Cocaine dose and self-administration history, but not initial cocaine locomotor responsiveness, affects sensitization to the motivational effects of cocaine in rats

Bruce H. Mandt, Emily Gomez, Nickie L. Johnston, Nancy R. Zahniser and Richard M. Allen

Department of Psychology (B.H.M, E.G., N.L.J, R.M.A.), University of Colorado Denver, Denver, Colorado; and Department of Pharmacology and Neuroscience Program (N.R.Z.), University of Colorado Anschutz Medical Campus, Aurora, Colorado
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b)  Bruce H. Mandt
    University of Colorado Denver
    Department of Psychology
    P.O. Box 173364, Campus Box 173
    Denver, CO 80217

    Phone: (303) 352-3990
    Fax: (303) 556-3520
    Bruce.mandt@ucdenver.edu

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Abstract

Cocaine addiction is a significant and complex disease. Part of this complexity is due to variability of the drug experience early in drug use (e.g., initial responsiveness, amount of use, etc.). In rats, individual differences in initial cocaine responsiveness and cocaine self-administration history both predict the development of cocaine sensitization, a putative mechanism contributing to development of cocaine addiction. Here we sought to determine the role of these factors and cocaine dose on the development of sensitization to cocaine’s motivational effects during the earliest stages of self-administration. Rats were classified as either low or high cocaine responders (LCRs or HCRs, respectively) based on acute cocaine-induced locomotor activity (10 mg/kg, i.p) before learning to self-administer cocaine (0.6 mg/kg/infusion, i.v.) under a fixed ratio 1 (FR1) schedule of reinforcement. Following acquisition, rats self-administered cocaine (0.6 or 1.2 mg/kg/inf) under a progressive ratio (PR) schedule of reinforcement either immediately or after an additional 5 FR1 sessions (0.6 or 1.2 mg/kg/inf cocaine). No LCR/HCR differences in sensitization were observed. However, regardless of LCR/HCR classification, exposure to the higher dose of cocaine produced sensitization to cocaine’s motivational effects on the PR schedule (i.e., increased break points) and an escalation of consumption on the FR schedule. Thus, our results reveal a novel model for studying escalation and sensitization very early post-acquisition and suggest that sensitization may be important in the earliest stages of the cocaine addiction process.
**Introduction**

Cocaine addiction remains a significant public health issue. Recent statistics from the United States indicate that as of 2010, 37.2 million people aged 12 and over had tried cocaine at least once in their lifetime, with approximately 1.5 million current cocaine users (SAMHSA, 2011). These statistics are particularly troubling considering an estimated 10-15% of all initial intranasal cocaine users progress to addiction (Gawin, 1991). For a subset of these individuals, the transition from recreational use to addiction occurs very rapidly and is associated with routes of administration that result in more rapid and higher brain cocaine levels (Wagner and Anthony, 2002; O'Brien and Anthony, 2005). Further, individual differences in the initial subjective effects of cocaine have been found to correlate with long-term use and dependence (Lambert et al., 2006). Thus, understanding factors that contribute to the rapid development of this disease in susceptible individuals remains an important and significant challenge.

Addiction has been defined as “a chronic disorder characterized by the compulsive use of a substance resulting in physical, psychological, or social harm to the user and continued use despite that harm” (Rinaldi et al., 1988). Because of the complex etiology of addiction, animal models tend to focus on one aspect of the human condition (but see Deroche-Gamonet et al., 2004). For example, the long access model of cocaine self-administration and extinction/reinstatement paradigms model escalation in cocaine consumption and “relapse” to cocaine use, respectively (e.g., Ahmed and Koob, 1998; Shaham et al., 2003), but do so after stable patterns of self-administration have been established. Our lab is interested in factors that occur earlier in the drug-taking process and we have recently established a method for measuring cocaine consumption during the
earliest stages of self-administration. This method defines acquisition based on intake
criteria and then measures each subject’s post-acquisition intake relative to the day of
acquisition (day x), allowing for experimental manipulations following very limited
initial cocaine exposure (Mandt et al., 2012).

