avoid object or  
39 place biases. A test session comprised two trials, each with durations of 3 min. During the learning trial  
40 (T1) the apparatus contained two identical objects (object a1 and a2). Subsequently, rats were put back  
41 in their home cage for a 1 h interval. After the retention interval, rats were put back into the arena for  
42 the test trial (T2). In T2, the two objects from T1 are replaced by one identical copy "a" and a different

1 novel object “b”. The times spent in exploring each object during T1 and T2 were recorded manually on  
2 a personal computer using the same criteria as for mice. In order to avoid the presence of olfactory  
3 cues, the objects were thoroughly cleaned with a 70% ethanol solution before each trial. The  
4 discrimination index (d2) was determined as described for mice. Testing was always on Monday,  
5 Wednesday or Friday in order to have a sufficient wash-out period between compound sessions. Prior to  
6 compound testing, rats were handled and adapted to the procedures and compound administration  
7 similarly as with the mice. All rats showed sufficient exploration to have a reliable memory performance  
8 [43].

## 9 **2.4 Pharmacokinetics**

10 After behavioral testing all mice were subsequently used for the determination of plasma and brain  
11 concentrations following s.c. administration. Pharmacokinetic (PK) measurements were expected to be  
12 close to the detection limit after dosing with the behaviorally active dose of 0.03 mg/kg of both  
13 compounds in the OLT. For this reason doses were increased and animals were sacrificed for blood and  
14 brain sampling at 30 min and 21 h after dosing of 0.3 or 3 mg/kg. For rolipram 11 animals were used and  
15 for roflumilast 12 animals; n = 3 per time point (except for the 3 mg/kg rolipram condition, n=2).

16 Blood was drawn from the saphenous vein using heparin-coated tubes (Microcuvette CB300,  
17 Sarstedt, Germany), which were temporarily stored on ice and then centrifuged within 15 min of  
18 collection. Plasma was isolated using centrifugation (1500 g for 10 min at 4°C) and pipetted into vials.  
19 Immediately after blood collection the animal was decapitated. The complete brain was collected,  
20 rinsed with ice-cold saline, placed in a cup and weighed. Plasma and brain samples were immediately  
21 stored at -80°C until analytical processing. Roflumilast, roflumilast-N-oxide and rolipram were quantified  
22 by Agilux laboratories (Worcester, USA). Roflumilast-N-oxide was measured in the same samples as  
23 roflumilast. For analytical sample preparation, plasma was used as is, while brain samples were first  
24 homogenized in 80:20 water:acetonitrile. Both matrices were processed for drug quantification using  
25 liquid–liquid extraction methodology followed by a characterized liquid chromatography-tandem mass  
26 spectrometry (LC-MS/MS) assay. Standard curves were prepared in control matrices, an appropriate  
27 dynamic range was achieved, and instrument settings and potentials were adjusted to optimize the MS  
28 signal for the compounds using Masslynx software with the Quanlynx application manager (Waters Ltd).  
29 For both roflumilast and rolipram the lowest level of quantification (LLOQ) was 0.5 ng/ml for plasma and  
30 1.25 ng/g for brain. If the plasma concentration (Cp) or brain concentration (Cb) of a sample was below  
31 the quantification limit (BQL), but one or more of the other samples in the same compound/dose group  
32 had measurable values, the BQL was treated as zero.

## 33 **2.5 Statistics**

34 One-sample t-statistics were performed in order to assess whether the d2 index for each treatment  
35 condition differed significantly from zero (chance level) in the OLT or ORT. Effects between treatment  
36 conditions were analyzed using a one-way ANOVA, followed by a post-hoc analysis with Dunnett’s  
37 multiple comparison test. In the Y-maze, one-sample t-statistics were used to assess whether the  
38 percentage of time spent in the novel arm for each treatment condition differed significantly from  
39 33.33% (chance level). Differences between treatment conditions in the Y-maze were analyzed using a  
40 one-way ANOVA followed by Dunnett’s multiple comparison test. The latter analysis was also applied in  
41 the xylazine/ketamine test. An  $\alpha$  level of 0.05 was considered significant.



### 3. Results

#### 3.1 Memory

In the OLT, the exploration times between treatment conditions for both T1 (e1:  $F(6,113) = 1.27$ , n.s.) and T2 (e2:  $F(6,113) = 1.66$ , n.s.) were comparable (data not shown). One mouse was excluded from the analysis in the rolipram 0.1 mg/kg and roflumilast 0.01 mg/kg condition, due to insufficient exploration times ( $< 7.5$  sec). One-sample t-tests showed that the d2 indices of the rolipram 0.03 mg/kg and roflumilast 0.03 mg/kg conditions significantly differed from zero, indicating that mice discriminated between locations of the objects after 24 h (Figure 1). Comparisons between rolipram conditions showed significant differences ( $F(3,68) = 3.99$ ,  $p < 0.05$ ). Post-hoc analysis revealed that the d2 index in the rolipram 0.03 mg/kg condition differed significantly from the vehicle condition (Figure 1). Between group comparisons of the roflumilast conditions also showed significant differences ( $F(3,68) = 15.71$ ,  $p < 0.001$ ). Post-hoc analysis revealed that the d2 index of the roflumilast 0.03 mg/kg condition differed significantly from the vehicle condition (Figure 1).

Subsequently, the mice were tested for spatial memory in the Y-maze. Herein, the exploration time of the novel arm is quantified as a measure for spatial memory. Before starting the Y-maze experiments, one mouse died for reasons unknown. Further, in the 0.3 mg/kg rolipram condition, one mouse showed no exploration and one animal ignored one arm completely and these animals were consequently excluded from analysis. The distance moved during the test trial was neither significantly different between the vehicle and rolipram conditions ( $F(3,86) = 0.46$ , n.s.), nor between the vehicle and roflumilast conditions ( $F(3,88) = 1.64$ , n.s.). **One-sample t-tests showed that the percentage time spent in the novel arm during the second trial was significantly above the chance threshold (33.33%) only for the roflumilast 0.1 mg/kg condition ( $t(22) = 2.11$ ,  $p < 0.05$ ) (Figure 2). However, comparisons between treatment conditions showed no significant difference on novel arm exploration between vehicle and roflumilast conditions ( $F(3,88) = 1.64$ , n.s) or vehicle and rolipram conditions ( $F(3,86) = 0.46$ , n.s.).**

#### 3.2 Emetic-like behavior

The results for both rolipram and roflumilast on the duration of the  $\alpha_2$ -adrenergic receptor-mediated anesthesia are shown in Figure 3. One mouse was excluded because it showed the righting reflex before being treated with 0.3 mg/kg roflumilast. Rolipram treatment significantly affected the duration of xylazine/ketamine-induced anesthesia ( $F(2,33) = 8.10$ ,  $p < 0.001$ ). Post-hoc analysis showed that the rolipram 0.3 mg/kg condition had a significantly reduced delay until the righting reflex compared with the vehicle condition (Figure 3). Roflumilast conditions also differed significantly from the vehicle condition ( $F(3,42) = 2.90$ ,  $p < 0.05$ ). Post-hoc analysis showed a reduced righting reflex delay for the 3.0 mg/kg roflumilast condition (Figure 3).

