Divergent Effects of Anandamide Transporter Inhibitors With Different Target Selectivity on Social Play Behavior in Adolescent Rats

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Running title: Anandamide transporter inhibitors and social behavior

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Number of text pages: 36
Number of tables: 2
Number of figures: 6
Number of references: 40
Number of words in: Abstract: 248; Introduction: 748; Discussion: 1500

Abbreviations:
2-AG: 2-arachidonoylglycerol
FAAH: fatty acid amide hydrolase

Section: Behavioral Pharmacology
ABSTRACT

The endocannabinoid system plays an important role in the modulation of affect, motivation and emotion. Social play behavior is a natural reinforcer in adolescent rats, and we have recently shown that interacting endocannabinoid, opioid and dopamine systems modulate social play. In the present study, we tested the hypothesis that, in contrast to administration of exogenous cannabinoid agonists, increasing local endocannabinoid signaling through anandamide transporter inhibition enhances social play. To this aim, we tested the effects of two anandamide transporter inhibitors with different target selectivity on social play behavior in adolescent rats. Interestingly, we found that the prototypical anandamide transporter inhibitor AM404 reduced social play, whereas its more selective analogue VDM11 enhanced it. The effects of AM404 were not mediated through its known pharmacological targets, since they were not blocked by the CB₁ cannabinoid receptor antagonist SR141716A, the CB₂ cannabinoid receptor antagonist SR144528, or by the TRPV1 vanilloid receptor antagonist capsazepine. In contrast, the increase in social play induced by VDM11 was dependent on cannabinoid, opioid and dopaminergic neurotransmission, since it was blocked by the CB₁ cannabinoid receptor antagonist SR141716A, the opioid receptor antagonist naloxone and the dopamine receptor antagonist alpha-flupenthixol. These findings support the notion that anandamide plays an important role in the modulation of social interaction in adolescent rats, and suggest that selective anandamide transporter inhibitors might be useful for the treatment of social dysfunctions. Furthermore, these results suggest that off-target effects may be responsible for some of the conflicting effects of anandamide transporter inhibitors on behavior.
INTRODUCTION

Under physiological circumstances, brain CB₁ cannabinoid receptors are activated by lipid derivatives called endocannabinoids, including anandamide and 2-arachidonoylglycerol (2-AG). Endocannabinoids are released on demand; that is, there is little, if any, tonic endocannabinoid signalling in the brain (Piomelli, 2003). Thus, the effects of exogenous cannabinoid receptor agonists, that lack the spatial and temporal specificity of locally released endocannabinoids, do not necessarily mimic the physiological functions of the endocannabinoid system. An alternative pharmacological approach to study the physiological and behavioral functions of endocannabinoid neurotransmission is to use indirect cannabinoid agonists, i.e. compounds that selectively interfere with endocannabinoid signalling by inhibiting either endocannabinoid synthesis or deactivation. These indirect (ant)agonists might be useful pharmacotherapeutic agents, since local modulation of endocannabinoid activity produces more subtle and selective effects than treatment with direct cannabinoid receptor agonists.

Upon discovery of fatty acid amide hydrolase (FAAH) (Cravatt et al., 1996), which catalyzes the intracellular hydrolysis of anandamide, several FAAH inhibitors were developed (Lambert and Fowler, 2005). For example, URB597 is a potent FAAH inhibitor that has no affinity for cannabinoid receptors and does not induce the well-known effects of CB₁ cannabinoid receptor agonists, such as catalepsy, hypothermia or hyperphagia (Kathuria et al., 2003). However, it exerts analgesic, anxiolytic- and antidepressant-like effects (Gobbi et al., 2005; Kathuria et al., 2003).
Given the involvement of the endocannabinoid system in affect, motivation and emotion (Solinas et al., 2008), we recently started to investigate the role of endocannabinoids in social play behavior. Social play is the most characteristic and vigorous form of social interaction displayed by adolescent mammals, and it is crucial for social and cognitive development (Panksepp et al., 1984; Vanderschuren et al., 1997; Hol et al., 1999; Van den Berg et al., 1999). Thus, animals housed in isolation during adolescence, when social play is most abundant, show several behavioral impairments in adulthood (Van den Berg et al., 1999; Hol et al., 1999). Consistent with its importance for development, social play is a natural reinforcer (Calcagetti and Schechter, 1992; Humphreys and Einon, 1981).

Interestingly, we found that the FAAH inhibitor URB597 increases social play behavior (Trezza and Vanderschuren, 2008a; -2008b). The effect of URB597 on social play was exerted through neurotransmitter systems known to play key roles in positive emotions, i.e. cannabinoid, opioid and dopaminergic neurotransmission. In contrast, the CB1 cannabinoid receptor agonist WIN55,212-2 reduced social play behavior, through a non-opioid, non-dopaminergic, CB1-receptor mediated mechanism. These results suggest that release of anandamide within the neural circuits mediating social behavior facilitates social play, whereas stimulating cannabinoid neurotransmission outside this circuitry may interfere with the normal execution of complex social acts (Trezza and Vanderschuren, 2008a; -2008b). Moreover, these results highlight once more that direct and indirect cannabinoid agonists can have very different effects on behavior.