One factor postulated to be important for the transition from recreational drug use
to addiction is sensitization (Robinson and Berridge, 1993; Robinson and Berridge,
2001). In animals, sensitization to the locomotor stimulating effects of drugs like cocaine
has been demonstrated for years (e.g., Post, 1980; Zahniser et al., 1988; Kalivas and
Duffy, 1993); however, whether or not sensitization is seen in humans and non-human
primates is an area of active debate (Bradberry, 2007). One possibility for this
discrepancy is that sensitization in humans may occur while addiction is developing,
before the individual has entered treatment and subsequent clinical studies. Similarly,
sensitization may also be more difficult to demonstrate during contingent (i.e., drug self-
administration) than non-contingent (i.e., experimenter-administered) cocaine exposure
because it occurs very early in the drug taking process while animals are being trained on
the operant. Nonetheless, sensitization during paradigms of cocaine self-administration
has been demonstrated. For example, Roberts and colleagues have reported
environmental conditions that result in sensitization to the reinforcing effects of cocaine
measured with a progressive ratio (PR) schedule of reinforcement (Morgan and Roberts,
2004; Liu et al., 2005; Morgan et al., 2006).

Over the past 10 years, we have worked with a model of individual differences in
rats that distinguishes animals based on the magnitude of their acute locomotor response
to a single cocaine injection (10 mg/kg, i.p.; e.g., Sabeti et al., 2002). One of the most
consistent behavioral findings has been that rats with lower, but not higher, initial responsiveness to cocaine (low cocaine responders, LCRs, but not high cocaine responders, HCRs) more readily develop cocaine-induced locomotor sensitization following repeated non-contingent cocaine (10 mg/kg, i.p.; Sabeti et al., 2003; Allen et al., 2007; Mandt et al., 2008; Mandt et al., 2009; Nelson et al., 2009). Interestingly, the LCR/HCR difference in cocaine-induced locomotor sensitization was not found to predict acquisition of low dose cocaine self-administration (Mandt et al., 2008). However, whether or not LCRs and HCRs differ in the development of other forms of sensitization (e.g., during contingent cocaine self-administration) remains unknown.

Thus, the present study sought to investigate the role of self-administration history and initial cocaine responsiveness on the development of sensitization to the motivational effects of cocaine. Specifically, we utilized our new method of acquisition analysis combined with PR schedules of cocaine reinforcement to determine: 1) whether or not we could establish conditions that reveal sensitization to the motivational effects of contingent cocaine administration and 2) whether or not LCRs and HCRs differed in development of this form of sensitization.
Materials and Methods

Animals Four separate groups of outbred male Sprague-Dawley rats ($N = 70$; Group A, $n = 16$; Group B, $n = 14$; Group C, $n = 20$; Group D, $n = 20$) weighing between 225-250 g (~8 weeks of age) were purchased from Charles River Laboratories (Portage, MI) and used in this study. All rats were housed individually with *ad libitum* access to food and water in an animal care facility at the University of Colorado Denver (UCD). To remain consistent with all previous LCR/HCR studies, rats were housed on a 12-h light/dark cycle (lights on at 0600 h), and all testing was conducted during the light cycle. All animal care and use procedures were in strict accordance with the NIH Guide for the Care and Use of Laboratory Animals and were approved by the UCD Institutional Animal Care and Use Committee.

Catheter construction and placement Intravenous catheters were constructed in the laboratory and surgically implanted into the right jugular vein under ketamine (100 mg/kg, i.m.) and xylazine (10 mg/kg, i.m.) anesthesia using established procedures (Thomsen and Caine, 2005). Rats received acetaminophen as an analgesic in their drinking water (20 mg/ml) for 48 h pre- and post-surgery. Rats recovered from surgery for at least 1 week before self-administration training began. Catheters were flushed with 0.3 ml of bacteriostatic 0.9% sodium chloride containing heparin (30 Units/ml) both before and after each self-administration session. Sodium thiopental (20 mg/kg, i.v.) was administered at the conclusion of the experiment to verify catheter patency.

Locomotor activity Locomotor activity testing was conducted as previously described (e.g., Sabeti et al., 2002; Mandt and Zahniser, 2010) and consisted of a single cocaine exposure 48-72 h prior to self-administration training. Briefly, rats were taken to
the behavioral testing room in their home cage and allowed to habituate for 45 – 60 min. At the start of the behavioral recording session, rats were placed in open field activity chambers consisting of Plexiglas boxes (43.2 x 43.2 cm) fitted with a photobeam frame (16 beams per dimension; Med Associates, St. Albans, VT, USA). After acclimation to the novel environment for 90 min, rats were injected with cocaine (10 mg/kg, i.p.) and returned to the chamber for 30 min. Locomotor activity was quantified using the automated consecutive horizontal photobeam interruptions converted to distance traveled (cm) per 10-min bin. The sum of distance traveled over the 30 min post-cocaine was used to determine the median split for all rats within each of the four groups, which was then used to classify rats as either LCRs or HCRs.