#### 3.3 Pharmacokinetics

Respectively, 0.5 h and 21 h after administration, rolipram or roflumilast and its active metabolite roflumilast N-oxide were measured in the plasma and brain of the mice. 0.5 h after administration of a dose of 3 mg/kg of either compound, rolipram or roflumilast and roflumilast N-oxide were readily detectable in plasma and brain (Table 1). Administration of 0.3 mg/kg of rolipram or roflumilast yielded similar results, although roflumilast N-oxide was not detected in the brain anymore. However, 21 h after administration, only with the high dose of 3 mg/kg, roflumilast and its metabolite were still detected and in plasma only.

1

### 2 3.4 Combination therapy

3 First, a dose-response experiment was performed in the scopolamine-induced memory deficit model to  
4 determine a sub-eficacious dose of roflumilast. No significant differences between treatment  
5 conditions were observed in the level of exploration in T1 (e1:  $F(7,120) = 1.09$ , n.s.) and T2 (e2:  $F(7,120)$   
6  $= 0.82$ , n.s.) (data not shown). One sample *t*-tests showed that the d2 indices of the 0.0003 to 0.03  
7 mg/kg roflumilast dose conditions were significantly higher than zero, just as was the case for the  
8 vehicle condition, while after scopolamine treatment the d2 index was equal to zero (Figure 4A). The d2  
9 index was different between treatment conditions ( $F(3,81) = 6.67$ ,  $p < 0.001$ ) and post-hoc analyses  
10 showed that the vehicle, 0.001 mg/kg, 0.003 mg/kg, 0.01 mg/kg and 0.03 mg/kg conditions had a  
11 significantly higher d2 value compared to the scopolamine condition (figure 4A). On the other hand, only  
12 the scopolamine, 0.0001 mg/kg, and 0.0003 mg/kg conditions were significantly lower compared to the  
13 vehicle condition.

14 Next we tested the combination of the previously established sub-eficacious dose of roflumilast  
15 and the nootropic donepezil, also at a sub-eficacious dose (0.1 mg/kg), in the scopolamine-induced  
16 memory deficit model. There were no differences between treatment conditions in the level of  
17 exploration in T1 (e1:  $F(4,115) = 0.44$ , n.s.) and T2 (e2:  $F(4,115) = 1.46$ , n.s.) (data not shown). One  
18 sample *t*-tests showed that only the d2 index of the vehicle and the combination of roflumilast and  
19 donepezil upon scopolamine were significantly higher than zero (Figure 4B). The other treatment  
20 conditions showed no differences from chance performance. A significant differences in d2 between  
21 treatment conditions was found ( $F(4,115) = 13.78$ ,  $p < 0.001$ ) and post-hoc analyses showed that the  
22 vehicle and the combined treatments of roflumilast and donepezil had a significantly higher d2 index  
23 when compared with scopolamine alone. At the same time, separate testing conditions of scopolamine,  
24 donepezil and roflumilast were all significantly lower when compared with the vehicle condition (Figure  
25 4B).

## 26 4. Discussion

27 We found that the PDE4-I roflumilast appears equally potent (OLT) than the classic PDE4-I rolipram in  
28 improving spatial memory of mice. The potential to induce emesis appears to be at least 10 times lower  
29 in roflumilast when compared with rolipram. Combining sub-eficacious doses of roflumilast and  
30 donepezil reversed a scopolamine-induced memory deficit of rats in the ORT. Importantly, none of the  
31 compounds had any effects on exploratory activity which could have influenced memory performances.

32

33 PDE4 inhibition has been studied intensively using the PDE4-I rolipram and it was found to enhance  
34 cognition in various experimental animal models including healthy, age- and pharmacologically  
35 impaired, and transgenic Alzheimer mice models (for reviews see [17-19]). However, PDE4 inhibition in  
36 humans results in unwanted side effects including emesis [9, 25, 26]. Recently, new generation PDE4-Is  
37 including MK-0952, HT-0712, D159687, and Gebr-7b were developed and all were shown preclinically to  
38 improve memory [46-48]. In addition, emetic effects were reduced in rodents or monkeys (e.g. Gebr-7b  
39 [35] and D159687 [10], respectively). Until now only roflumilast made it to the clinic because of its  
40 favorable emetic/clinical profile in humans, though this has been demonstrated for the FDA approved  
41 treatment of COPD [29, 30]. Both rolipram and roflumilast inhibit most PDE4 isoforms, in particular the

1 PDE4B and PDE4D isoforms in the hippocampus [49]. Interestingly, when compared with rolipram,  
2 roflumilast has a preferable emetic profile as emetic effects were demonstrated in fewer human  
3 subjects and emesis appears to be only nausea-related without effects on vomiting [28], suggesting a  
4 difference in intrinsic properties still.

5  
6 When directly comparing doses of roflumilast with the PDE4-I rolipram, both compounds were equally  
7 effective (0.03 mg/kg, s.c.) in improving OLT performance of mice. Interestingly, the discrimination index  
8 (d2) for the roflumilast treatment group displayed an even higher absolute value compared with the  
9 rolipram treatment group, indicating that roflumilast may have a stronger impact on spatial memory  
10 performance. The optimal dose of rolipram was in line with previous studies [46]. The potent effect of  
11 roflumilast was further confirmed by the data of the spatial Y-maze test, where the effective dose of  
12 roflumilast differed significantly from vehicle at an effective dose of 0.1 mg/kg (s.c.). The same dose of  
13 rolipram did not show a significant improvement in spatial memory, yet this might be prevalent with  
14 higher power.

