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High novelty preference rats are predisposed to compulsive cocaine self- administration

David Belin^{1,2,3}, PhD, Nadège Berson^{1,2}, PhD, Eric Balado^{1,2}, Pier Vincenzo Piazza^{1,2}, MD, PhD and Véronique Deroche-Gamonet^{1,2} PhD

¹University of Bordeaux, 147 Rue Léo Saignat, 33077, Bordeaux Cedex, France. ²INSERM U862, Pathophysiology of Addiction, NeuroCentre Magendie, 146 rue Léo Saignat, 33077 Bordeaux Cedex, France. ³INSERM AVENIR team Psychobiology of Compulsive Disorders, Pôle Biologie Santé. CNRS UMR 6187 & University of Poitiers. 40, avenue du Recteur Pineau. 86022 Poitiers cedex – France.

Running title: novelty preference predicts cocaine addiction

Correspondence to : Véronique Deroche-Gamonet, INSERM U862, NeuroCentre Magendie, 146 rue Léo Saignat, 33077 Bordeaux, France. E-mail: veronique.deroche@inserm.fr

Abstract

Sensation/novelty seeking is amongst the best markers of cocaine addiction in humans. However, its implication in the vulnerability to cocaine addiction is still a matter of debate since it is unclear if this trait precedes or follows the development of addiction. Sensation/novelty seeking trait has been identified in rats based on either novelty-induced locomotor activity (high responder trait, HR) or novelty-induced place preference (high novelty preference trait, HNP). HR and HNP traits have been associated with differential sensitivity to psychostimulants. However, it has recently been demonstrated that HR rats do not develop compulsive cocaine self-administration after protracted exposure to the drug, thereby suggesting that at least one dimension of sensation/novelty seeking in the rat is dissociable from the vulnerability to switch from controlled to compulsive cocaine self-administration. We therefore investigated whether high novelty preference trait (HNP), as measured as the propensity to choose a new environment in a free choice procedure, as opposed to novelty-induced locomotor activity, predicts the vulnerability to, and the severity of, addiction-like behavior for cocaine. For this we identified HR/LR rats and HNP/LNP rats prior to any exposure to cocaine. After 60 days of cocaine self-administration, each rat was given an addiction score based on three addiction-like behaviours [persistence of responding when the drug is signalled as not available, high breakpoint under progressive ratio schedule and resistance to punishment] that resemble the clinical features of drug addiction, namely inability to refrain from drug seeking, high motivation for the drug and compulsive drug use despite adverse consequences. We show that, as opposed to HR rats, HNP rats represent a sub-population predisposed to compulsive cocaine intake, displaying higher addiction scores than LNP rats. This study thereby provides new insights into the factors predisposing to cocaine addiction, supporting the hypothesis that addiction is sustained by two vulnerable phenotypes: a “drug use prone” phenotype such as HR which brings an individual to develop drug use and an “addiction prone” phenotype, such as HNP, which facilitates the shift from sustained to compulsive drug intake and addiction.

Keywords: addiction, cocaine, compulsivity, distributions, novelty, locomotor reactivity

Introduction

A major challenge for addiction research is to identify the mechanisms involved in the vulnerability to switch from controlled to compulsive cocaine use, thereby allowing efficient preventive and therapeutical strategies targeting those at risk of developing addiction. Thus, even though only 15 to 20% of the individuals exposed to addictive drugs (Anthony et al., 1994) develop an addiction (DSM-IV, APA, 2000), the direct and indirect social and economical costs of this behavioral disorder reach 500 \$ billions (Uhl and Grow, 2004; for review see Koob and Le Moal, 2005).

Epidemiological studies have revealed a striking association between the sensation/novelty seeking trait and cocaine abuse or addiction (Franques et al., 2000; Franques, 2003; Kreek et al., 2005). Thus, sensation/novelty seekers are more prone to experience addictive drugs, akin to various risky activities (Zuckerman et al., 1990; Horvath and Zuckerman, 1993; Kalichman et al., 1994; Wills et al., 1994; Jonah, 1997; Sher et al., 2000; Zuckerman and Kuhlman, 2000; Buckman et al., 2009; Woicik et al., 2009). However, whether the sensation/novelty seeking trait actually predisposes to develop compulsive cocaine use or is part of the behavioral adaptations induced by protracted drug use remains a matter of debate. Indeed, the demonstration of a relationship between high sensation/novelty seeking trait, measured prior to any exposure to addictive drugs and the vulnerability to switch from controlled to compulsive cocaine intake in an experimentally well-controlled condition remains to be established.

It has been proposed that the sensation/novelty seeking trait can be studied in rodents both by high locomotor reactivity to a new inescapable environment (high responder phenotype, HR) (Dellu et al., 1996a; Blanchard et al., 2009), and high propensity to visit a new environment in a free-choice procedure, i.e., novelty-induced conditioned place preference (CPP) (high novelty preferring phenotype, HNP) (Bardo et al., 1996; Cain et al., 2005). Although both traits are dependent upon the dopaminergic system (Bardo et al., 1996), they do not seem to be correlated [(Bardo et al., 1996; Cain et al., 2005, but see (Dellu et al., 1996b)] and predict different dimensions of drug reward (Bardo et al., 1996). Thus, HR rats are more vulnerable than low responder (LR) littermates in their propensity to acquire drug self-administration (SA) (Piazza et al., 1989, 1990, 2000). In contrast, high novelty preferring rats (HNP) differ from their low novelty preferring (LNP) littermates in their vulnerability to express CPP for amphetamine (Bardo et al., 1996) but not in their propensity to acquire drug self-administration (Klebaur et al., 2001). Hence HR and HNP traits may differently contribute to the vulnerability to cocaine addiction.