**Self-administration training** Rats self-administered cocaine during the light cycle in 16 Plexiglas and metal operant conditioning chambers (29 x 24 x 21 cm; Med Associates) that were housed within sound-attenuating cabinets. The chambers had two retractable levers on the front wall with stimulus lights positioned 6 cm above each lever. A tone presentation speaker (Sonalert Tone Generator, 2900 Hz) and a white noise speaker (90 dB) were mounted 12 cm above the floor on the wall opposite the levers. A houselight (100 mA) was mounted 6 cm above the tone speaker, and a computer-controlled syringe pump delivered cocaine infusions. All behavioral events were monitored and controlled by a personal computer using MED-PC for Windows software (Med Associates).

All self-administration sessions began with the extension of the retractable levers, white noise activation, and illumination of the stimulus light on the right side of the chamber. For fixed ratio 1 (FR1) sessions, one sec after session initiation, a cocaine
priming infusion was delivered (0.6 or 1.2 mg/kg/infusion in a volume of 0.2 ml over 5-7 sec, based on the weight of the rat). During this priming infusion and during all subsequent self-administered infusions, the stimulus light over the active lever was turned off, and a tone-houselight stimulus complex was activated for 15 sec coinciding with a “time-out” period.

Acquisition of cocaine self-administration was measured in 2 h sessions and testing was conducted five days a week. Responses on the right lever were reinforced with a cocaine infusion (0.6 mg/kg) according to a FR1 schedule of reinforcement. All groups (A, B, C, and D) acquired cocaine self-administration with this training dose. Responses emitted on the right lever during cocaine infusion and stimulus complex (i.e., “time-out”) were not reinforced and were recorded separately from reinforced responses. Responses on the left lever were recorded but had no programmed consequence. Acquisition in these experiments was defined as the first of three consecutive sessions during which a rat consumed at least 4 mg/kg cocaine (Mandt et al., 2012). In our lab, rats that meet these criteria continue to reliably self-administer cocaine; and these criteria are similar to intake-based acquisition criterion used by other labs (e.g., Carroll and Lac, 1997; Mantsch et al., 2001).

Following acquisition, rats that met criterion were advanced to progressive ratio (PR) testing either immediately (Groups A and B) or after an additional 5 FR1 sessions (Groups C and D). Similar to FR testing, PR testing was conducted five days a week and responding was reinforced with either 1.2 mg/kg/infusion cocaine (Groups A and C) or 0.6 mg/kg/infusion cocaine (Groups B and D). PR sessions were 5 h in duration, and the response requirement increased progressively according to the following schedule: 1, 2,
4, 6, 9, 12, 15, 20, 25, 32, 40, 50, 62, 77, 95, 118, 145, 178, 219, 268, 328, 402, 492, 603, and 737 for cocaine infusions 1-25, respectively (Richardson and Roberts, 1996). Break point was defined as the last response ratio completed before 1 h without earned reinforcement or the end of 5 h. As with the FR sessions, left lever responses were recorded but had no programmed consequences. The details of experimental conditions for each group are shown in Table 1.

**Exclusions and exceptions** In total, 20 of the 70 rats used in this study were excluded from final PR analysis. One rat in Group A, two rats in Group B, four rats in Group C, and six rats in Group D did not acquire cocaine self-administration. An additional three rats (1 in Group B and 2 in Group D) had catheter patency failure before the end of the acquisition phase of the study. Two rats (1 in group A and 1 in Group C) had catheter patency failure after acquisition, but before the end of PR testing, and as such, these rats were included in acquisition, but not PR analysis. One rat in Group C underwent locomotor classification, but was not advanced to self-administration testing because of health concerns. Finally, one rat in Group D was advanced prematurely to PR testing and thus, was not included in Group D intake or PR analysis.

**Data analysis** All statistical analyses were conducted using PASW Statistics, version 18.0 (IBM Corp., Somers, NY, USA). For acquisition analysis, cocaine intake on the session prior to acquisition and three post-acquisition sessions was analyzed with three-way repeated measures ANOVA (RMANOVA). Classification (LCR or HCR), group (A and B, or C and D), and session (within subjects variable) were treated as independent variables; and intake was treated as the dependent measure. Post-acquisition intake analysis in Groups C and D was analyzed with three-way RMANOVA.
Classification, dose (0.6 or 1.2 mg/kg/infusion), and session were treated as independent variables; and cocaine intake was treated as the dependent measure. The PR experiments were analyzed with three-way RMANOVA. Classification, dose (0.6 or 1.2 mg/kg/infusion), and session were treated as independent variables; and break point associated infusions were treated as the dependent measure. When main or interaction effects were revealed, independent samples t-tests or one-way RMANOVA were used for post-hoc analyses. When the assumption of sphericity was violated for a particular repeated-measures analysis, as revealed by Mauchly’s test statistic, tests of significance were based on the more conservative Huynh-Feldt corrected degrees of freedom. The symbol, \(^a\), indicates Huynh-Feldt corrected values throughout the text. Between groups analysis of break point associated infusions on the first PR session were analyzed with independent samples t-tests (Group A vs. C, or Group B vs. D).