15  
16 Since emesis is a side-effect of PDE4-Is in general, this measure was investigated using the  
17 xylazine/ketamine induced  $\alpha$ 2-adrenergic receptor-mediated anesthesia task. Rolipram showed a strong  
18 effect on emetic-like effect with a dose (0.3 mg/kg) 10 times higher than the effective dose of 0.03  
19 mg/kg in the OLT. In contrast, roflumilast showed an emetic potential only at a dose (3 mg/kg) 100 times  
20 the effective dose of 0.03 mg/kg in the OLT and 30 times the effective dose of 0.1 mg/kg in the spatial Y-  
21 maze. Based on these data, the emetic potential of roflumilast is estimated to be more than 10 times  
22 lower than that of rolipram.

23  
24 The dose-response study evaluated the effects of different doses of roflumilast in a memory deficit  
25 model, induced by the muscarinic acetylcholine receptor antagonist scopolamine. The d2 comparisons  
26 with the scopolamine condition revealed that roflumilast was able to fully restore object recognition  
27 memory function in rats at doses of 0.001-0.03 mg/kg (i.p.). Whereas single sub-efficacious doses of  
28 roflumilast (0.0001 mg/kg) and donepezil (0.1 mg/kg) could not reverse the scopolamine-induced deficit,  
29 testing the combination of both compounds at these sub-efficacious doses completely reversed the  
30 scopolamine-induced deficit. This suggest that the procognitive effects of both AChE-Is and PDE4-Is,  
31 which both have dose limitations due to primarily gastrointestinal side-effects including emesis [9, 25,  
32 26, 50], could be enhanced when combined at low doses.

33  
34 The approximate cerebral blood volume relative to total unperfused brain volume is 0.04 [51], thus a  
35 Cb/Cp of >0.04 indicates that a compound is brain penetrant. The Cb/Cp of roflumilast in our mice is  
36 close to 1, clearly indicating that the compound is brain penetrant. However, the metabolite roflumilast  
37 N-oxide is less brain penetrant with a Cb/Cp of 0.08. Likewise, it has very recently been demonstrated  
38 that roflumilast is clearly brain penetrant, and to a lower degree its metabolite, after 10 days of  
39 treatment in hypertensive rats [47]. In that particular study roflumilast was also able to ameliorate the  
40 hypertension-induced memory deficit of the rats in the ORT, again supporting a procognitive effect of  
41 roflumilast.

1 Between doses we assume linear concentrations in plasma and brain as has been demonstrated for  
2 roflumilast [47]. Extrapolating our PK measurements to the behaviorally active dose of 0.03 mg/kg in the  
3 OLT, one could expect a total C<sub>b</sub> of 4.18 ng/ml (10.37 nM) in the brain. PDE4D is assumed to be the most  
4 important PDE4 subtype for memory function [34, 52] and the IC<sub>50</sub> value of roflumilast for PDE4D  
5 inhibition is maximally 0.4 nM [49]. To our knowledge, only the free fraction in plasma has been very  
6 well established for roflumilast. In humans and pigs the free fraction of roflumilast is about 1, while in  
7 other species it is slightly higher, as is also evident in mice with a free plasma fraction of roflumilast of  
8 3.7% (personal communication Dr. Hermann Tenor). When assuming an IC<sub>50</sub> concentration to be  
9 biologically active in the OLT, the hypothetical free fraction in the mouse brain can be calculated, which  
10 is  $(0.4/10.37) = 3.85\%$ . This is very close to the value of 3.7% of the free plasma fraction. Alternatively,  
11 when assuming a similar free fraction of 3.7% for roflumilast in the brain, this results in a free brain  
12 concentration of 0.37 nM. Interestingly, this is almost similar to the IC<sub>50</sub> for roflumilast. Thus, there are  
13 indications that roflumilast is biologically active at least already 30 min after its administration, thus  
14 improving the memory performance of the mice in the OLT. This also accounts for the improved  
15 performance in the Y-maze as its optimum dose was approximately three times higher as in the OLT. The  
16 contribution of the metabolite in this respect is likely very minor based on the lower potency (PDE4D  
17 IC<sub>50</sub> is maximally 0.8 nM) and brain penetration. With respect to roflumilast attenuating the  
18 scopolamine-induced memory deficit of rats in the OLT, future PK studies are needed to establish the  
19 exact level of PDE4 inhibition.

20  
21 Rolipram is clearly brain penetrant in our mice with the C<sub>b</sub>/C<sub>p</sub> around 2, which is very similar to previous  
22 studies (e.g. [53]). As linear concentrations of rolipram in plasma and brain can be assumed [53], a total  
23 C<sub>b</sub> of 3.15 ng/ml (11.44 nM) after the behaviorally active dose of 0.03 mg/kg in the OLT can be  
24 extrapolated from our PK measurements. To our knowledge, in rodents only free fractions of plasma  
25 have been established [54-56], which seem to be higher as for instance in other species including pigs.  
26 When assuming that the free fraction in the mouse brain is similar to that in the pig brain, i.e. 19.2%  
27 [56], this results in a free brain concentration of 2.20 nM rolipram. This is very close to the IC<sub>50</sub> of 3 nM  
28 for the rolipram high-affinity binding site [57]. Thus, rolipram appears to be sufficiently biologically  
29 active in the brain of our mice to improve the memory performance in the OLT.

30  
31 In agreement with our previous studies, we observed that a PDE4-I improves late consolidation  
32 processes when injected 3 h after the learning trial. Late consolidation processes are very likely  
33 dependent on glutamatergic postsynaptic cAMP/PKA signalling [58]. Based on our PK measurement,  
34 both rolipram and roflumilast are not present in brain or plasma anymore at 21 h after their injection,  
35 corresponding to the time point of the test trial in the OLT and Y-maze. This rules out the possibility of  
36 PDE4 inhibition influencing retrieval processes. The memory improvement after roflumilast inhibition in  
37 the scopolamine-induced memory deficit is in agreement with previous findings with rolipram [16].  
38 Muscarinic receptors are crucially important for memory acquisition [59, 60] and it is assumed that  
39 scopolamine induces an acquisition deficit. The mechanism of action behind the attenuation of the  
40 cholinergic memory deficit is likely related to the presynaptic release of neurotransmitters including  
41 acetylcholine which might be mediated by increased levels of cAMP [61, 62], as a result of inhibition of  
42 PDE4.