Before hydrolysis by intracellular FAAH can take place, anandamide needs to be transported into the cell (Beltramo et al., 1997; Glaser et al., 2005). Several ligands
have been found to inhibit this process. In particular, AM404 is the best characterized anandamide uptake inhibitor *in vivo*. Its effects are comparable to those of URB597, i.e. increases in brain anandamide levels without the well-known effects of CB$_1$ cannabinoid receptor agonists (Beltramo et al., 1997), and potentially beneficial properties for the treatment of pain, motor impairments and anxiety disorders (Bortolato et al., 2006; Fernandez-Espejo et al., 2004; La Rana et al., 2006). These similarities led us to investigate whether URB597 and AM404 have comparable effects on social play behavior.

One important point of concern is that the behavioral effects of anandamide transporter inhibitors can be difficult to interpret. Some drugs currently available, including AM404, lack selectivity and have effects on non-cannabinoid targets (Glaser et al., 2005; Lambert and Fowler, 2005). For these reasons, we compared the effects of AM404 on social play with those of its more selective analogue VDM11 (De Petrocellis et al., 2000). In addition, we investigated the pharmacological mechanisms underlying the effects of these drugs on social play behavior.

Lack of cooperative play with peers and atypical social behavior are core symptoms of autism and antisocial personality disorders (American Psychiatric Association, 2000). By clarifying the role of endocannabinoid neurotransmission in the regulation of social behavior, the present findings may help to understand how the adolescent brain processes social information and may provide novel therapeutic targets for the treatment of developmental social dysfunctions. Furthermore, by investigating how target selectivity of anandamide transporter inhibitors influences behavioral responses, this study may aid in the development of more selective...
compounds to optimize the therapeutic opportunities offered by cannabinoid neurotransmission.
METHODS

Animals
Male Wistar rats (Charles River, Sulzfeld, Germany) arrived in our animal facility at 21 days of age and were housed in groups of four in 40 x 26 x 20 (l x w x h) Macrolon cages under controlled conditions (i.e. temperature 20–21 °C, 60–65% relative humidity and 12/12 h light cycle with lights on at 7.00 a.m.). Food and water were available ad libitum.

All animals were experimentally naive and were used only once, with the following exception: the effects of AM404, VDM11 and (R)-methanandamide on locomotor activity (Table 2), which have been widely described in the literature (Bortolato et al., 2006; de Lago et al., 2004), were assessed using animals that had previously been used as vehicle controls in a behavioral experiment.

All experiments were approved by the Animal Ethics Committee of the University Medical Center Utrecht and were conducted in agreement with Dutch laws (Wet op de Dierproeven, 1996) and European regulations (Guideline 86/609/EEC).

Drugs
The endocannabinoid uptake inhibitors AM404 (N-(4-hydroxyphenyl)-arachidonamide) and VDM11 (N-arachidonoyl-(2-methyl-4-hydroxyphenyl)amine) in bioavailable aqueous soya suspension (Tocrisolve, Tocris Cookson, Avonmouth, UK) were diluted to the final concentration with saline. The stable anandamide analogue (R)-methanandamide ((R)-(+)arachidonyl-1’-hydroxy-2’-propylamide) in absolute ethanol (Tocris Cookson, Avonmouth, UK) was desiccated under a stream of nitrogen;
the residue was then dissolved in a solution of 5% Tween-80/5% polyethylene glycol/saline. The CB₁ cannabinoid receptor antagonist SR141716A (National Institute of Mental Health’s Chemical Synthesis and Drug Supply Program, Bethesda, MD, USA) and the CB₂ cannabinoid receptor antagonist SR144528 (National Institute of Mental Health’s Chemical Synthesis and Drug Supply Program, Bethesda, MD, USA) were dissolved in 5% Tween-80/5% polyethylene glycol/saline. The TRPV₁ vanilloid receptor antagonist capsazepine (Tocris Cookson, Avonmouth, UK) was dissolved in 10% Tween-80/10% polyethylene glycol/saline. The opioid receptor antagonist naloxone (Tocris Cookson, Avonmouth, UK) and the dopamine receptor antagonist alpha-flupenthixol (Sigma-Aldrich, Schnelldorf, Germany) were dissolved in saline. AM404 and (R)-methanandamide were given intraperitoneally (i.p.) 30 min before testing, whereas VDM11 (i.p.) was administered 15 min before test. SR141716A (i.p.), SR144528 (i.p.), capsazepine (i.p.), naloxone (s.c.) and alpha-flupenthixol (i.p.) were given 30 min before AM404, (R)-methanandamide or VDM11, respectively. Drug doses and pretreatment intervals were based on literature and on pilot experiments. In particular, we used the highest doses of SR141716A, capsazepine, naloxone and alpha-flupenthixol that had no effect on social play by themselves (Table 1). Solutions were freshly prepared on the day of the experiment and were administered in a volume of 2 ml/kg. Because of the importance of the neck area in the expression of social play behavior (Pellis and Pellis, 1987), s.c. injections were administered in the flank.

Procedures

Social play behavior
All the experiments were performed in a sound attenuated chamber under dim light conditions. The testing arena consisted of a Plexiglas cage measuring 40 x 40 x 60 cm (l x w x h), with approximately 2 cm of wood shavings covering the floor. The behavior of the animals was videotaped using a video camera with zoom lens, video tape recorder and television monitor.

At 26-28 days of age, rats were individually habituated to the test cage for 10 min on each of the two days prior to testing. On the test day, the animals were socially isolated for 3.5 h before testing, to enhance their social motivation and thus facilitate the expression of social play behavior during testing. This isolation period has been shown to induce a half-maximal increase in the amount of social play behavior (Niesink and Van Ree, 1989). At the appropriate time before testing, pairs of animals were treated with drugs or vehicle. The test consisted of placing two similarly treated animals into the test cage for 15 min. The animals of each pair did not differ more than 10 g in body weight and had no previous common social experience.