**Drugs** The National Institute on Drug Abuse generously provided the (-)cocaine hydrochloride used in these studies. For i.p. injections, cocaine was dissolved in sterile saline (0.9% sodium chloride) at a concentration of 10 mg/ml and administered in a volume of 1 ml/kg. For i.v. infusions, cocaine was dissolved in sterile saline containing 1.7 USP Units/ml heparin. To check catheter patency, sodium thiopental (Sigma-Aldrich, St. Louis, MO, USA) was dissolved in saline and administered i.v. at 20 mg/kg. Drug weights refer to the salt.
Results

Groups A and B: Cocaine self-administration on a FR1 schedule of reinforcement

Groups A and B were given 20 sessions to acquire cocaine self-administration (0.6 mg/kg/infusion) utilizing a FR1 schedule of reinforcement. Overall, 15/16 rats in Group A and 11/13 rats in Group B met criteria within this timeframe with average times to acquisition of 6.5 ± 1.3 and 6.9 ± 1.2 days, respectively. Cocaine intake over the two sessions prior to and three acquisition sessions are shown in Figure 1A. It should be noted that 3 rats in Group A met criterion starting on the first day of the experiment and consequently, do not have x – 2 and x – 1 values. Thus, N values are decreased for those time points in both the data analysis and Figures 1A and B. Analysis of cocaine intake over the session prior to (x – 1) and three acquisition sessions (x to x + 2) with three-way RMANOVA revealed a significant effect of session [$F (3, 66) = 70.7, p < 0.001$], but no other significant effects or interactions. Compared to sessions x – 1 and x, rats in both groups consumed significantly more cocaine on sessions x + 1 and x + 2, but intake was not significantly different between groups.

Active and inactive lever responding in Groups A and B over the two sessions prior to and three acquisition sessions are shown in Figure 1B. While the ratio of active to inactive lever responding was not part of the acquisition criterion, rats in both groups displayed clear lever discrimination upon meeting our intake criterion. By the third acquisition session, rats in Groups A and B displayed a greater than 10:1 ratio of active to inactive lever responding (Fig. 1B).
Groups A and B: Post-acquisition cocaine self-administration on a PR schedule of reinforcement

Following acquisition, rats were immediately advanced to PR testing reinforced by either a higher dose (1.2 mg/kg/infusion; Group A) or the training dose (0.6 mg/kg/infusion; Group B) of cocaine. Analysis with three-way RMANOVA revealed a significant effect of session [$^a F (9, 189) = 8.5, p < 0.001$], dose [$F (1, 21) = 6.9, p = 0.015$] and a session x dose interaction [$^a F (9, 189) = 2.4, p = 0.048$], but no other significant effects or interactions.

Consistent with previous reports (Liu et al., 2005), break points did not differ on the first PR session despite the different cocaine doses (Fig. 1C). However, break points in Group A (1.2 mg/kg/infusion) increased significantly over the next nine sessions, whereas break points in Group B (0.6 mg/kg/infusion) did not change. Separate post-hoc analyses with one-way RMANOVA revealed a significant effect of session for Group A [$F (9, 117) = 11.6, p < 0.001$], but not for Group B. Compared to the first PR session, break points in Group A were significantly increased on sessions 2 – 10. There were additional significant differences between other sessions in Group A (e.g., session 2 vs. session 10) that are not indicated. Additionally, independent samples $t$-tests revealed that although initial break points in Groups A and B were not different, break points in Group A were significantly increased on each of the next nine sessions (Fig. 1C). A summary of self-administration parameters for LCRs and HCRs in Groups A and B, which did not differ, is presented in Table 2.

Groups C and D: Post-acquisition cocaine self-administration on a FR1 schedule and subsequent performance on a PR schedule of reinforcement

The increase in break
points seen in Group A, but not group B, was suggestive of a dose-related sensitization to
the motivational effects of cocaine. However, it was possible that a switch in cocaine
dose and reinforcement schedule (i.e., 0.6 mg/kg/infusion on a FR1 to 1.2 mg/kg/infusion
on a PR) produced competing behaviors in Group A resulting in the lower initial break
points. Thus, to investigate this possibility rats in Groups C and D were given five
additional FR1 sessions reinforced by either 1.2 or 0.6 mg/kg/infusion cocaine,
respectively, prior to advancement to PR testing at those same doses.