43

1 In conclusion, PDE4 inhibition is a promising pharmacological target for treatment of cognitive deficits.  
2 Roflumilast has a more optimal window for memory enhancement than rolipram since its emetic  
3 potential is more than 10 times lower than that of rolipram. Roflumilast in low doses, to further avoid  
4 possible emetic effects, can also be considered as a combination therapy with low doses of AChE-Is to  
5 avoid the latter's gastrointestinal effects. Considering the complexity of the PDE4 family with its many  
6 isoform specific subtypes, further research is needed to establish the diversity of effects on cognition,  
7 but also side effect profiles including emesis.  
8

## 9 5. References

- 10 [1] Silvestre JS, Fernández AG, Palacios JM. Preliminary evidence for an involvement of the cholinergic  
11 system in the sedative effects of rolipram in rats. *Pharmacology Biochemistry and Behavior*. 1999;64:1-  
12 5.
- 13 [2] Bailey CH, Bartsch D, Kandel ER. Toward a molecular definition of long-term memory storage.  
14 *Proceedings of the National Academy of Sciences*. 1996;93:13445.
- 15 [3] Barad M, Bourtchouladze R, Winder DG, Golan H, Kandel E. Rolipram, a type IV-specific  
16 phosphodiesterase inhibitor, facilitates the establishment of long-lasting long-term potentiation and  
17 improves memory. *Proceedings of the National Academy of Sciences*. 1998;95:15020.
- 18 [4] Frey U, Huang Y, Kandel E. Effects of cAMP simulate a late stage of LTP in hippocampal CA1 neurons.  
19 *Science*. 1993;260:1661-4.
- 20 [5] Li YF, Cheng YF, Huang Y, Conti M, Wilson SP, O'Donnell JM, et al. Phosphodiesterase-4D knock-out  
21 and RNA interference-mediated knock-down enhance memory and increase hippocampal neurogenesis  
22 via increased cAMP signaling. *The Journal of Neuroscience*. 2011;31:172-83.
- 23 [6] Zhang HT. Cyclic AMP-specific phosphodiesterase-4 as a target for the development of  
24 antidepressant drugs. *Current pharmaceutical design*. 2009;15:1688-98.
- 25 [7] Dal Piaz V, Giovannoni MP. Phosphodiesterase 4 inhibitors, structurally unrelated to rolipram, as  
26 promising agents for the treatment of asthma and other pathologies. *European journal of medicinal  
27 chemistry*. 2000;35:463-80.
- 28 [8] Martinez A, Gil C. cAMP-specific phosphodiesterase inhibitors: promising drugs for inflammatory and  
29 neurological diseases. *Expert opinion on therapeutic patents*. 2014;24:1311-21.
- 30 [9] Spina D. PDE4 inhibitors: current status. *British journal of pharmacology*. 2008;155:308-15.
- 31 [10] Burgin AB, Magnusson OT, Singh J, Witte P, Staker BL, Bjornsson JM, et al. Design of  
32 phosphodiesterase 4D (PDE4D) allosteric modulators for enhancing cognition with improved safety.  
33 *Nature biotechnology*. 2009;28:63-70.
- 34 [11] Reneerkens OAH, Rutten K, Steinbusch HWM, Blokland A, Prickaerts J. Selective phosphodiesterase  
35 inhibitors: a promising target for cognition enhancement. *Psychopharmacology*. 2009;202:419-43.
- 36 [12] Braun NN, Reutiman TJ, Lee S, Folsom TD, Fatemi SH. Expression of phosphodiesterase 4 is altered  
37 in the brains of subjects with autism. *Neuroreport*. 2007;18:1841-4.
- 38 [13] Ugarte A, Gil-Bea F, Garcia-Barroso C, Cedazo-Minguez A, Ramirez MJ, Franco R, et al. Decreased  
39 levels of cGMP in CSF are associated with cognitive decline and amyloid pathology in Alzheimer's  
40 disease. *Neuropathology and applied neurobiology*. 2014.
- 41 [14] de Lima MN, Presti-Torres J, Garcia VA, Guimaraes MR, Scalco FS, Roesler R, et al. Amelioration of  
42 recognition memory impairment associated with iron loading or aging by the type 4-specific  
43 phosphodiesterase inhibitor rolipram in rats. *Neuropharmacology*. 2008;55:788-92.
- 44 [15] McLachlan CS, Chen ML, Lynex CN, Goh DL, Brenner S, Tay SK. Changes in PDE4D isoforms in the  
45 hippocampus of a patient with advanced Alzheimer disease. *Archives of neurology*. 2007;64:456-7.