Analysis from the video tape recordings was performed afterwards. Coding of the drug solutions ensured that both during the experiment and analysis of behavior, the experimenter was unaware of the treatment of the animals. Behavior was assessed using the Observer 3.0 software (Noldus Information Technology B.V., Wageningen, The Netherlands).

In rats, a bout of social play behavior starts with one rat soliciting (‘pouncing’) another animal, by attempting to nose or rub the nape of its neck. The animal that is pounced upon can respond in different ways: if the animal fully rotates to its dorsal surface, ‘pinning’ is the result, i.e. one animal lying with its dorsal surface on the floor with the other animal standing over it. From this position, the supine animal can easily
initiate another play bout, by trying to gain access to the other animal’s neck. Thus, during social play, pinning, which is considered to be the most obvious posture in social play behavior in rats, is not an endpoint, but rather functions as a releaser of a prolonged play bout. If the animal that is pounced upon responds by evading, the soliciting rat may start to chase it, thus making another attempt to launch a play bout (Panksepp et al. 1984; Pellis and Pellis, 1987; Vanderschuren et al., 1997).

The following behaviors were scored per 15 min: frequency of pinning, frequency of pouncing, and time spent in social exploration, i.e. sniffing any part of the body of the test partner, including the anogenital area. Behaviors were scored per pair of animals, meaning that a test pair was treated as a single observation. Pinning is the result of an interaction between two animals, pouncing and social exploration were scored irrespective of which animal in a test pair performed the behavior.

**Locomotor activity**

To assess whether the effects of AM404, VDM11 and (R)-methanandamide on social play were secondary to changes in locomotor activity, rats were tested, at 28-30 days of age, for horizontal locomotor activity in plastic cages (50 x 33 x 40 cm; l x w x h) using a video tracking system (EthoVision, Noldus Information Technology B.V., Wageningen, The Netherlands), which determined the position of the animal five times per second.

At the appropriate time before testing, rats were treated with drugs or vehicle and then individually transferred from the home cage to the test cage, where locomotor activity was monitored for 15 min.
Statistical analysis

Behavior was analyzed per pair of animals. Thus, a pair of rats was treated as a single observation. Pinning and pouncing frequencies and time spent in social exploration were calculated per pair of animals and expressed as mean ± SEM. To assess the effects of single or combined treatments on social play behavior, data were analyzed using one-way or two-way ANOVA respectively, followed by Tukey's post hoc test where appropriate. Horizontal locomotor activity was expressed as mean ± SEM travelled distance (cm/15 min). The effects of drug treatment on locomotor activity were analyzed with one-way ANOVA.
RESULTS

Effects of AM404 on social play behavior

The endocannabinoid uptake inhibitor AM404 dose-dependently decreased social play. At a dose of 5 mg/kg, it reduced pinning \([F_{3,31}=6.19, p<0.01]\) (Figure 1a) and pouncing \([F_{3,31}=7.04, p=0.001]\) (Figure 1b). The reduction in social play induced by AM404 was behaviorally specific and not secondary to a general loss in social interest. In fact, AM404 increased social exploration (Table 2), but this increase was not consistently observed in subsequent experiments. Furthermore, at the dose that affected social play, AM404 did not alter locomotor activity (Table 2). The CB₁ cannabinoid receptor antagonist SR141716A (0.1 mg/kg, i.p.) did not block the reduction in pinning \([F_{(SR141),28}=2.73, n.s.; F_{(AM),1,28}=22.53, p<0.001; F_{(SR141xAM),1,28}=0.25, n.s.\] (Figure 2a) and pouncing \([F_{(SR141),1,28}=3.3, n.s.; F_{(AM),1,28}=34.73, p<0.001; F_{(SR141xAM),1,28}=0.13, n.s.\] (Figure 2b) induced by AM404 (5 mg/kg, i.p.). Post-hoc analysis showed that AM404 reduced pinning and pouncing in both vehicle- and SR141716A-pretreated rats. Furthermore, SR141716A did not alter the effect of AM404 on social exploration \([F_{(SR141),1,28}=3.37, n.s.; F_{(AM),1,28}=15.94, p<0.001; F_{(SR141xAM),1,28}=0.28, n.s.\] (data not shown). These data show that CB₁ cannabinoid receptors are not involved in the effects of AM404 on social play. Since CB₂ cannabinoid receptors have been recently described in brain regions involved in emotion, motivation and affect (Van Sickle et al., 2005), we tested whether CB₂ cannabinoid receptors were involved in the effects of AM404 on social play. Pretreatment with the CB₂ cannabinoid receptor antagonist SR144528 (0.1 mg/kg, i.p.) did not counteract the inhibitory effect of AM404 on social play (pinning: \([F_{(SR144),1,23}=0.00028, n.s.; F_{(AM),1,23}=22.32, p<0.001; F_{(SR144xAM),1,23}=0.002, p=0.001]\).
Post-hoc analysis showed that AM404 reduced pinning and pouncing in both vehicle- and SR144528-pretreated rats. Besides inhibition of endocannabinoid uptake, AM404 also activates a ligand-activated cation channel called TRPV1 vanilloid receptor (Zygmunt et al., 2000). We therefore also tested whether TRPV1 vanilloid receptors were involved in the effects of AM404 on social play. However, neither the TRPV1 vanilloid receptor antagonist capsazepine (10 mg/kg, i.p.; pinning: $F_{(CAP)}=4.28, p<0.05; F_{(AM)}=23.99, p<0.001; F_{(CAPxAM)}=0.24, n.s.$, figure 2e; pouncing: $F_{(CAP)}=2.42, n.s.; F_{(AM)}=23.37, p<0.001; F_{(CAPxAM)}=0.58, n.s.$, figure 2f) nor combined treatment with SR141716A (0.1 mg/kg, i.p.) and capsazepine (10 mg/kg, i.p.; pinning: $F_{(SR141+CAP)}=0.07, n.s.; F_{(AM)}=34.08, p<0.001; F_{(SR141+CAPxAM)}=0.33, n.s.$, figure 2g; pouncing: $F_{(SR141+CAP)}=0.67, n.s.; F_{(AM)}=30.75, p<0.001; F_{(SR141+CAPxAM)}=0.08, n.s.$, figure 2h) blocked the effects of AM404 on social play. Post-hoc analysis showed that AM404 reduced pinning and pouncing in vehicle-, capsazepine- and SR141716A plus capsazepine-pretreated rats. Together, these results show that the effects of AM404 on social play were not mediated by activation of the well-known pharmacological targets of this drug, i.e. CB1 and CB2 cannabinoid and TRPV1 vanilloid receptors. Furthermore, these results rule out the possibility that redundant binding of anandamide to either CB1 cannabinoid or TRPV1 vanilloid receptors underlies the reduction in social play induced by AM404.