Using a preclinical model that provides a measure of inter-individual vulnerability to switch from controlled drug use to addiction (Deroche-Gamonet et al., 2004), it has been shown that HR rats do not switch more than LRs to compulsive cocaine intake (Belin et al., 2008), thereby providing evidence for a dissociation between the propensity to acquire cocaine self-administration and the vulnerability to develop compulsive cocaine use. This study also suggests that at least one dimension of sensation/novelty seeking in the rat, namely high locomotor response to novelty, does not predict the vulnerability to switch from sustained drug use to addiction. We therefore investigated whether the alternative sensation/novelty seeking trait in the rat, namely high novelty preference, contributed to the vulnerability to cocaine addiction.

Because of the broad range of methodological procedures addressing locomotor response to novelty and novelty preference (Deminiere et al., 1992; Dellu et al., 1993; Klebaur and Bardo, 1999; Kabbaj et al., 2000; Cain et al., 2005; Abreuviaca et al., 2006; Ballaz et al., 2007; 2008; Turner et al., 2008) that may account for the discrepancies observed in the literature (for review see (Bardo et al., 1996; Dellu et al., 1996b), we tested within a

single experiment the involvement of both novelty-induced locomotor activity and novelty preference in the vulnerability to show an addiction-like behavior for cocaine. For this, HR/LR rats and HNP/LNP rats were selected in the upper (HR, HNP) and lower (LR, LNP) quartiles of a population of 40 outbred drug naive animals ranked according to their locomotor response to inescapable novelty and preference for a new environment, respectively. We then subjected the population to extended cocaine self-administration and measured three addiction-like criteria that are an operationalized version of the hallmarks of drug addiction in the DSM-IV (APA, 2000), namely: 1) inability to refrain from drug seeking, 2) high motivation for the drug and 3) compulsive drug use despite negative consequences. For this, we measured respectively: 1) responding for the drug during periods when the drug is not available and signalled as so, 2) increased breakpoints under progressive ratio schedule of reinforcement and 3) resistance to contingent punishment by electric footshocks (Deroche-Gamonet et al., 2004; Belin et al., 2008; Belin et al., 2009). We analyzed the dimensional relationships between addiction-like behaviors, locomotor reactivity to novelty and novelty preference as well as the phenotype differences, i.e., HR vs LR, HNP vs LNP, in the addiction-like behaviours and in the burst-like pattern of cocaine intake, a behavioural characteristic of addiction (Belin et al., 2009).

Materials and methods

Subjects

Forty adult male Sprague-Dawley rats (n=40) weighing 280-300g at the beginning of the experiments were individually housed under a reversed 12 h light/dark cycle (lights on at 8:00 P.M.). Temperature ($22 \pm 1^\circ\text{C}$) and humidity ($60 \pm 5\%$) were controlled. Food and water were available *ad libitum* throughout the experiment, at the exception of the behavioural and self-administration (SA) sessions. Experiments were performed between 8:00 A.M. and 8:00 P.M., 7 days per week.

Drugs

Cocaine hydrochloride (Cooper, Bordeaux, France) was dissolved in sterile 0.9% saline. The dose of cocaine was calculated as the salt.

Surgery

Intrajugular surgeries were performed according to a procedure previously described (Deroche-Gamonet et al., 2004) after locomotor reactivity and novelty preference tests. Briefly, a silastic catheter (internal diameter = 0.28 mm; external diameter = 0.61 mm; dead volume = 12 μl) was implanted in the jugular vein under ketamine (100 mg/kg) /xylazine (1 mg/kg) anaesthesia. The proximal end was placed in the right atrium while the distal end was passed under the skin and fixed in the mid scapular region. Rats were allowed to recover for 5 to 7 days after surgery. During the first 4 days following surgery, rats received an antibiotic treatment (gentamicine, 1 mg/kg i.p.). After surgery, catheters were flushed daily with a saline solution containing unfractionated heparin (100 IU/ml).

Apparatus

Cocaine self-administration

The self-administration (SA) setup was constituted of 16 chambers made of plexiglas and metal. Each chamber (40 cm long x 30 cm width x 52 cm high) was located within a larger exterior opaque box equipped with exhaust fans that assured air renewal and masked background noise. Briefly, animals were placed daily in a SA chamber where their chronically implanted intra-cardiac catheter was connected to a pump-driven syringe (infusion speed: 20 $\mu\text{l}/\text{sec}$). Two holes, located in opposite sides of the SA chamber at 5 cm from the grid floor, were used as devices to record responding. A white house light at the top of the chamber allowed its complete illumination. A white cue light (1.8 cm in diameter) was located 9.5 cm above the active hole. A green cue light (1.8 cm in diameter) was located 10 cm right to the white cue light. A blue cue light (1.8 cm in diameter) was located on the opposite wall at 33 cm of the floor on the left side. Experimental contingencies were controlled and data collected with a PC-windows-compatible software.

Novelty-induced locomotor activity

The setup was constituted of 16 circular corridors (10 cm wide and 70 cm in diameter). Four photoelectric cells placed at the perpendicular axes of this apparatus automatically recorded locomotion. The locomotor response was recorded over 10 min intervals for a period of 2 h. The score of each animal (number of photocell beam breaks cumulated over this period) was used as an index of individual reactivity to the novel environment.