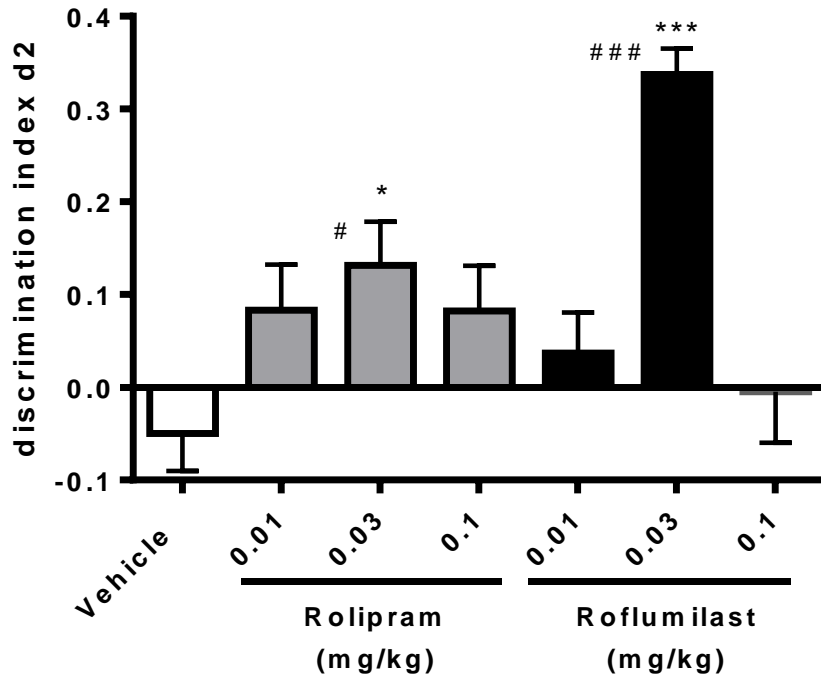
- 1 [16] Rutten K, Prickaerts J, Blokland A. Rolipram reverses scopolamine-induced and time-dependent  
2 memory deficits in object recognition by different mechanisms of action. *Neurobiology of learning and*  
3 *memory*. 2006;85:132-8.
- 4 [17] Hansen RT, 3rd, Zhang HT. Phosphodiesterase-4 modulation as a potential therapeutic for cognitive  
5 loss in pathological and non-pathological aging: possibilities and pitfalls. *Curr Pharm Des*. 2015;21:291-  
6 302.
- 7 [18] Heckman PR, Blokland A, Ramaekers J, Prickaerts J. PDE and cognitive processing: Beyond the  
8 memory domain. *Neurobiology of learning and memory*. 2015;119:108-22.
- 9 [19] Richter W, Menniti FS, Zhang HT, Conti M. PDE4 as a target for cognition enhancement. *Expert*  
10 *opinion on therapeutic targets*. 2013;17:1011-27.
- 11 [20] Bach ME, Barad M, Son H, Zhuo M, Lu YF, Shih R, et al. Age-related defects in spatial memory are  
12 correlated with defects in the late phase of hippocampal long-term potentiation in vitro and are  
13 attenuated by drugs that enhance the cAMP signaling pathway. *Proceedings of the National Academy of*  
14 *Sciences of the United States of America*. 1999;96:5280-5.
- 15 [21] Gong B, Vitolo OV, Trinchese F, Liu S, Shelanski M, Arancio O. Persistent improvement in synaptic  
16 and cognitive functions in an Alzheimer mouse model after rolipram treatment. *Journal of Clinical*  
17 *Investigation*. 2004;114:1624-34.
- 18 [22] Rutten K, Basile JL, Prickaerts J, Blokland A, Vivian JA. Selective PDE inhibitors rolipram and sildenafil  
19 improve object retrieval performance in adult cynomolgus macaques. *Psychopharmacology (Berl)*.  
20 2008;196:643-8.
- 21 [23] Sutcliffe JS, Beaumont V, Watson JM, Chew CS, Beconi M, Hutcheson DM, et al. Efficacy of selective  
22 PDE4D negative allosteric modulators in the object retrieval task in female cynomolgus monkeys  
23 (*Macaca fascicularis*). *PloS one*. 2014;9:e102449.
- 24 [24] Gallant M, Aspiotis R, Day S, Dias R, Dube D, Dube L, et al. Discovery of MK-0952, a selective PDE4  
25 inhibitor for the treatment of long-term memory loss and mild cognitive impairment. *Bioorganic &*  
26 *medicinal chemistry letters*. 2010;20:6387-93.
- 27 [25] Girod V. Nausea and emesis models for the safety evaluation of PDE4 inhibitors. *Journal of*  
28 *Pharmacological and Toxicological Methods*. 2010;62:e13-e4.
- 29 [26] Hebenstreit G, Fellerer K, Fichte K, Fischer G. Rolipram in Major Depressive Disorder: Results of a  
30 double-blind comparative study with imipramine. *Pharmacopsychiatry; Pharmacopsychiatry*. 1989.
- 31 [27] Puhan M. Phosphodiesterase 4 inhibitors for chronic obstructive pulmonary disease. *The Cochrane*  
32 *database of systematic reviews*. 2011:ED000028.
- 33 [28] Rabe KF, Bateman ED, O'Donnell D, Witte S, Bethke TD. Roflumilast--an oral anti-inflammatory  
34 treatment for chronic obstructive pulmonary disease: a randomised controlled trial. *The Lancet*.  
35 2005;366:563-71.
- 36 [29] Chong J, Poole P, Leung B, Black PN. Phosphodiesterase 4 inhibitors for chronic obstructive  
37 pulmonary disease. *Cochrane Database of Systematic Reviews*. 2011;5.
- 38 [30] Izquierdo J, Aparicio J. Roflumilast for COPD. *Drugs of today (Barcelona, Spain: 1998)*. 2010;46:823.
- 39 [31] Claveau D, Chen SL, O'Keefe S, Zaller DM, Styhler A, Liu S, et al. Preferential inhibition of T helper 1,  
40 but not T helper 2, cytokines in vitro by L-826,141 [4-[2-(3,4-Bisdifluoromethoxyphenyl)-2-[4-(1,1,1,3,3,3-  
41 hexafluoro-2-hydroxypropan- 2-yl)-phenyl]-ethyl]3-methylpyridine-1-oxide], a potent and selective  
42 phosphodiesterase 4 inhibitor. *The Journal of pharmacology and experimental therapeutics*.  
43 2004;310:752-60.
- 44 [32] Robichaud A, Savoie C, Stamatiou P, Lachance N, Jolicoeur P, Rasori R, et al. Assessing the emetic  
45 potential of PDE4 inhibitors in rats. *British journal of pharmacology*. 2002;135:113-8.
- 46 [33] Robichaud A, Stamatiou PB, Jin SLC, Lachance N, MacDonald D, Laliberté F, et al. Deletion of  
47 phosphodiesterase 4D in mice shortens alpha~2-adrenoceptor-mediated anesthesia, a behavioral  
48 correlate of emesis. *Journal of Clinical Investigation*. 2002;110:1045-52.