Similar to Groups A and B, Groups C and D were given 20 sessions to acquire
cocaine self-administration (0.6 mg/kg/infusion) according to a FR1 schedule of
reinforcement. Overall, 15/19 rats in Group C and 12/17 rats in Group D met criteria in
this timeframe with average days to acquisition of 7.1 ± 0.7 and 10.2 ± 1.5 days,
respectively; this difference was not significant. Following acquisition (i.e., after session
x + 2), Groups C and D self-administered cocaine (1.2 or 0.6 mg/kg/infusion,
respectively) on a FR1 schedule for 5 additional sessions. Cocaine intake over the two
sessions prior to acquisition, the three acquisition sessions, and the 5 additional FR1
sessions are shown in Figure 2A. Analysis of cocaine intake over the session prior to (x –
1) and three acquisition sessions (x to x +2) with three-way RMANOVA revealed a
significant effect of session [aF (3, 69) = 24.6, p < 0.001], but no other significant effects
or interactions. Relative to session x – 1, rats in both Groups C and D consumed
significantly more cocaine on sessions x to x + 2.

In contrast to the acquisition sessions, analysis of the 5 additional FR1 sessions
revealed significant effects of session [F (4, 92) = 21.6, p < 0.001], dose [F (1, 23) =
15.4, p = 0.001], classification x session [F (4, 92) = 2.9, p = 0.026] and dose x session [F
\((4, 92) = 5.7, p < 0.001\) interactions. Separate analysis of intake with one-way RMANOVA revealed a significant effect of session in Group C \([F (4, 56) = 26.3, p < 0.001]\), but not Group D. Relative to the first session of 1.2 mg/kg/infusion cocaine self-administration \((x + 3)\), rats in Group C consumed significantly more cocaine on sessions 3 – 5 \((x + 5 \text{ to } x + 7; \text{Fig. 2A})\). Furthermore, pairwise comparisons revealed that whereas intake on session \(x + 3\) was not significantly different between Groups C and D, rats in Group C consumed significantly more cocaine than rats in Group D on each of the next four sessions \((\text{Fig. 2A})\). Analysis of classification on each of the additional 5 FR1 sessions did not reveal significant differences in intake between LCRs and HCRs at any point \((\text{Table 2})\).

Following the additional 5 FR1 sessions, Groups C and D were advanced to PR testing reinforced by either 1.2 or 0.6 mg/kg/infusion cocaine, respectively. Analysis of break point associated infusions with three-way RMANOVA revealed significant effects of classification \([F (1, 22) = 6.5, p = 0.018]\) and dose \([F (1, 22) = 19.4, p < 0.001]\), but no other significant effects or interactions \((\text{Fig. 2B})\). Pairwise comparison of the main effect of classification revealed that HCRs exhibited significantly greater break points than LCRs \((15.2 \pm 0.8 \text{ vs. } 12.6 \pm 0.7, \text{respectively})\) and that Group C rats self-administering 1.2 mg/kg/infusion cocaine exhibited significantly greater break points than Group D rats self-administering 0.6 mg/kg/infusion cocaine \((16.1 \pm 0.7 \text{ vs. } 11.6 \pm 0.7, \text{respectively})\). A summary of self-administration parameters for LCRs and HCRs in Groups C and D is presented in Table 2.

Finally, to determine whether or not the additional 5 FR1 sessions altered the reinforcing effects of cocaine, break point associated infusions were compared either
between Groups A and C or Groups B and D (i.e., groups with different histories on the FR schedule, but self-administering the same doses on the PR schedule). Analysis with independent samples $t$-tests revealed that break points on the first PR session were significantly greater in Group C than Group A ($p = 0.011$), but there was no difference in break points between Groups B and D ($p = 0.795$; Fig. 2C).
Discussion

The current study had two aims. First, we sought to identify conditions that reveal sensitization to the motivational effects of cocaine. Second, we sought to determine whether or not individual differences in acute cocaine-induced locomotor activity (i.e., LCRs and HCRs) predict this form of sensitization. Although this study did not reveal differences in this form of sensitization between LCRs and HCRs, we did identify conditions that reveal sensitization to the motivational effects of cocaine. Similar to other reports (e.g., Liu et al., 2005; Morgan et al., 2006), cocaine dose and exposure history were important for sensitization on the PR schedule. Interestingly, a switch in cocaine dose also produced escalation of cocaine consumption on the FR1 schedule. Thus, this study replicates previous findings on the important role of cocaine dose and exposure history for sensitization to the effects of contingent cocaine and provides new evidence that sensitization may occur very early during the drug-taking process.