We have previously shown that the increase in social play induced by the FAAH inhibitor URB597 involves opioid and dopaminergic neurotransmission, since it was blocked by the opioid receptor antagonist naloxone and the dopamine receptor
antagonist alpha-flupenthixol (Trezza and Vanderschuren, 2008a). However, neither naloxone (1 mg/kg, s.c.; pinning: [F(NAL)1,29=0.11, n.s.; F(AM)1,29=28.45, \( p<0.001; F(NAL\times AM)1,29=0.081, n.s.\], figure 2j; pouncing: [F(NAL)1,29=0.24, n.s.; F(AM)1,29=44.08, \( p<0.001; F(NAL\times AM)1,29=0.56, n.s.\], figure 2k) nor alpha-flupenthixol (0.125 mg/kg, i.p.; pinning: [F(FLUP)1,29=0.34, n.s.; F(AM)1,29=23.14, \( p<0.001; F(FLUP\times AM)1,29=0.05, n.s.\], figure 2l; pouncing: [F(FLUP)1,29=2.51, n.s.; F(AM)1,29=23.65, \( p<0.001; F(FLUP\times AM)1,29=0.22, n.s.\], figure 2m) blocked the reduction in social play induced by AM404 (5 mg/kg, i.p.). Post-hoc analysis showed that AM404 reduced pinning and pouncing in rats pretreated with vehicle, naloxone and alpha-flupenthixol.

Effects of VDM11 on social play behavior

VDM11 increased pinning \([F(2,37)=4.66, p<0.05]\) (Figure 3a) and pouncing \([F(2,37)=6.88, p<0.01]\) (Figure 3b) at doses of 0.5 and 1 mg/kg. Social exploration and locomotor activity were not affected by VDM11 (Table 2). The increase in pinning \([F(SR)1,43=6.67, p<0.05; F(VDM)1,43=4.78, p<0.05; F(SR\times VDM)1,43=8.01, p<0.01]\) (Figure 4a) and pouncing \([F(SR)1,43=10.08, p<0.01; F(VDM)1,43=7.82, p<0.01; F(SR\times VDM)1,43=9.30, p<0.01]\) (Figure 4b) induced by VDM11 (0.5 mg/kg, i.p.) was blocked by the CB1 cannabinoid receptor antagonist SR141716A, at a dose that by itself had no effects on social play behavior (0.1 mg/kg, i.p.; Table 1). Post-hoc analysis showed that VDM11 increased pinning and pouncing in vehicle-, but not in SR141716A-pretreated animals, indicating that the effects of VDM11 on social play were mediated by activation of CB1 cannabinoid receptors.

Subsequently, we investigated whether the effects of VDM11 on social play behavior also involved activation of opioid and dopaminergic neurotransmission.
Pretreatment with a dose of naloxone that had no effect on social play by itself (1 mg/kg, s.c.; Table 1) prevented the effect of VDM11 (0.5 mg/kg, i.p.) on pinning \( [F_{(NAL)}1,43=9.58, p<0.01; F_{(VDM)}1,43=4.70, p<0.05; F_{(NALxVDM)}1,43=3.14, p=0.08] \) (Figure 5a) and pouncing \( [F_{(NAL)}1,43=5.50, p<0.05; F_{(VDM)}1,43=19.01, p<0.001; F_{(NALxVDM)}1,43=1.84, p<0.001] \) (Figure 5b). Post-hoc analysis revealed that VDM11 increased pinning and pouncing in vehicle-, but not in naloxone-pretreated animals, demonstrating that stimulation of opioid receptors is involved in the effect of VDM11 on social play. At a dose that had no effect on social play behavior by itself, the dopamine receptor antagonist alpha-flupenthixol (0.125 mg/kg, i.p.; Table 1) blocked the effect of VDM11 (0.5 mg/kg, i.p.) on pinning \( [F_{(FLUP)}1,43=9.73, p<0.001; F_{(VDM)}1,43=3.61, p=0.06; F_{(FLUPxVDM)}1,43=8.72, p<0.01] \) (Figure 5c) and pouncing \( [F_{(FLUP)}1,43=9.75, p<0.01; F_{(VDM)}1,43=11.67, p<0.01; F_{(FLUPxVDM)}1,43=7.84, p<0.01] \) (Figure 5d). Post-hoc analysis showed that VDM11 increased pinning and pouncing in vehicle-, but not in alpha-flupenthixol-pretreated rats. Together, these results show that, similar to the FAAH inhibitor URB597, the effects of VDM11 on social play depend on stimulation of opioid and dopamine receptors.