- 1 [34] Gurney ME, D'Amato EC, Burgin AB. Phosphodiesterase-4 (PDE4) molecular pharmacology and  
2 Alzheimer's disease. *Neurotherapeutics : the journal of the American Society for Experimental*  
3 *NeuroTherapeutics*. 2015;12:49-56.
- 4 [35] Bruno O, Fedele E, Prickaerts J, Parker L, Canepa E, Brullo C, et al. GEBR-7b, a novel PDE4D selective  
5 inhibitor that improves memory in rodents at non-emetic doses. *British journal of pharmacology*. 2011.
- 6 [36] Ricciarelli R, Fedele E. Phosphodiesterase 4D: an enzyme to remember. *Br J Pharmacol*.  
7 2015;172:4785-9.
- 8 [37] Rutten K, Van Donkelaar EL, Ferrington L, Blokland A, Bollen E, Steinbusch HW, et al.  
9 Phosphodiesterase inhibitors enhance object memory independent of cerebral blood flow and glucose  
10 utilization in rats. *Neuropsychopharmacology : official publication of the American College of*  
11 *Neuropsychopharmacology*. 2009;34:1914-25.
- 12 [38] Ennaceur A, Delacour J. A new one-trial test for neurobiological studies of memory in rats. 1:  
13 Behavioral data. *Behavioural brain research*. 1988;31:47-59.
- 14 [39] Loveman E, Green C, Kirby J, Takeda A, Picot J, Payne E, et al. The clinical and cost-effectiveness of  
15 donepezil, rivastigmine, galantamine and memantine for Alzheimer's disease: Gray Publishing; 2006.
- 16 [40] Rutten K, Prickaerts J, Hendrix M, van der Staay FJ, Sik A, Blokland A. Time-dependent involvement  
17 of cAMP and cGMP in consolidation of object memory: studies using selective phosphodiesterase type 2,  
18 4 and 5 inhibitors. *Eur J Pharmacol*. 2007;558:107-12.
- 19 [41] Prickaerts J, van Goethem NP, Chesworth R, Shapiro G, Boess FG, Methfessel C, et al. EVP-6124, a  
20 novel and selective alpha7 nicotinic acetylcholine receptor partial agonist, improves memory  
21 performance by potentiating the acetylcholine response of alpha7 nicotinic acetylcholine receptors.  
22 *Neuropharmacology*. 2012;62:1099-110.
- 23 [42] Vanmierlo T, Rutten K, Dederen J, Bloks VW, van Vark-van der Zee LC, Kuipers F, et al. Liver X  
24 receptor activation restores memory in aged AD mice without reducing amyloid. *Neurobiology of aging*.  
25 2011;32:1262-72.
- 26 [43] Akkerman S, Blokland A, Reneerkens O, van Goethem NP, Bollen E, Gijsselaers HJ, et al. Object  
27 recognition testing: methodological considerations on exploration and discrimination measures.  
28 *Behavioural brain research*. 2012;232:335-47.
- 29 [44] Dellu F, Contarino A, Simon H, Koob GF, Gold LH. Genetic differences in response to novelty and  
30 spatial memory using a two-trial recognition task in mice. *Neurobiology of learning and memory*.  
31 2000;73:31-48.
- 32 [45] Sierksma AS, Prickaerts J, Chouliaras L, Rostamian S, Delbroek L, Rutten BP, et al. Behavioral and  
33 neurobiological effects of prenatal stress exposure in male and female APP<sup>swe</sup>/PS1<sup>dE9</sup> mice. *Neurobiol*  
34 *Aging*. 2013;34:319-37.
- 35 [46] Bruno O, Fedele E, Prickaerts J, Parker LA, Canepa E, Brullo C, et al. GEBR-7b, a novel PDE4D  
36 selective inhibitor that improves memory in rodents at non-emetic doses. *Br J Pharmacol*.  
37 2011;164:2054-63.
- 38 [47] Jabaris SG, Sumathy H, Kumar RS, Narayanan S, Thanikachalam S, Babu CS. Effects of rolipram and  
39 roflumilast, phosphodiesterase-4 inhibitors, on hypertension-induced defects in memory function in  
40 rats. *Eur J Pharmacol*. 2015;746:138-47.
- 41 [48] Peters M, Bletsch M, Stanley J, Wheeler D, Scott R, Tully T. The PDE4 inhibitor HT-0712 improves  
42 hippocampus-dependent memory in aged mice. *Neuropsychopharmacology : official publication of the*  
43 *American College of Neuropsychopharmacology*. 2014;39:2938-48.
- 44 [49] Hatzelmann A, Morcillo EJ, Lungarella G, Adnot S, Sanjar S, Beume R, et al. The preclinical  
45 pharmacology of roflumilast--a selective, oral phosphodiesterase 4 inhibitor in development for chronic  
46 obstructive pulmonary disease. *Pulmonary pharmacology & therapeutics*. 2010;23:235-56.
- 47 [50] Birks J, Flicker L. Donepezil for mild cognitive impairment. *The Cochrane database of systematic*  
48 *reviews*. 2006:CD006104.

- 1 [51] Hitchcock SA, Pennington LD. Structure-brain exposure relationships. *Journal of medicinal*  
2 *chemistry*. 2006;49:7559-83.
- 3 [52] Li YF, Cheng YF, Huang Y, Conti M, Wilson SP, O'Donnell JM, et al. Phosphodiesterase-4D knock-out  
4 and RNA interference-mediated knock-down enhance memory and increase hippocampal neurogenesis  
5 via increased cAMP signaling. *J Neurosci*. 2011;31:172-83.
- 6 [53] Krause W, Kuhne G. Pharmacokinetics of rolipram in the rhesus and cynomolgus monkeys, the rat  
7 and the rabbit. *Studies on species differences. Xenobiotica*. 1988;18:561-71.
- 8 [54] Fujita M, Zoghbi SS, Crescenzo MS, Hong J, Musachio JL, Lu JQ, et al. Quantification of brain  
9 phosphodiesterase 4 in rat with (R)-[11C]Rolipram-PET. *NeuroImage*. 2005;26:1201-10.
- 10 [55] Lourenco CM, Houle S, Wilson AA, DaSilva JN. Characterization of r-[11C]rolipram for PET imaging of  
11 phosphodiesterase-4: in vivo binding, metabolism, and dosimetry studies in rats. *Nuclear medicine and*  
12 *biology*. 2001;28:347-58.
- 13 [56] Guo Q, Brady M, Gunn RN. A biomathematical modeling approach to central nervous system  
14 radioligand discovery and development. *Journal of nuclear medicine : official publication, Society of*  
15 *Nuclear Medicine*. 2009;50:1715-23.
- 16 [57] Barnette MS, Grous M, Cieslinski LB, Burman M, Christensen SB, Torphy TJ. Inhibitors of  
17 phosphodiesterase IV (PDE IV) increase acid secretion in rabbit isolated gastric glands: correlation  
18 between function and interaction with a high-affinity rolipram binding site. *The Journal of pharmacology*  
19 *and experimental therapeutics*. 1995;273:1396-402.
- 20 [58] Bollen E, Puzzo D, Rutten K, Privitera L, De Vry J, Vanmierlo T, et al. Improved long-term memory via  
21 enhancing cGMP-PKG signaling requires cAMP-PKA signaling. *Neuropsychopharmacology : official*  
22 *publication of the American College of Neuropsychopharmacology*. 2014;39:2497-505.
- 23 [59] Gil-Bea FJ, Solas M, Mateos L, Winblad B, Ramirez MJ, Cedazo-Minguez A. Cholinergic hypofunction  
24 impairs memory acquisition possibly through hippocampal Arc and BDNF downregulation.  
25 *Hippocampus*. 2011;21:999-1009.
- 26 [60] Robinson L, Platt B, Riedel G. Involvement of the cholinergic system in conditioning and perceptual  
27 memory. *Behavioural brain research*. 2011;221:443-65.
- 28 [61] Imanishi T, Sawa A, Ichimaru Y, Miyashiro M, Kato S, Yamamoto T, et al. Ameliorating effects of  
29 rolipram on experimentally induced impairments of learning and memory in rodents. *Eur J Pharmacol*.  
30 1997;321:273-8.
- 31 [62] Schoffelmeer AN, Wardeh G, Mulder AH. Cyclic AMP facilitates the electrically evoked release of  
32 radiolabelled noradrenaline, dopamine and 5-hydroxytryptamine from rat brain slices. *Naunyn-*  
33 *Schmiedeberg's archives of pharmacology*. 1985;330:74-6.