Sensitization has been suggested to be important during the transition from recreational to compulsive cocaine use, and this idea has been argued most formally by proponents of the incentive-sensitization theory of addiction (Robinson and Berridge, 1993; Robinson and Berridge, 2001). In animals, sensitization to the locomotor stimulating effects of drugs like cocaine has been demonstrated for years and a great deal is known about its neurobiological mechanisms (e.g., Post, 1980; Zahniser et al., 1988; Kalivas and Duffy, 1993; Churchill et al., 1999; Grignaschi et al., 2004). However, it is not clear whether sensitization is seen in humans and non-human primates (Bradberry, 2007). One likely factor in this discrepancy is that humans actively take drugs, whereas animals passively receive drugs during locomotor sensitization paradigms. Consequently,
demonstrating sensitization under paradigms of cocaine self-administration becomes extremely important for understanding the contribution of this phenomenon to complex emitted behaviors.

Roberts and colleagues have reported conditions that produce sensitization to the reinforcing effects of cocaine in rats evident by increasing break points on a PR schedule of reinforcement (Liu et al., 2005; Morgan et al., 2006). The authors found that a dose of 1.5 mg/kg/infusion cocaine produced the most robust increase in break points and that limited initial exposure (e.g., 60 – 160 mg/kg total exposure before PR) was necessary to produce this effect (Liu et al., 2005; Morgan et al., 2006). However, these studies employed very specific conditions (e.g., animals housed in self-administration chambers and 12-h access to cocaine) and whether or not this type of sensitization could be produced under more widely utilized conditions (e.g., animals housed in separate rooms and 2-h sessions) remained unknown.

We have recently established a method for determining acquisition that allows for experimental manipulation of self-administration behavior during the earliest stages of the drug-taking process (Mandt et al., 2012). This method defines acquisition as the first of three consecutive sessions when a rat consumes ≥ 4 mg/kg cocaine during a 2-h FR1 session and aligns intake to that session (i.e., day x; see Fig. 1A). Previously, we found that rats consuming 1.2 mg/kg/infusion cocaine rapidly increased consumption from this point, whereas rats self-administering a range of lower doses exhibited more stable intake (Mandt et al., 2012). However, this new method of analysis was a product of that study and not part of the design. Thus, the present study used this method of analysis to assess
sensitization to the motivational effects of cocaine following very limited initial cocaine exposure, similar to other reports (Liu et al., 2005; Morgan et al., 2006).

Interestingly, when rats were given limited exposure prior to PR testing (Groups A and B), we found a robust replication of the Liu et al. 2005 study. Both in that study and ours, break points did not differ on the first PR session regardless of cocaine dose. However, rats given the higher cocaine doses (1.5 mg/kg/infusion in their study or 1.2 mg/kg/infusion cocaine presently) progressively increased break points over the next 5 – 10 sessions, whereas rats given the lower doses exhibited stable break points. It was possible that in our study the initial low break points for 1.2 mg/kg/infusion cocaine were an artifact of the switch in cocaine dose and reinforcement schedule, due either to learning or dose-induced rate limiting effects. Indeed, it has been reported that stability of responding on a PR schedule can take time to develop (Depoortere et al., 1993). However, given that rats exposed to 5 additional FR1 sessions at 1.2 mg/kg/infusion cocaine prior to PR testing (Group C) exhibited significantly greater rates of responding (i.e., break points) than the limited exposure group on the first session, these differences are not likely explained by the need to learn to respond at higher rates. Further, in the Liu et al. 2005 study, rats were trained with 1.5 mg/kg/infusion cocaine prior to PR testing with that same dose and still exhibited break points similar to those in our study on the first session. Thus, it also seems unlikely that the switch in cocaine dose produced competitive behaviors on the first session preventing higher break points.