Novelty-preference

The setup has already been described elsewhere (Darnaudery et al., 2002). It consisted of 6 boxes constituted of two equal compartments (30×30×45 cm) connected by an alley (30×10 cm large, 45 cm high) with two opposite openings (8 cm), one per compartment, that could be closed by sliding doors. Boxes were covered with opaque plates (30×70 cm large) that isolated apparatus from visual cues in the testing room and maintained light intensity into the boxes at about 0.25 lux. Square parallelepipeds (12×2 cm large, 45 cm high) made of grey Plexiglas were used to create two distinct spatial configurations between the two compartments. The apparatus was equipped with photoelectric beams to record locomotor activity, number of visits and time spent in each compartment.

General Procedures

Novelty-induced locomotor activity

After fifteen days of habituation to the facility all the rats were exposed to circular corridors for two hours starting six hours after the beginning of the light period.

Novelty-preference

A week after the exposure to the circular corridors, the subjects were tested for their preference for novelty in a free-choice procedure. The rats were placed 5 min in the central alley, and then exposed 25 min to one compartment ("familiar"). At the end of this habituation phase, the rats were immediately placed in the central alley for 5 seconds after which the two doors were simultaneously opened to let the animal explore the whole box (central alley, familiar and new compartments) for 15 min. The index of novelty preference used was calculated as followed: $\text{time spent in the new compartment} / (\text{time spent in the new compartment} + \text{time spent in the familiar compartment}) \times 100$.

Self-administration (SA)

All the SA experiments were performed during the dark phase of the light/dark cycle as previously described (Deroche-Gamonet et al., 2004). Cocaine SA and the three addiction-like behaviours were conducted in exactly the same conditions as previously described (Deroche-Gamonet et al., 2004).

Basal training protocol. The daily SA session was composed of three drug components (40 min each) separated by 15 min drug free periods. "Drug" periods were signalled by the blue cue light, while the "no- drug" periods were signaled by illumination of the entire SA box and extinction of the blue cue light. During the "no-drug" periods, nose-pokes were without scheduled consequences. During the "drug" periods, introduction of the animal's nose into one hole (active device) turned on the white cue light located above it and then, 1 sec later, switched on the infusion pump. The cue light remained on for a total of 4 sec. Nose- pokes in the other hole (inactive device) had no scheduled consequences. The self-infusion volume was 40 μL (2 sec/infusion) and contained 0.8 mg/kg of cocaine. Each infusion was followed by a 40 sec time-out period. During the first 5 days, an FR1 schedule of reinforcement (i.e. one nose-poke resulted in an infusion of 0.8 mg/kg of cocaine) was applied. Then, the FR was first increased to 3 (1 to 2 sessions) and finally to 5 for the rest of the experiment. Criterion for acquisition of cocaine SA was defined by a stable number of self- infusions over at least three consecutive SA sessions ($\pm 10\%$).

Persistence in drug seeking. It was evaluated daily in the basal training protocol by measuring the responding in the active hole during the "no drug" periods; drug being unavailable and signalled as such.

Motivation for the drug. It was measured in a progressive-ratio schedule. During the progressive-ratio schedule of reinforcement, drug availability was signalled by the blue cue light. The ratio of responses per infusion was

increased after each infusion according to the following progression (10, 20, 30, 45, 65, 85, 115, 145, 185, 225, 275, 325, 385, 445, 515, 585, 665, 745, 835, 925, 1025, 1125, 1235, 1345, 1465, 1585). The maximal number of responses that a rat performed to obtain one infusion (the last ratio completed) is referred to as the breakpoint (BP). The session ceased after either 5 hr or when a period of 1 hr elapsed since the previously earned infusion.

Resistance to punishment. It was measured when cocaine infusions were associated with an electric shock. During this session, rats were placed for 40 min in the SA chamber. The blue cue light signalling drug availability was on. The schedule was the following. FR1 led to the illumination of the green cue light signalling the presence of the shock. When an FR4 was completed, rats received an electric shock (0.8 mA, 2 sec). When FR5 was reached, rats received both an electric shock (0.8 mA, 2 sec) and a cocaine infusion (0.8 mg/kg) associated with the corresponding conditioned stimulus (CS) (white cue light). Then the green cue light was turned off. The schedule could reinitiate at the end of the time-out period, i.e. 40 sec after the infusion. If, within a minute, animals did not complete an FR4 or an FR5 leading to shock and shock plus infusion respectively, the green cue light turned off and the sequence was reinitiated, i.e. the following FR1 turned on the green cue light.

Progressive ratio and punishment sessions were performed on day 60 and 72, respectively. Persistence in drug seeking measured over basal training sessions 53-59 was considered for analysis.

Data Analysis

For locomotor reactivity to novelty and novelty preference the upper and lower quartiles of the population were selected as high and low responders or novelty-preferring rats, respectively.

For the addiction-like criteria, as previously described (Deroche-Gamonet et al., 2004), a subject is positive for one criterion if he belongs to the 35% highest part of the population. Thus, when a rat belongs to the 35% highest part of the population for none of the criteria, it is identified as 0crit rat and is considered resilient to addiction, however, when one rat belongs to the 35% highest part of the population for each of the three addiction-like criteria, it is identified as 3crit rat and is considered addicted.

The addiction score was calculated for each animal as the sum of the normalized scores for each of the three addiction-like criteria. To calculate a normalized score, the mean of the population is subtracted to each individual value and the result is divided by the standard deviation of the population (see Belin et al., 2008; Belin et al., 2009).