**Effects of (R)-methanandamide on social play behavior**

To compare the effects of indirect versus direct activation of CB1 cannabinoid receptors by anandamide on social play behavior, we tested the hydrolytically stable analogue of anandamide, (R)-methanandamide. (R)-methanandamide decreased social play, since it reduced pinning \( [F_{3,31}=3.98, p<0.05] \) (Figure 6a) at the dose of 3 mg/kg and pouncing \( [F_{3,31}=7.79, p<0.001] \) (Figure 6b) at the doses of 0.3 and 3 mg/kg. These effects were
behaviorally specific, since (R)-methanandamide did not alter social exploratory
behavior or locomotor activity (Table 2).

The reduction in pinning \(F_{(SR)1,28}=0.018, \text{n.s.}; F_{(M-AEA)1,28}=8.01, p<0.01; F_{(SR\times M-AEA)1,28}=1.58, \text{n.s.}\) (Figure 6c) and pouncing \(F_{(SR)1,28}=0.62, \text{n.s.}; F_{(M-AEA)1,28}=5.62, p<0.05; F_{(SR\times M-AEA)1,28}=3.12, p=0.08\) (Figure 6d) induced by (R)-methanandamide (3 mg/kg, i.p.) was blocked by the CB\(_1\) cannabinoid receptor antagonist SR141716A. Post hoc analysis showed that (R)-methanandamide reduced pinning and pouncing in vehicle-, but not in SR141716A-pretreated animals, demonstrating that the effects of (R)-methanandamide on social play were mediated by activation of CB\(_1\) cannabinoid receptors.
DISCUSSION

Anandamide transporter inhibitors represent a novel class of positive modulators of endocannabinoid neurotransmission. These compounds are useful pharmacological tools to unravel the physiological functions of endocannabinoid signaling. In addition, these drugs also hold promise from a clinical perspective, because they can enhance endocannabinoid signalling, but lack the adverse effects of direct cannabinoid receptor agonists such as catalepsy and hypothermia. In the present study, we used anandamide uptake inhibitors with different target selectivity to investigate the role of endocannabinoid neurotransmission in social play behavior in adolescent rats.

We found that anandamide uptake inhibitors with different target selectivity have divergent effects on social play behavior. The prototypical anandamide uptake inhibitor AM404 reduced social play, whereas its more selective analogue VDM11 enhanced it. The effects of AM404 on social play were behaviorally specific: AM404 did not alter locomotor activity, and slightly increased social exploration in some experiments but did not affect it in others. AM404 was the first developed synthetic inhibitor of anandamide uptake (Beltramo et al., 1997). It enhances CB₁ cannabinoid receptor-mediated anandamide responses both in vitro and in vivo, without mimicking the typical effects of CB₁ cannabinoid receptor agonists, such as catalepsy and hypothermia (Beltramo et al., 1997; -2000; Fegley et al., 2004). The doses of AM404 used in the present study have been shown to increase anandamide levels in several brain areas (Bortolato et al., 2006). However, the effects of this drug on social play were not blocked by the CB₁ cannabinoid receptor antagonist SR141716A at a dose that blocks the effects of the FAAH inhibitor URB597 on social play, nor by the CB₂
receptor antagonist SR144528, suggesting that they were not mediated by increased anandamide signalling at CB1 or CB2 cannabinoid receptors.

In addition to its inhibitory effects on anandamide transport, AM404 directly interacts with non-cannabinoid pharmacological targets (Glaser et al., 2005). In particular, it is a full agonist at TRPV1 vanilloid receptors, with affinity and efficacy at least 10-fold higher than for the anandamide transporter (De Petrocellis et al., 2000; Zygmunt et al., 2000). TRPV1 vanilloid receptors are cation channels primarily involved in the integration of noxious stimuli in peripheral sensory nerve terminals (Szallasi and Di Marzo, 2000). They have also been found in several brain areas, where they might be involved in the modulation of synaptic plasticity (Mezey et al., 2000). Anandamide binds to TRPV1 receptors, but with lower affinity and efficacy than to CB1 cannabinoid receptors (Szallasi and Di Marzo, 2000). At a dose that had no effects on social play by itself, the TRPV1 vanilloid antagonist capsazepine did not block the reduction in social play induced by AM404, showing that this effect was not the result of stimulation of TRPV1 vanilloid receptors. The possibility that increased anandamide binding to either CB1 or TRPV1 receptors as a result of treatment with AM404 reduces social play can also be ruled out, since the effect of AM404 persisted following combined pretreatment with SR141716A and capsazepine. Furthermore, neither the opioid receptor antagonist naloxone nor the dopamine receptor antagonist alpha-flupenthixol antagonized the reduction in social play induced by AM404. Thus, rather than being the consequence of increased endocannabinoid tone, we suggest that the reduction in social play induced by AM404 is due to effects on non-cannabinoid targets. For example, it has been shown that AM404 inhibits Na+ channels through non-CB1, non-TRPV1 mechanisms (Kelley and Thayer, 2004; Nicholson et al., 2003).
These off-target interactions complicate the interpretation of the behavioral effects of AM404, and indicate that AM404 may not be an optimal tool to study the effects of endocannabinoid transport inhibition (see also Cippitelli et al., 2007).