34

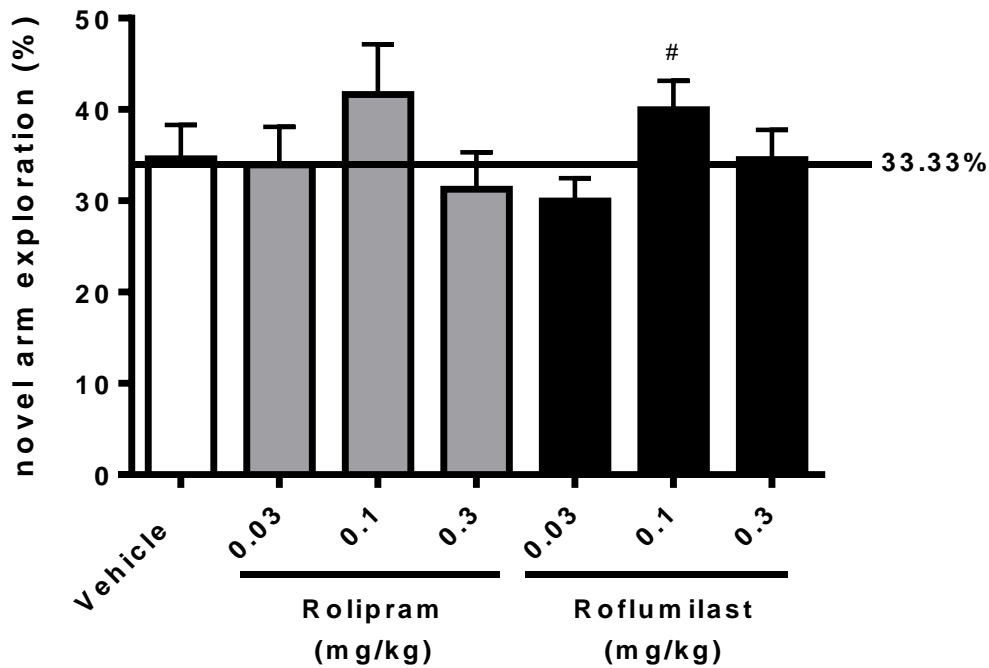




1

2 **Figure 1.** Effects of rolipram (s.c.) and roflumilast (s.c.) on the discrimination index (d2) in an object  
 3 location task after a 24 h retention interval in 7 months old C57BL/6NCrl mice (means + SEMs). The d2  
 4 index of the rolipram and roflumilast 0.03 mg/kg dose conditions were significantly higher than zero, i.e.  
 5 indicating discrimination between object locations (one-sample t-tests: #:  $p < 0.05$ , ###:  $p < 0.001$ ).  
 6 When compared with vehicle treatment, both these rolipram and roflumilast conditions had a  
 7 significantly higher d2 index. A significant difference from the vehicle condition is depicted with asterisks  
 8 (Dunnett's multiple comparison test: \*:  $p < 0.05$ , \*\*\*:  $p < 0.001$ ). n=15-24 per condition.

1



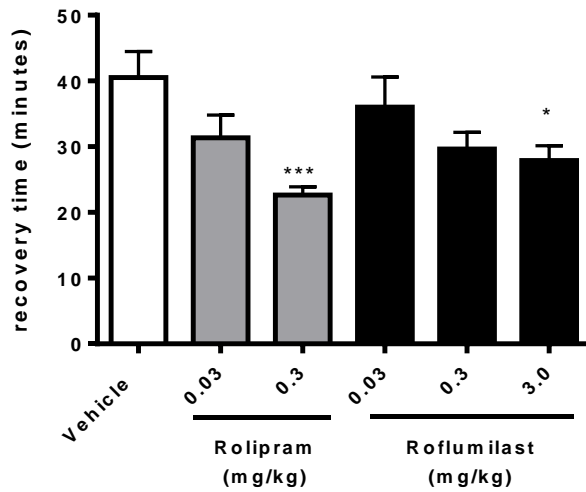
2

3 **Figure 2.** Effects of rolipram (s.c.) and roflumilast (s.c.) on novel arm exploration (%) in the spatial Y-  
4 maze after a 24 h retention interval in 7 months old C57BL/6NCrl mice (means + SEMs). The 0.1 mg/kg  
5 dose of roflumilast differed from chance performance with a novel arm performance above 33.33%  
6 (one-sample t-test; #: p < 0.05). When compared with the vehicle condition, neither rolipram, nor  
7 roflumilast had a significant effect on novel arm exploration in the Y-maze. n=21-23 per condition.