The burst-like pattern of cocaine SA was determined by the quantification of events of more than 5 infusions earned in less than 5 min occurring during the drug periods of the basal training protocol. Briefly, infusion events were analyzed from a 1-min bin Excel (Microsoft Corporation, Redmond, Washington) file. For an infusion n , a 5-min window was drawn that scanned up to the 5 min preceding or the 5 min following the infusion. Then if the sum of the infusions counted within this window was higher than 5, the program initiated the same sequence from the first following infusion that was not included in the window. However, if the sum of the selected events did not reach 5, the same sequence was initiated from the infusion " $n + 1$ " and so on. The data presented for sessions 10, 30 and 60 are averages of sessions 9-11, 31-33 and 58-60, respectively.

Statistical analysis

All the data are presented as mean \pm SEM.

Analyses of variance (ANOVA) were used to determine the behavioral differences between the experimental groups. For each analysis, 0, 1, 2 and 3 criteria, LR/HR or LNP/HNP were used as between-subject factor and

time as within-subject factor. Upon confirmation of significant main effects, differences among individual means were analysed using the Newman-Keuls post-hoc test.

The distributions of the populations were assessed by Kolmogorov-Smirnov (K-S) and Khi2 goodness of fit tests.

The relationship between locomotor reactivity to novelty and novelty preference was assessed by a Pearson correlation. The relationships between the addiction-like criteria (breakpoint, active lever presses during 'no-drug periods' and maintenance of cocaine self-infusions when associated with electric foot-shocks), addiction score, burst-like pattern of intake (number of events of more than 5 infusions in 5 minutes) and locomotor reactivity to novelty (total photocell beam breaks over two hours) and / or novelty preference (percentage of time spent in the novel compartment) were assessed by the non-parametric Spearman correlation analysis.

A principal components analysis was performed to investigate the potential dimensional inter-relationships between addiction, novelty preference and locomotor reactivity (Shaw, 2003). The variables used were: 1) the addiction score, 2) the percentage of time spent in the new environment of the novelty preference test and 3) the total number of photocell beam breaks in the novelty-induced locomotor activity test. Although three factors were extracted from the analysis, we only represented the two with the highest explanatory value, i.e., those which eigenvalue was >0.9.

Results

Locomotor reactivity to novelty and novelty preference are two independent behavioral traits

HR rats (n=10) displayed greater locomotor reactivity to novelty than LR rats (n=10) (figure 1A) but did not differ in their novelty preference in a free choice situation (figure 1B). High novelty preference (HNP) rats (n=10) obviously displayed higher preference towards the new compartment than low novelty preference rats (LNP, n=10) (figure 1C) but showed similar locomotor reactivities to an inescapable novel environment [effect of group: $F_{1,18}=1.72$, $p=0.2$] (figure 1D) The dissociation between novelty preference and locomotor reactivity to novelty traits was further supported by the absence of correlation between the two phenotypes ($R=-0.11$, $p>0.49$).

A sub-population of rats develops addiction-like behavior after chronic exposure to cocaine self-administration (SA).

After 60 days of cocaine SA, the 40 rats were challenged for their addiction-like behaviors (Deroche-Gamonet et al., 2004; Belin et al., 2008; Belin et al., 2009). A systematic analysis of the distributions of each of the three addiction-like behaviors revealed that the motivation for the drug and the persistence of drug seeking (figures 2A and 2B, table 1) (n=40) were best fitted by a log-normal regression (Khi2 and K-S: $p>0.05$), as revealed by the high R^2 value of both log-normal fitting curves (table 1). In contrast, the distribution of resistance to punishment was bimodal, composed of a first log-normal distribution (n=27 or 67.5% of the total population, K-S: $d = 0.22451$, $p>0.1$), and a second normal sub-distribution (n=13 or 32.5% of the total population, K-S: $d = 0.15604$ $p>0.1$) (figure 2C) which general regression fit can be described as a 3 order polynomial equation (table 1). 3crit addicted rats thus belong to a divergent subpopulation comprising 13 subjects, or 32.5% of the population, highly vulnerable to the development of compulsive cocaine SA. Thus, 3crit addicted rats belong to the extreme percentiles of a continuous population for the motivation for cocaine or the persistence in drug seeking whereas they belong to an independent, clustered, sub- population for resistance to punishment.

By combining the individual scores of the three addiction-like behaviors, rats were given an addiction score that was highly proportional to the number of addiction-like criteria they met [significant effect of group: $F_{3,36}=80.03$, $p<0.001$] (figure 2D). As previously described, 3crit, addicted, rats were the only group whose score was above the standard deviation (2.49) and 0crit addiction resilient, rats were the only group with negative scores (Belin et al., 2008; Belin et al., 2009). When compared to 0crit rats, 3crit rats thus displayed higher motivation to self-administer the drug, as revealed by a higher breakpoint during a progressive ratio schedule of reinforcement [$F_{1,20}=51.01$, $p<0.001$] (Figure S1A), higher persistence of drug- seeking when the drug was no longer available [$F_{1,20}=112.28$, $p<0.001$] (Figure S1B) and maintained cocaine SA despite its adverse consequences as revealed by the higher resistance to punishment of drug taking by an electric foot-shock [$F_{1,20}=94.53$, $p<0.001$] (Figure S1C). As compared to 0crit rats, 3crit addicted rats also developed a characteristic burst-like pattern of cocaine intake throughout the SA history (Belin et al., 2009), as revealed by a progressive increase in episodes of infusions bursts from day 30 to day 60 [group effect: $F_{1,20}=5.03$, $p<0.05$, time: $F_{2,40}=4.5$, $p<0.05$, group x time interaction: $F_{2,40}=3.82$, $p<0.05$] (Figure S1D) that were related to the addiction score ($R=0.46$, $p<0.05$).