Because the effects of AM404 on social play were difficult to interpret pharmacologically, we tested the more selective anandamide uptake inhibitor VDM11 to characterize the effects of anandamide transporter inhibitors on social play behavior. VDM11 is an anandamide derivate which inhibits the anandamide transporter as potently as AM404, but has no agonistic activity at TRPV1 receptors and is a weaker CB1 receptor agonist than AM404 (De Petrocellis et al., 2000). At doses that did not alter social exploratory behavior or locomotor activity, VDM11 increased social play. This effect was mediated by activation of CB1 cannabinoid receptors, since it was blocked by the CB1 receptor antagonist SR141716A. Furthermore, the increase in social play induced by VDM11 was dependent on opioid and dopaminergic neurotransmission, since it was blocked by the opioid receptor antagonist naloxone and the dopamine receptor antagonist alpha-flupenthixol. Thus, the pharmacological profile of VDM11 in the modulation of social play is similar to that of the FAAH inhibitor URB597 (Trezza and Vanderschuren, 2008a), i.e. increased social play behavior which is dependent on cannabinoid, opioid and dopaminergic neurotransmission. The present data therefore confirm and extend our previous findings (Trezza and Vanderschuren, 2008a; -2008b), supporting the notions that 1. endogenous anandamide plays an important role in the positive modulation of social behavior in adolescent rats; 2. cannabinoid-opioid interactions known to be involved in food and drug reinforcement, also play an important role in the positive subjective properties of another natural reinforcer, i.e. social play behavior; 3. the effects of indirect cannabinoid agonists on
social play are dependent on dopaminergic neurotransmission, likely mediated through an endocannabinoid-induced increase in the activity of mesoaccumbens dopaminergic neurons.

Since endocannabinoids are synthesized and released on-demand following neuronal depolarization (Piomelli, 2003), inhibiting their deactivation prolongs their signaling in active synapses only, preserving the spatiotemporal specificity of endocannabinoid activity. The effects of the FAAH inhibitor URB597 (Trezza and Vanderschuren, 2008a; -2008b) and the anandamide transporter inhibitor VDM11 (present study) therefore suggest that during social play, endocannabinoids are released in brain areas mediating this behavior. This endocannabinoid activity facilitates social play, so that URB597 and VDM11, by preventing anandamide hydrolysis and anandamide transport, respectively, enhance social play by magnifying endocannabinoid tone. In contrast, we have previously shown that stimulation of CB1 cannabinoid receptors throughout the brain using the cannabinoid receptor agonist WIN55,212-2 reduced social play (Trezza and Vanderschuren, 2008a; -2008b), perhaps by disrupting cognitive functions necessary to perform adequate social interactions (Egerton et al., 2006). In keeping with this finding, systemic administration of the stable analogue of anandamide, (R)-methanandamide, reduced social play, through stimulation of CB1 cannabinoid receptors, because the effect of (R)-methanandamide was blocked by the CB1 cannabinoid receptor antagonist SR141716A. The latter finding also indicates that it is unlikely that increased anandamide levels as a result of anandamide transporter inhibition account for the effects of AM404 on social play. Rather, a non-CB1 target seems to be responsible of the effects of AM404 on social play. Furthermore, these data support the hypothesis...
that the increase in social play induced by indirect cannabinoid agonists is due to enhanced anandamide signalling only in those brain areas mediating the positive subjective properties of social play behavior, rather than to increased anandamide signalling per se.

The molecular mechanism of anandamide uptake is a matter of debate. Since the anandamide transporter protein has not been cloned yet, its existence has been questioned and other mechanisms have been proposed, including FAAH-mediated simple diffusion (Glaser et al., 2003). However, genetic deletion of FAAH does not affect anandamide uptake, which argues against this possibility (Fegley et al., 2004). Furthermore, by using a selective ligand, a high-affinity anandamide transporter binding site distinct from FAAH has recently been identified (Moore et al., 2005). Together, these data suggest that the uptake and hydrolysis of anandamide are mediated by independent, but functionally linked mechanisms.

VDM11 was originally found to selectively inhibit anandamide uptake (De Petrocellis et al., 2000). Studies into the effects of VDM11 on FAAH activity have yielded inconsistent results (Fowler et al., 2004; Vandevoorde and Fowler, 2005), which makes it unlikely that the increase in social play induced by VDM11 is the result of FAAH inhibition. Moreover, AM404, which is more potent than VDM11 in inhibiting FAAH (De Petrocellis et al., 2000), reduced social play through non-cannabinoid mechanisms, further indicating that FAAH is not the pharmacological target responsible for the opposite effects of AM404 and VDM11 on social play.