Rather, we believe the dose-dependent change in break points seen in the limited exposure group reflects sensitization to the motivational effects of cocaine, similar to previous reports (Liu et al., 2005; Morgan et al., 2006). In addition, our results also
revealed a dose-dependent early escalation in cocaine consumption that occurs during 2-h FR1 sessions. Rats given limited initial exposure to moderate dose cocaine (0.6 mg/kg/infusion) during acquisition and then switched to higher dose cocaine (1.2 mg/kg/infusion) increased consumption 45% over 5 additional sessions (see Fig. 2A). While at first this may be surprising given reports in the literature of well-trained animals’ ability to regulate intake when cocaine dose is varied (e.g., Pickens and Thompson, 1968; Gerber and Wise, 1989; Lynch et al., 1998; Panlilio et al., 2003), our animals received minimal training prior to the switch in cocaine dose. Further, there are now many paradigms that model an escalation of consumption, and these all demonstrate conditions that produce *instability* of intake (i.e., escalation; Carroll et al., 1989; Fitch and Roberts, 1993; Ahmed and Koob, 1998; Tornatzky and Miczek, 2000). Thus, we believe we have established an exciting new model of escalation in cocaine consumption that can be revealed under standard self-administration conditions (i.e., FR1 schedules, 2 hr sessions, separate housing rooms, etc.).

It is tempting to conclude that the increase in consumption on the FR1 schedule is related to sensitization, as was revealed on the PR schedule, given the similar time-course of the two effects (i.e., first 5 sessions at the higher dose; see Fig. 1C and 2A). Additionally, rats that escalated consumption (Group C) displayed significantly greater break points than rats in the limited exposure group on the first PR session (Fig. 2C), possibly because some change in the motivational effects of cocaine had occurred as a result. However, until we are able to fully assess the reinforcing efficacy of cocaine following this escalation on the FR schedule (e.g., with dose-consumption analysis), we
are unable to know whether or not this truly is a sensitization effect revealed under the FR schedule.

While we were able to identify conditions that produced sensitization to the motivational effects of cocaine, we did not observe differences between LCRs and HCRs in this form of sensitization. Thus, under conditions that produced sensitization, break points increased for both LCRs and HCRs. It should be noted that the relationship between locomotor sensitization and sensitization to the effects of self-administered cocaine is unclear. While some studies have found that prior non-contingent stimulant exposure decreases latency to acquisition and increases break points for cocaine (e.g., Schenk and Partridge, 2000; Suto et al., 2002), other studies (including our own LCR/HCR study) have found that cocaine-induced locomotor sensitization does not predict acquisition or break points (Lack et al., 2008; Mandt et al., 2008) and is dissociable from the motivational effects following compulsive cocaine consumption (Ahmed and Cador, 2006). Further, non-contingent cocaine administration, like that used to induce locomotor sensitization, is known under some conditions to produce different neurobiological effects than contingent cocaine administration (e.g., Chen et al., 2008; Miguens et al., 2008). Finally, the amount of cocaine exposure during self-administration far exceeds that of multiple intermittent injections, making direct comparison of these findings difficult.

The current study replicated previous findings on the important role of cocaine dose and exposure history for sensitization to the effects of self-administered cocaine. In addition, we extended these findings to show that this form of sensitization can be revealed under standard training conditions and occurs very early in the drug taking
process. Further, we revealed conditions (i.e., switch from moderate to high dose cocaine) that lead to an early escalation of cocaine consumption on a FR1 schedule of reinforcement during 2-h sessions. Thus, this study provides important evidence that sensitization may be a process involved during the earliest stages of drug taking when experience is limited and may help explain the contribution of this phenomenon to the rapid progression of cocaine addiction in some people.
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Authorship Contributions

Participated in research design: Mandt, Gomez, Johnston, Zahniser and Allen
Conducted experiments: Johnston, Gomez, and Mandt
Contributed new reagents or analytic tools: NA
Performed data analysis: Mandt and Allen
Wrote or contributed to the writing of the manuscript: Mandt, Zahniser, and Allen
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Zahniser NR, Peris J, Dwoskin LP, Curella P, Yasuda RP, O'Keefe L and Boyson SJ

Footnotes

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Figure Legends

Figure 1: Cocaine self-administration in Groups A and B, regardless of LCR/HCR classification, which were advanced to PR testing immediately after acquisition (see Table 1). A) Cocaine intake (0.6 mg/kg/inf) is shown for the two sessions prior to and three acquisition sessions in Groups A ($n = 15$) and B ($n = 11$). X represents the day of acquisition. $p < 0.05$ each session vs. session $x - 1$ and $x$. NS = not significant. B) Active and inactive lever responding for the same acquisition sessions as in (A). C) Break point associated infusions over the ten PR sessions in Groups A (1.2 mg/kg/inf; $n = 14$) and B (0.6 mg/kg/inf; $n = 11$). $p < 0.05$ Group A vs. Group B; $p < 0.05$ each session vs. session 1. Data in (A), (B) and (C) are mean values ± SEM. It should be noted that $N$ values in (A and B) represent data for sessions X to X+3, as 3 animals in Group A do not have data from sessions prior to X (i.e., acquisition occurred on the first session) and thus, $N$ values are lower for those data points.