Novelty preference, but not locomotor reactivity to novelty, predicts the development of addiction-like behavior

Whereas HR and LR rats showed no difference in either their addiction score [$F<1$] (figure 3A) or each of the three addiction-like criteria [F values <1] (figure 3 B-D) HNP rats displayed a higher score than LNP animals in their addiction score [$F_{1,18}=10.59$, $p<0.01$] (Figure 3A) or each of the addiction-like criteria [group effect, $F_{1,18}=5.95$,

$p < 0.05$, group x behaviour interaction: $F_{1,18} = 1.74$, $p = 0.19$] (figure 3B-D). These behavioural differences were not attributed to a differential propensity, either between HNP and LNP or HR and LR rats, to acquire cocaine SA at the dose of 0.8 mg/kg used in the present study (figure S2A).

Akin to 3crit addicted rats (Deroche-Gamonet et al., 2004, present study, data not shown), HNP rats progressively became unable to refrain from drug seeking during 'no-drug' periods as compared to LNP rats [group effect: $F_{1,18} = 9.23$, $p < 0.01$, group x time interaction: $F_{59,1062} = 1.73$, $p < 0.001$] (figure 3E), a difference that was not observed between HR and LR rats (figure 3E). However, HNP rats did not resemble 3crit addicted rats in their development of burst-like pattern of cocaine SA since HNP rats did not differ from LNP rats, as neither did HR from LR rats in this behavioural feature (figure S2B).

Importantly, the behavioural differences observed between HNP and LNP rats cannot be attributed to a differential cocaine exposure since the two groups did not differ for their total cocaine intake during the 60 days preceding the assessment of the addiction-like criteria [$F_{1,18} < 1$] (figure 3F).

A dimensional analysis further confirmed that novelty preference, but not locomotor reactivity to novelty, predicts addiction-like behaviour (table 2). Thus not only was novelty preference correlated with the addiction score ($R = 0.389$, $p < 0.02$), but novelty preference was also related to resistance to punishment ($R = 0.31$, $p < 0.05$) and persistence of cocaine seeking ($R = 0.339$, $p < 0.05$) (table 2). As opposed to novelty preference, locomotor response to novelty was related neither to the addiction-like criteria nor to the addiction score (table 2).

A principal component analysis was then carried out in order to further model the relationships between addiction-like behaviour, locomotor reactivity to novelty and novelty preference in the rat (figure 4). The Principal component analysis, with the addiction score, the percentage of time spent in the new compartment of a novelty-induced place preference procedure and the total photocell beam breaks in a two-hour novelty-induced locomotor activity session as variables, revealed that two main factors explain more than 75% of the total variance of the model. The first factor, which accounts for 46% of the general variance, is the most representative of the model. Both addiction score and novelty preference, loading more than 70%, were highly correlated to this Factor 1. However, Factor 2, which is orthogonal to Factor 1 and accounts for 30 % of the variance is correlated only to the locomotor reactivity variable (loading 85% on Factor 2) and therefore may only represent this behavioural dimension.

Discussion

The dimensional and between-subject analyses of the present study reveal that high novelty preference trait predicts the severity of addiction-like behavior for cocaine. Novelty preference was related to addiction both in simple correlation and multidimensional analyses, i.e. principal component analysis. In addition, High Novelty-Preferring (HNP) rats, identified prior to drug exposure, displayed a much higher addiction score than Low Novelty-Preferring (LNP) littermates after protracted cocaine self-administration (SA), without differing in their total cocaine intake. This difference was attributable to higher performance in the three addiction-like behaviors. Thus, novelty preference trait predicted several facets of the multi-symptomatic model of addiction-like behavior for cocaine used in this study (Deroche-Gamonet et al., 2004; Belin et al., 2008; 2009).

However, high novelty preference trait in the rat was not correlated to the three addiction-like criteria, but specifically to resistance to punishment and inability to refrain from drug seeking. This result suggests that high novelty preference trait may capture a particular form of vulnerability to compulsive-like behavior and further reinforces the fact that the present addiction model, through the three addiction-like behaviors, captures complementary, but distinct, aspects of a complex psychopathology. The somehow segregated association of novelty preference with specific addiction-like criteria extends a previous relationship described between a behavioral trait, namely high impulsivity trait, as measured as a high number of premature responses during long ITI (inter-trial interval) sessions in the 5-CSRTT (5-choice serial reaction time task), and addiction-like behavior in rats, which was attributable exclusively to a tight relationship between impulsivity and resistance to shock-induced punishment of cocaine taking (Belin et al., 2008).

Interestingly, whereas the present study replicates our previous demonstration that cocaine addiction in 3crit rats is preceded and accompanied by the development of a characteristic pattern of SA expressed by the emergence of bursts episodes of more than 5 infusions obtained in less than 5 minutes, HNP rats were shown not to develop such burst-like pattern of cocaine SA. This observation suggests that the etiological contribution of novelty preference to cocaine addiction is dissociable from the one of the drug-induced behavioural adaptations to drug taking, i.e., burst-like pattern of SA (Belin et al., 2009). This is of marked interest in the light of a recent study by Beckmann and colleagues (2010) that revealed a correlation between novelty preference and sign-tracking. Sign tracking has been suggested to reflect increased attribution of incentive salience (Tomie et al., 2008) and vulnerability to drug addiction (Tomie et al., 2008, Beckmann et al., 2010). Thereby, novelty preference may be contributing to increased vulnerability to addiction-like behaviour through strengthened propensity to acquire Pavlovian incentive salience processes.