Our results, supporting an important role for anandamide in the modulation of social play behavior, suggest that anandamide transporter inhibitors might be useful for the treatment of neuropsychiatric disorders characterized by impairments in social
behavior, and particularly by deficits in social play. For example, deficient cooperative play with peers and atypical social behavior are core symptoms of autism (Jordan, 2003) and lack of socialized patterns of play with subsequent social withdrawal are schizophrenic prodromal behaviors in children (Moller and Husby, 2000). Since social behaviors related and unrelated to play have different ontogenetic profiles and are mediated by dissociable neural systems (Vanderschuren et al., 1997), it is likely that the effects of indirect cannabinoid agonists on social behavior differ between young and adult individuals. Thus, further research into the effects of indirect cannabinoid agonists on social behavior is warranted. The present findings also suggest that target selectivity may account for the variability in the behavioral effects of these drugs, and highlight the need to develop high-affinity ligands to exploit the therapeutic potential of endocannabinoid neurotransmission.
ACKNOWLEDGEMENTS

We thank M.H. Broekhoven and R. Damsteegt for practical assistance.
REFERENCES


and inflammatory pain by the endocannabinoid transport inhibitor AM404 [N-(4-hydroxyphenyl)-eicosa-5,8,11,14-tetraenamide]. *J Pharmacol Exp Ther* **317**: 1365-1371.


FOOTNOTES

Supported by National Institute on Drug Abuse Grant R01 DA022628 (L.J.M.J.V.).

This research was performed within the framework of project T5-107 of the Dutch Top Institute Pharma. V. Trezza was a visiting scientist from the Dept. of Human Physiology and Pharmacology, University of Rome 'Sapienza', Rome, Italy, supported by a fellowship from “Fondazione Enrico ed Enrica Sovena”, Rome.

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LEGENDS FOR FIGURES

**Fig. 1.** Effects of the anandamide uptake inhibitor AM404 on social play behavior. AM404 (AM; 0.5-2-5 mg/kg, i.p., 30 min before test) dose-dependently reduced pinning (a) and pouncing (b). Data represent mean ± SEM frequency of pinning and pouncing. **p<0.01 vs. vehicle (i.e. 0 mg/kg AM404; Tukey’s post hoc test, n=8 per group).

**Fig. 2.** The effects of AM404 (AM; 5 mg/kg, i.p., 30 min before test) on pinning (a,c) and pouncing (b,d) were not blocked by the CB$_1$ cannabinoid receptor antagonist SR141716A (SR141; 0.1 mg/kg, i.p., 30 min before AM404; a, b) or by the CB$_2$ cannabinoid receptor antagonist SR144528 (SR144; 0.1 mg/kg, i.p., 30 min before AM404; c, d). Furthermore, neither the TRPV1 vanilloid receptor antagonist capsazepine (CAP; 10 mg/kg, i.p., 30 min before AM404; e, f) nor combined treatment with SR141716A (SR141; 0.1 mg/kg, i.p., 30 min before AM404) and capsazepine (CAP; 10 mg/kg, i.p., 30 min before AM404; g, h) blocked the effects of AM404 on social play. AM404 also reduced pinning (j, l) and pouncing (k, m) after pretreatment with the opioid receptor antagonist naloxone (NAL; 1 mg/kg, s.c., 30 min before AM404; j, k) and the dopamine receptor antagonist alpha-flupenthixol (FLUP; 0.125 mg/kg, i.p., 30 min before AM404; l, m). Data represent mean ± SEM frequency of pinning and pouncing. *p<0.05 and **p<0.01 vs. vehicle (i.e. 0 mg/kg AM404 plus 0 mg/kg SR141716A/SR144528/capsazepine/naloxone/alpha-flupenthixol), #p<0.05 and ##p<0.01 vs. SR141716A alone (a,b), SR144528 alone (c,d), capsazepine alone (e,f).
capsazepine plus SR141716A (g,h), naloxone alone (j,k) or flupenthixol alone (l,m) (Tukey’s post hoc test, n=7-13 per group).

Fig. 3. Effects of the anandamide uptake inhibitor VDM11 on social play behavior. VDM11 (VDM; 0.5-1 mg/kg, i.p., 15 min before test) enhanced pinning (a) and pouncing (b). Data represent mean ± SEM frequency of pinning and pouncing. *p<0.05 and **p<0.01 vs. vehicle (i.e. 0 mg/kg VDM11; Tukey’s post hoc test, n=12-15 per group).

Fig. 4. The effects of VDM11 (VDM; 0.5 mg/kg, i.p., 15 min before test) on pinning (a) and pouncing (b) were mediated by activation of CB₁ cannabinoid receptors, since they were blocked by the CB₁ cannabinoid receptor antagonist SR141716A (SR141; 0.1 mg/kg, i.p., 30 min before VDM11). Data represent mean ± SEM frequency of pinning and pouncing. *p<0.05 and **p<0.01 vs. vehicle (i.e. 0 mg/kg VDM11 plus 0 mg/kg SR141716A; Tukey’s post hoc test, n=12 per group).

Fig. 5. The effects of VDM11 (VDM; 0.5 mg/kg, i.p., 15 min before test) on pinning (a, c) and pouncing (b, d) were blocked by the opioid receptor antagonist naloxone (NAL; 1 mg/kg, s.c., 30 min before VDM11, a, b) and by the dopamine receptor antagonist alpha-flupenthixol (FLUP; 0.125 mg/kg, i.p., 30 min before VDM11, c, d). Data represent mean ± SEM frequency of pinning and pouncing. *p<0.05 and **p<0.01 vs. vehicle (i.e. 0 mg/kg VDM11 plus 0 mg/kg naloxone/alpha-flupenthixol; Tukey’s post hoc test, n=12 per group).
Fig. 6. Effects of (R)-methanandamide on social play behavior. (R)-methanandamide (M-AEA; 0.3-1-3 mg/kg, i.p., 30 min before test) dose-dependently reduced pinning (a) and pouncing (b). The effects of (R)-methanandamide (M-AEA; 0.3 mg/kg, i.p., 30 min before test) on pinning (c) and pouncing (d) were blocked by the CB1 cannabinoid receptor antagonist SR141716A (SR; 0.1 mg/kg, i.p., 30 min before M-AEA). Data represent mean ± SEM frequency of pinning and pouncing. *p<0.05 and **p<0.01 vs. vehicle (i.e. 0 mg/kg (R)-methanandamide (a,b); 0 mg/kg (R)-methanandamide plus 0 mg/kg SR141716A (c,d); Tukey’s post hoc test, n=8 per group).
Table 1. Effects of SR141716A (SR141; i.p., 30 min before test), capsazepine (CAP; i.p., 1 h before test), naloxone (NAL; s.c., 30 min before test) and alpha-flupenthixol (FLUP; i.p., 30 min before test) on pinning and pouncing frequencies.