8

9

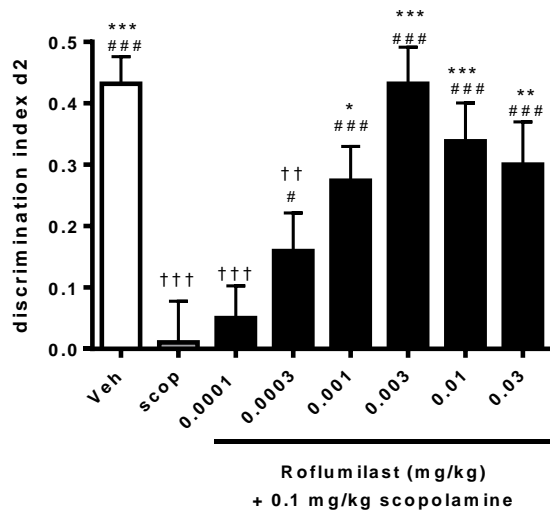
1



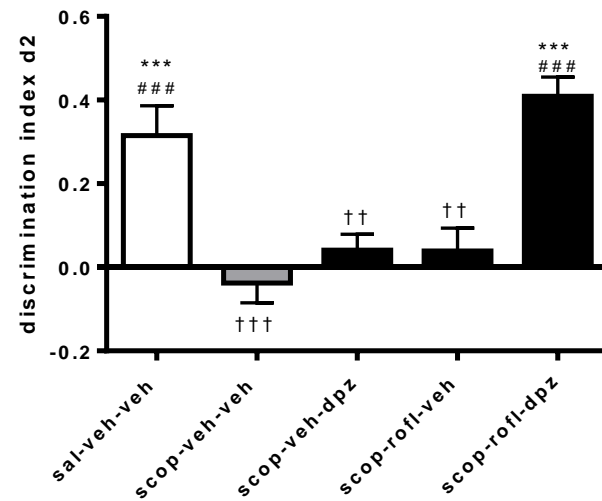
2

3 **Figure 3.** Effects of roflumilast (s.c.) and rolipram (s.c.) on the duration of anesthesia (min) induced by  
4 the combination of xylazine (10 mg/kg, i.p.) and ketamine (60 mg/kg, i.p) in C57BL/6NCrl mice. Fifteen  
5 min following the induction of anesthesia, mice were treated with of rolipram or roflumilast. The  
6 duration of anesthesia was assessed by the return of righting reflex (means + SEMs). When compared  
7 with the vehicle condition, 0.3 mg/kg rolipram significantly reduced the anesthesia time. Roflumilast  
8 only showed a tendency towards a reduced anesthesia time at the 3.0 mg/kg condition, compared with  
9 vehicle (Dunnett's multiple comparison test: (\*):  $0.05 < p < 0.1$ , \*\*\*:  $p \leq 0.001$ ). n=11-12 per condition.

1 A



B



2

3 **Figure 4.** Effects of roflumilast (i.p.) and its combination with donepezil (dpz; p.o.) on the discrimination  
 4 index (d2) in an object recognition task on a scopolamine (scop; i.p.)-induced memory deficit in 4  
 5 months old Wistar rats. (A) When treated with vehicle (Veh), rats clearly recognized the familiar object  
 6 as the d2 is different from zero. Scopolamine treatment impaired memory performance, whereas when  
 7 roflumilast was given at the same time, d2 was different from zero again (except for the 0.0001 mg/kg  
 8 dose) (one-sample t-tests: #:  $p < 0.05$ ; ###:  $p < 0.001$ ). Compared with the scopolamine condition, the  
 9 0.003-0.03 doses of roflumilast had a higher d2 (Dunnett's multiple comparison test: \*:  $p < 0.05$ , \*\*:  $p <$   
 10  $0.01$ ; \*\*\*:  $p < 0.001$ ). Of note, scopolamine alone and in combination with the lowest dose of 0.0001  
 11 roflumilast was different from the vehicle condition (Dunnett's multiple comparison test: ††:  $p < 0.01$ ;  
 12 †††:  $p < 0.001$ ).  $n=16$  per condition. (B) When combined with scopolamine, neither a sub-  
 13 efficacious dose of donepezil (0.1 mg/kg) nor a sub-  
 14 efficacious dose of roflumilast (0.0001 mg/kg) was able to  
 15 increase the value of d2 above zero. When combining both compounds at the sub-  
 16 efficacious doses, the  
 17 d2 was higher than zero, indicating recognition (one sample t-test: ###:  $p < 0.001$ ). This condition is also  
 18 different from the scopolamine condition (Dunnett's multiple comparison test: \*\*\*:  $p < 0.001$ ). Of note,  
 the scopolamine and both sub-  
 efficacious compound conditions were different from the vehicle  
 condition (††:  $p < 0.01$ ; †††:  $p < 0.001$ ).  $n=24$  per condition.

1 **Table 1.** Pharmacokinetics of roflumilast, roflumilast N-oxide and rolipram in the mouse

<b>interval</b>	<b>0.5 h</b>	<b>21 h</b>
<i>roflumilast (0.3 mg/kg)</i>		
$C_p$ (ng/ml)	14.90 (1.72)	BQL
$C_b$ (ng/g)	13.83 (2.47)	BQL
$C_b:C_p$	0.97 (0.25)	BQL
<i>roflumilast (3 mg/kg)</i>		
$C_p$ (ng/ml)	69.27 (17.03)	7.87 (n.a.)
$C_b$ (ng/g)	45.77 (14.40)	BQL
$C_b:C_p$	0.88 (0.44)	BQL
<i>roflumilast N-oxide (0.3 mg/kg)</i>		
$C_p$ (ng/ml)	3.83 (0.78)	BQL
$C_b$ (ng/g)	BQL	BQL
$C_b:C_p$	BQL	BQL
<i>roflumilast N-oxide (3 mg/kg)</i>		
$C_p$ (ng/ml)	15.53 (2.76)	0.58 (0.29)
$C_b$ (ng/g)	0.44 (n.a.)	BQL
$C_b:C_p$	0.08 (n.a.)	BQL
<i>rolipram (0.3 mg/kg)</i>		
$C_p$ (ng/ml)	46.50 (6.89)	BQL
$C_b$ (ng/g)	65.05 (4.95)	BQL
$C_b:C_p$	1.63 (0.06)	BQL
<i>rolipram (3 mg/kg)</i>		
$C_p$ (ng/ml)	433.67 (125.06)	BQL
$C_b$ (ng/g)	596.67 (178.67)	BQL
$C_b:C_p$	2.11 (1.35)	BQL

2 Neuropharmacokinetics of roflumilast, roflumilast N-oxide and rolipram (0.3 and 3 mg/kg, s.c.) 0.5 and  
3 21 h after administration (n=3 per condition, except rolipram 3 mg/kg with n=2). Total plasma ( $C_p$ ) and  
4 total brain ( $C_b$ ) concentrations are reported as means ( $\pm$  SEMs). For all compounds, the LLOQ for plasma  
5 and brain were 0.5 ng/ml and 1.25 ng/g, respectively. n.a.: not applicable; BQL: below quantification  
6 limit.