These data suggest that more insights into the behavioural factors contributing to increased vulnerability to compulsive cocaine intake may be better achieved from a dimensional approach combining different behavioural traits, each predicting preferentially one dimension of the addiction process. This is also supported by the distributions analysis performed in the present study. Because of the large number of animals used here, we were able to carry out an analysis of the distributions for each of the addiction-like behavior. Motivation and inability to refrain from drug seeking were distributed according to a log-normal regression, suggesting that the population was spread along a continuum with some outliers (Limpert et al., 2001). Resistance to shock-induced punishment, however, was characterized by a bimodal distribution, composed of a log-normal sub-population for the low scores besides which a normal sub-population was identified for the highest scores. A bimodal distribution for compulsive cocaine SA has already been suggested in previous studies (Pelloux et al., 2007; Belin et al., 2009) in which it was

not possible to carry out any mathematical modeling because of the small number of animals they used. Bimodal distributions are very common in life science literature, especially during speciation process (Dieckmann and Doebeli, 1999) whereby one whole population is somehow segregated to two independent populations (Hasegawa et al., 2006). Rare in behavioural neuroscience, bimodal distributions have however been observed for drug-induced behaviors (Ellenbroek and Cools, 2002), suggesting that the neurobiological substrates of behavioural inter-individual differences need in some cases to be challenged in order to reveal bimodal distribution. Our results suggest that a specific subpopulation in the rat has diverged so that it has become specifically more vulnerable to maintain drug use despite adverse consequences, as measured as resistance to punishment, when chronically exposed to the drug. This hypothesis, although speculative, when transferred to the human situation may resonate well with the Nesse and Berridge's suggestion that the vulnerability to drug addiction is a matter of evolution (Nesse and Berridge, 1997).

While providing the first evidence for a positive relationship between novelty preference and addiction-like behaviors, this study confirms our previous observation that locomotor reactivity to novelty does not predict the vulnerability to shift from sustained drug use to cocaine addiction (Belin et al., 2008), but does rather predict the propensity to self-administer drugs (Piazza et al., 1989; Piazza et al., 2000; Belin et al., 2008). Thus HR rats readily self-administer cocaine or amphetamine, as well as other addictive drugs, at doses that are not reinforcing in LR rats (Piazza et al., 1989; Belin et al., 2008; Blanchard et al., 2009). However, HR rats do not develop cocaine addiction-like behavior more than LR after extended exposure to the drug (Belin et al., 2008) and, as compared to 0crit rats, 3crit, addicted, rats do not show a higher locomotor response to novelty (Deroche-Gamonet et al., 2004). Additionally, confirming previous observations (Belin et al., 2008), no dimensional relationship was revealed in the present study, both from correlation and principal component analyses, between locomotor reactivity and addiction-like behaviour. Indeed, the latent variable model resulting from the principal component analysis reveals that only factor 1 represents a latent variable, i.e., a theoretical construct that accounts for both novelty preference and addiction severity. Thus Factor 1 may represent the dimension whereby the etiological factor "novelty preference" contributing to increased risk of addiction is related to the severity of addiction-like behaviour in rats. However, factor 2 does not provide any new, integrative, construct about the dimensions of the model in that it represents only the locomotor response to novelty dimension.

The dissociation between novelty preference and novelty-induced locomotor activity reported here is consistent with previous studies which repeatedly failed to identify a relationship between these two behavioural traits measured with various approaches including open field, locomotor activity chamber, novel object recognition, place preference tests (Bevins et al., 1997; Klebaur et al., 2001; Cain et al., 2004; Pelloux et al., 2004). Both pharmacological (Bardo et al., 1990) or molecular (Adriani et al., 2009) manipulations of novelty preference have been shown not to impact onto novelty-induced locomotor activation. Thus, although novelty preference and locomotor reactivity to novelty are both blocked by microinfusions of dopaminergic antagonists directly into the nucleus accumbens of rats (Bardo et al., 1989; Hooks and Kalivas, 1995; for review see Bardo et al., 1996), these two behavioral traits are underlined by dissociable neurobiological mechanisms. These include a prominent role of D1 dopamine receptors in the expression of novelty preference (Bardo et al., 1993) as opposed to an implication of the HPA axis specifically in novelty-induced locomotor activity. Indeed, whereas the HR phenotype is associated with specific alterations of the HPA axis (Piazza et al., 1991), novelty preference is not associated with changes in corticosterone secretion (Misslin et al., 1982). Thus, while stress-related mechanisms involved in the high sensitivity to addictive drugs found in HR rats (Deroche et al., 1993; Rouge-Pont et al., 1998; Kabbaj et al., 2000) may subserve vulnerability to drug use (for review Piazza and Le Moal, 1998), they may not be implicated in the vulnerability to switch to compulsive cocaine SA (Deroche-Gamonet and Piazza, 2010).