Figure 2: Cocaine self-administration in Groups C and D, regardless of LCR/HCR classification, which were advanced to PR testing after an additional 5 post-acquisition FR1 sessions (see Table 1). A) Cocaine intake (0.6 mg/kg/inf) is shown for the two sessions prior to acquisition, the three acquisition sessions in Groups C ($n = 15$) and D ($n = 12$) and the five additional post-acquisition FR1 sessions (1.2 or 0.6 mg/kg/inf, respectively). X represents the day of acquisition. $p < 0.05$ Group C vs. Group D; $p < 0.05$ each session vs. session 1. B) Break point associated infusions over the ten PR sessions in Groups C (1.2 mg/kg/inf; $n = 14$) and D (0.6 mg/kg/inf; $n = 12$). C) Break point associated infusions on the first PR session in Groups A, B, C and D. $p < 0.05$ Group C vs. Group A. Data in (A), (B) and (C) are mean values ± SEM.
Table 1. Experimental groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>Acquisition sessions and cocaine doses</th>
<th>Post-acquisition sessions and cocaine doses</th>
<th>PR sessions and cocaine doses</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3 x FR1 (0.6 mg/kg/inf)</td>
<td>-</td>
<td>10 x PR (1.2 mg/kg/inf)</td>
</tr>
<tr>
<td>B</td>
<td>3 x FR1 (0.6 mg/kg/inf)</td>
<td>-</td>
<td>10 x PR (0.6 mg/kg/inf)</td>
</tr>
<tr>
<td>C</td>
<td>3 x FR1 (0.6 mg/kg/inf)</td>
<td>5 x FR1 (1.2 mg/kg/inf)</td>
<td>10 x PR (1.2 mg/kg/inf)</td>
</tr>
<tr>
<td>D</td>
<td>3 x FR1 (0.6 mg/kg/inf)</td>
<td>5 x FR1 (0.6 mg/kg/inf)</td>
<td>10 x PR (0.6 mg/kg/inf)</td>
</tr>
</tbody>
</table>

*One rat in Group A and one rat in Group C were excluded after the acquisition phase and as such, n values for PR testing were 14 for both Groups A and C; see Materials and Methods, Exclusions and exceptions.*
Table 2: Cocaine self-administration in rats classified as LCRs or HCRs

<table>
<thead>
<tr>
<th>Group</th>
<th>Cocaine-induced locomotor activity (cm/30 min)</th>
<th>Percent Acquisition</th>
<th>Avg. Intake (X to X+2; mg/kg)</th>
<th>Avg. Intake (X+3 to X+7; mg/kg)</th>
<th>Avg. BP associated infusions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Mean</td>
<td>Avg. BP</td>
<td>Avg. BP</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCR (n = 8)</td>
<td>2382</td>
<td>1331 ± 221</td>
<td>88% (7/8)</td>
<td>10.3 ± 1.4</td>
<td>-</td>
</tr>
<tr>
<td>HCR (n = 8)</td>
<td></td>
<td>4204 ± 532</td>
<td>100% (8/8)</td>
<td>11.3 ± 1.5</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCR (n = 7)</td>
<td>2772</td>
<td>2065 ± 175</td>
<td>100% (7/7)</td>
<td>9.5 ± 1.8</td>
<td>-</td>
</tr>
<tr>
<td>HCR (n = 7)</td>
<td></td>
<td>4914 ± 749</td>
<td>67% (4/6)</td>
<td>8.9 ± 1.6</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCR (n = 10)</td>
<td>2750</td>
<td>1332 ± 275</td>
<td>89% (8/9)</td>
<td>9.7 ± 1.5</td>
<td>15.4 ± 1.4</td>
</tr>
<tr>
<td>HCR (n = 10)</td>
<td></td>
<td>4272 ± 349</td>
<td>70% (7/10)</td>
<td>9.5 ± 2.6</td>
<td>16.6 ± 1.6</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCR (n = 10)</td>
<td>2363</td>
<td>1271 ± 144</td>
<td>88% (7/8)</td>
<td>7.4 ± 0.8</td>
<td>9.1 ± 1.2</td>
</tr>
<tr>
<td>HCR (n = 10)</td>
<td></td>
<td>4375 ± 644</td>
<td>56% (5/9)</td>
<td>10.0 ± 1.5</td>
<td>12.6 ± 2.2</td>
</tr>
</tbody>
</table>