<table>
<thead>
<tr>
<th></th>
<th>PINNING</th>
<th>POUNCING</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F = 14.8, ( p &lt; 0.001 )</td>
</tr>
<tr>
<td>Vehicle</td>
<td>30 ± 3</td>
<td>52 ± 4</td>
</tr>
<tr>
<td>SR141 0.1 mg/kg</td>
<td>30 ± 6</td>
<td>52 ± 7</td>
</tr>
<tr>
<td>SR141 0.3 mg/kg</td>
<td>10 ± 2**</td>
<td>23 ± 3**</td>
</tr>
<tr>
<td>SR141 1 mg/kg</td>
<td>4 ± 1**</td>
<td>14 ± 3**</td>
</tr>
<tr>
<td>Vehicle</td>
<td>26 ± 4</td>
<td>49 ± 8</td>
</tr>
<tr>
<td>CAP 10 mg/kg</td>
<td>29 ± 4</td>
<td>51 ± 6</td>
</tr>
<tr>
<td>CAP 20 mg/kg</td>
<td>13 ± 3</td>
<td>25 ± 4</td>
</tr>
<tr>
<td>Vehicle</td>
<td>31 ± 5</td>
<td>52 ± 6</td>
</tr>
<tr>
<td>NAL 0.3 mg/kg</td>
<td>21 ± 3</td>
<td>40 ± 6</td>
</tr>
<tr>
<td>NAL 1 mg/kg</td>
<td>22 ± 5</td>
<td>36 ± 7</td>
</tr>
<tr>
<td>NAL 3 mg/kg</td>
<td>13 ± 2*</td>
<td>23 ± 4**</td>
</tr>
<tr>
<td>Vehicle</td>
<td>35 ± 3</td>
<td>72 ± 5</td>
</tr>
<tr>
<td>FLUP 0.125 mg/kg</td>
<td>30 ± 6</td>
<td>60 ± 9</td>
</tr>
<tr>
<td>FLUP 0.25 mg/kg</td>
<td>20± 4</td>
<td>44± 5*</td>
</tr>
<tr>
<td>FLUP 0.5 mg/kg</td>
<td>10 ± 3**</td>
<td>25 ± 6**</td>
</tr>
</tbody>
</table>

Data are mean ± SEM frequency of pinning and pouncing. \( n=6-8 \) per group. **\( p<0.01 \), *\( p<0.05 \) (One-Way ANOVA, followed by Tukey’s post hoc test where appropriate).
Table 2. Social exploration and locomotor activity after treatment with AM404 (5 mg/kg, 30 min before test), VDM11 (0.5 mg/kg, 15 min before test) and (R)-methanandamide (3 mg/kg, 30 min before test).

<table>
<thead>
<tr>
<th></th>
<th>Social exploration (sec/15 min)</th>
<th>Traveled distance (cm/15 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vehicle AM404</td>
<td>Vehicle AM404</td>
</tr>
<tr>
<td></td>
<td>39 ± 6</td>
<td>1570 ± 188</td>
</tr>
<tr>
<td></td>
<td>84 ± 11*</td>
<td>1502 ± 115</td>
</tr>
<tr>
<td></td>
<td>F = 5.1, p &lt; 0.01</td>
<td>F = 0.09, p = 0.76</td>
</tr>
<tr>
<td></td>
<td>Vehicle VDM11</td>
<td>Vehicle VDM11</td>
</tr>
<tr>
<td></td>
<td>41 ± 4</td>
<td>2080 ± 257</td>
</tr>
<tr>
<td></td>
<td>55 ± 7</td>
<td>2380 ± 122</td>
</tr>
<tr>
<td></td>
<td>F = 1.8, p = 0.18</td>
<td>F = 1.1, p = 0.31</td>
</tr>
<tr>
<td></td>
<td>Vehicle (R)-methanandamide</td>
<td>Vehicle (R)-methanandamide</td>
</tr>
<tr>
<td></td>
<td>28 ± 2</td>
<td>1887 ± 505</td>
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<tr>
<td></td>
<td>29 ± 3</td>
<td>1547 ± 150</td>
</tr>
<tr>
<td></td>
<td>F = 0.07, p = 0.97</td>
<td>F = 2.13, p = 0.17</td>
</tr>
</tbody>
</table>

Data are mean ± SEM of the total time spent in social exploration (sec) and total distance travelled (cm) during a 15 min test. Note that these parameters were measured in separate experiments. n=7-10 per group. *p<0.05 (ANOVA).
Figure 1
Figure 2
Figure 3
Figure 4
Figure 5
Figure 6