Such a conclusion needs nevertheless further research to fully address the implication of the stress system in the novelty preference test used in the present study, especially when one considers the demonstration by Dellu and colleagues in our laboratory that HR rats do seem to prefer a new unexplored arm on a Y maze test (Dellu et al., 1993). This apparent discrepancy actually illustrates the importance of a standardization of novelty preference procedures. Indeed, depending on the study, novelty preference has been measured in a Y-maze (Dellu et al., 1993) or a CPP box (present study, Klebaur et al., 2001; Cain et al., 2004), considering 2-5 (Dellu et al., 1993) or 15 minutes of novelty exploration (present study, Klebaur et al., 2001; Cain et al., 2004) tested immediately (present study), 30 minutes (Dellu et al., 1993) or 24 hours after the familiar environment exploration (Klebaur et al., 2001; Cain et al., 2004). Clearly, our procedure and behavioural measures differ in several aspects from the one by Dellu and colleagues, such as, among others, duration of the measure of novelty preference, familiar/new compartment size ratio (1:1 in the present study, 2:1 in Dellu et al. 1993), latency between habituation and novelty preference test. These methodological differences might be responsible for a distinct involvement of stress-related factors in the novelty preference tests in the present study and the one by Dellu et al., 1993.

Nevertheless, the present data suggest that the HR phenotype and its underlying neurobiological mechanisms may be involved in facilitating the initiation of cocaine use, but not in the transition to switch from controlled to compulsive cocaine use (Deroche-Gamonet and Piazza, 2010) that is instead predicted by novelty preference (present study) and high impulsivity trait (Belin et al., 2008). Further research is necessary to determine whether impulsivity and novelty-preference contribute additively or interactively to the etiology of cocaine addiction. Also, provided that high impulsive (Economidou et al., 2009) and addicted rats (Belin et al. 2009, Deroche-Gamonet et al., 2004) are highly vulnerable to cue- and cocaine-induced reinstatement of cocaine seeking, respectively, an important follow-up study should focus on the relationships between novelty preference trait and vulnerability to reinstatement, a procedure with great heuristic value for the study of long-term maintenance of drug addiction (Bossert et al., 2005; Shaham et al., 2003).

These data are consistent with the two step hypothesis of addiction recently developed by Piazza and Deroche-Gamonet (Deroche-Gamonet and Piazza, 2010) according to which the development of addiction would be mediated by two different vulnerable phenotypes. The first, a “drug use prone” phenotype, which is positively correlated with reactivity to novelty, facilitates the development of drug intake and subsequently sustained drug use, setting the conditions for addiction to develop. Indeed addiction appears only after a prolonged period of sustained drug use (Deroche-Gamonet et al., 2004). However to shift from sustained drug use to addiction, a second vulnerable phenotype would be necessary, i. e., a “drug addiction prone” phenotype that is predicted so far by novelty seeking (present data) or impulsivity (Belin et al., 2008), and that predisposes to compulsive drug intake. This hypothesis fits well with recently published epidemiological data (Swendsen et al., 2010) indicating distinct mental disorders as risk factors for substance use and addiction. In conclusion, in conditions like the ones of the real world where drugs have to be actively sought at all stages of the addiction process, an individual will need both phenotypes to develop addiction.

Therefore the present preclinical data suggest that the correlates of the increased propensity shown by human sensation seekers to use addictive drugs (Zuckerman, 1986) should be dissociated from those associated with the transition from sustained to compulsive drug use. Indeed, not only is sensation seeking a heterogeneous, multifaceted, construct (Zuckerman et al., 1978) but it is quantified according to different, not necessarily overlapping (Cloninger, 1988), personality scales including the Zuckerman, Eysenck, Arnett and Cloninger's scales. A factorial analysis of the different items of the sensation seeking scale developed by Zuckerman (Zuckerman and Neeb, 1979) revealed four dimensions (Arnett, 1994) namely Thrill and Adventure Seeking,

Experience Seeking, Disinhibition, and Boredom Susceptibility, of which the Thrill and Adventure Seeking and Disinhibition sub-scales have been suggested to refer to sensation seeking whereas the Experience Seeking and Boredom Susceptibility sub-scales would refer to novelty seeking (Wohlwill, 1984; Arnett, 1994). Further research is needed to investigate which of these sub-scales is the most predictive of the vulnerability to switch to compulsive cocaine use, thereby clearly refining the relationships between sensation seeking trait and vulnerability to cocaine addiction.

In conclusion, in this study, we developed a behavioural procedure that allows identifying a novelty seeking trait in the rat based on the preference for a new compartment in a free choice procedure. High novelty preference rats in this procedure were shown to be vulnerable to develop a high compulsive cocaine taking behavior. Thus this study provides new insights into the factors predisposing to cocaine addiction, comforting the hypothesis that different behavioural phenotypes predispose to different stages of the addiction process, some, such as the HR phenotype, predisposing to drug use, and others, including the high impulsive and HNP phenotypes facilitating the shift to compulsive cocaine intake and addiction.

Disclosure/Conflict of Interest

The authors declare they have no competing interests.

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Titles and legends to figures

Figure 1: Novelty-induced locomotor activity and novelty preference are unrelated behavioural traits.

A. High responder rats (HR, n=10) displayed greater locomotor activity than low responder rats (LR, n=10) throughout a 2 hours exposure to a novel inescapable environment. B. However, LR and HR rats did not differ in their novelty seeking when given the opportunity to choose between a familiar and a novel compartment, since they spend the same percentage of time in the new compartment. C. High novelty preference rats (HNP, n=10) spent more time in the new compartment than low novelty preference rats (LNP, n=10). D. However, HNP and LNP rats did not differ in their locomotor response to a novel inescapable environment.

Figure 2: A sub-population of rats develops addiction-like behaviour after chronic exposure to cocaine self-administration.

A-C Representation of the distribution of each addiction-like criterion. Data are represented as frequencies of observations for each range of score. The whole population (n=40) was log-normal distributed for both motivation for cocaine (measured by the breakpoint during a progressive ratio session) (A) and inability to refrain from cocaine seeking when it was not available and signalled as so (non reinforced active nose-pokes) (B). However, resistance to punishment (maintenance of drug use and drug seeking despite contingent electric foot-shocks as measured by self-infusions as a percentage of baseline) was best characterized by a bimodal distribution, with a specific normal subpopulation, on the right side of the general distribution, prone to compulsive cocaine intake (C) (see table 1 for more details). D. Addiction scores of 0crit (addiction resistant rats), 1crit, 2crit and 3crit (addicted) rats. After 60 days of cocaine SA, 0, 1, 2 and 3 addiction-like criteria rats were identified and their addiction score was computed from their respective scores in each of the addiction-like criteria. 3crit rats (n=6) were the only group whose score was above the standard deviation (2.49) and 0crit, addiction resilient, rats (n=16) were the only group with negative scores.

Figure 3: Novelty preference, but not locomotor reactivity to novelty, predicts the development of cocaine addiction-like behaviour.

Not only did HNP rats show higher addiction score than LNP rats (A) but they scored higher on each of the three addiction-like criteria, namely motivation for cocaine (measured by the breakpoint during a progressive ratio session) (B) and inability to stop seeking cocaine when it was not available and signalled as so (non reinforced active nose-pokes) (C) and resistance to punishment (maintenance of drug use and drug seeking despite contingent electric foot-shocks) (D). Compared to LNP rats, HNP rats even displayed a progressive development of this inability to refrain from drug seeking over time that has been previously described for 3crit addicted rats (E). These behavioural differences between HNP and LNP rats could not be attributable to differential cocaine intake since the two groups have been exposed to the same amount of cocaine throughout the experiment (F). When compared to LR rats, HR rats showed no difference in the addiction-like behavioural measures, thereby illustrating that locomotor reactivity to novelty, as opposed to novelty preference, does not predict addiction-like behaviour for cocaine.

Figure 4: Dimensional analysis of the theoretical relationships between addiction-like behaviour, novelty preference and locomotor reactivity to novelty in the rat.

A principal component analysis, with the addiction score, the percentage of time spent in the new compartment of a novelty-induced place preference procedure and the total photocell beam breaks in a two-hour novelty-induced locomotor activity session as variables, revealed two factors explaining 77% of the total variance of the model. The first factor, which accounts for 46% of the model, represents the novelty preference/addiction dimension since the variables used for these two constructs load heavily (more than 70%) on this factor. However, factor 2, which is orthogonal to the first one, represents the dimension relative to reactivity to novelty since its representative variable, i.e., novelty-induced locomotor activity loads (85%) almost alone on this factor.

Tables

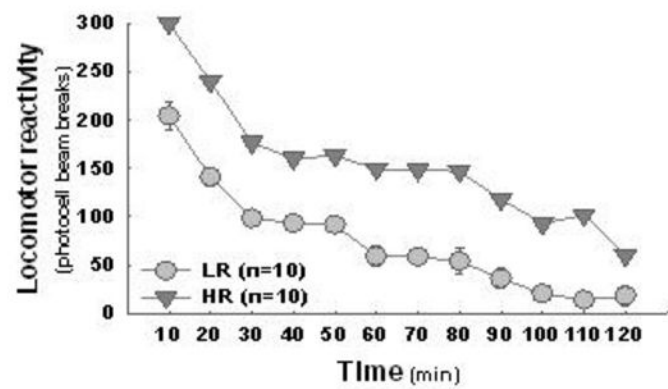
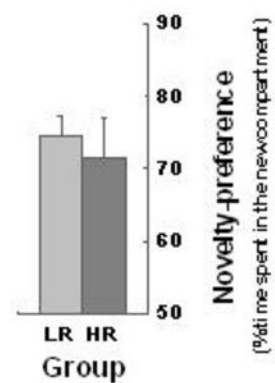
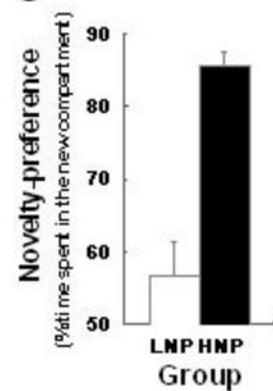
	Persistence of drug seeking (Non-reinforced active nose-pokes)	Motivation (Breakpoint)	Resistance to punishment (% basal self-infusions)
Fitting curve	$y=109819-109816e(-0.5(\ln(x/4.78)/47.74)^2)$	$y=87777-87776e(-0.5(\ln(x/4.12)/36.79)^2)$	$y=-3.2407x^3+37.331x^2-130.86x+146.67$
R²	0,99	0,96	0,98
	Test value	p	Test value
K-S	0,11895	0,1	0,14
khi²	1,46715	0,2	0,24

Table 1: Equation of the regression function, scores and p-values of the goodness of fit tests for each addiction-like criterion.

	Novelty preference	Locomotor reactivity to novelty
Addiction score	0,389493*	-0,057976
Resistance to punishment	0,310745*	-0,149163
Motivation	0,252752	0,118787
Persistence in drug seeking	0,339024*	-0,074531

Table 2: Dimensional relationships between novelty preference, locomotor reactivity, addiction score and the three addiction-like criteria.

Spearman correlations revealed significant associations between novelty preference and addiction-like behaviour in that the novelty preference trait was correlated to the addiction score, as well as resistance to punishment and persistence of cocaine seeking. However, locomotor response to novelty was correlated to none of the addiction measures. * p<0.05.

A**B****C****D**