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## Repetitive Self-grooming Behavior in the BTBR Mouse Model of Autism is Blocked by the mGluR5 Antagonist MPEP

Jill L. Silverman, Seda S. Tolu, Charlotte L. Barkan, and Jacqueline N. Crawley

### Abstract

Autism is a neurodevelopmental disorder characterized by abnormal reciprocal social interactions, communication deficits, and repetitive behaviors with restricted interests. BTBR T+tf/J (BTBR) is an inbred mouse strain that displays robust behavioral phenotypes with analogies to all three of the diagnostic symptoms of autism, including well-replicated deficits in reciprocal social interactions and social approach, unusual patterns of ultrasonic vocalization, and high levels of repetitive self-grooming. These phenotypes offer straightforward behavioral assays for translational investigations of pharmacological compounds. Two proposed treatments for autism were evaluated in the BTBR mouse model. Methyl-6-phenylethynyl-pyridine (MPEP), an antagonist of the mGluR5 metabotropic glutamate receptor, blocks aberrant phenotypes in the *Fmr1* mouse model of Fragile X, a comorbid neurodevelopmental disorder with autistic features. Risperidone has been approved by the United States Food and Drug Administration for the treatment of irritability, tantrums and self-injurious behavior in autistic individuals. We evaluated the actions of MPEP and risperidone on two BTBR phenotypes, low sociability and high repetitive self-grooming. Open field activity served as an independent control for non-social exploratory activity and motor functions. C57BL/6J (B6), an inbred strain with high sociability and low self-grooming, served as the strain control. MPEP significantly reduced repetitive self-grooming in BTBR, at doses that had no sedating effects on open field activity. Risperidone reduced repetitive self-grooming in BTBR, but only at doses that induced sedation in both strains. No overall improvements in sociability were detected in BTBR following treatment with either MPEP or risperidone. Our findings suggest that antagonists of mGluR5 receptors may have selective therapeutic efficacy in treating repetitive behaviors in autism.

### Keywords

autism; social behavior; repetitive behavior; mouse models; mGluR5; BTBR

### Introduction

Autism is a neurodevelopmental disorder affecting approximately 1 in 150 children (Landa, 2008). Diagnosis is behaviorally defined by three core symptom domains: unusual reciprocal social interactions, impaired communication, and stereotyped, repetitive behaviors with restricted interests (DiCicco-Bloom *et al*, 2006; Geschwind *et al*, 2001; Happe and Ronald, 2008; Lord *et al*, 2000). Linkage and association studies have identified

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**Correspondence to:** Dr. Jill L. Silverman Laboratory of Behavioral Neuroscience National Institute of Mental Health, NIH Porter Neuroscience Research Center Building 35 Room 1C-707 9000 Rockville Pike, MSC 3730 Bethesda, MD 20892  
silvermanj@mail.nih.gov Phone: 301-451-9388 Fax: 301-480-1315.

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large numbers of de novo and familial candidate genes that may be responsible for susceptibility to autism (Abrahams and Geschwind, 2008; Bourgeron, 2009; Buxbaum, 2009; Lintas and Persico, 2009; Persico and Bourgeron, 2006). Pharmacological treatments for symptoms of autism are currently under investigation. Several potential therapeutic targets have emerged from the autism literature. High platelet serotonin is one of the most common biological findings in the autism literature (Cook and Leventhal, 1996), serotonin transporter polymorphisms appear in some autistic individuals (Anderson *et al*, 2002), and low serotonin during early development produces cortical abnormalities (Boylan *et al*, 2007; Janusonis *et al*, 2006; Whitaker-Azmitia, 2005). In knock-in mice with a tryptophan hydroxylase 2 mutation that reduces brain serotonin levels, Gsk3 $\beta$  genetic reduction and inhibition by thiadiazolidinone reversed behavioral abnormalities in anxiety-like and social interaction paradigms (Beaulieu *et al*, 2008). In clinical studies, selective serotonin reuptake inhibitors (SSRIs), including fluoxetine and citalopram, have produced some therapeutic improvements when targeted to various symptoms (Hollander *et al*, 2000; Hollander *et al*, 2005; Kolevzon *et al*, 2006; Parikh *et al*, 2008; Soorya *et al*, 2008). However, a more recent multicenter citalopram trial failed to detect significant behavioral improvements, and reported some adverse effects in children (King *et al*, 2009; Volkmar, 2009). Based on the large literature implicating oxytocin in social affiliation (Ferguson *et al*, 2001; Winslow *et al*, 2000; Winslow and Insel, 2002), oxytocin treatments have been administered to autistic individuals with some success (Bartz and Hollander, 2008). A recent discovery of synaptic defects in several mouse models of neurodevelopmental disorders has led to the proposal of pharmacotherapeutic targets that may normalize synaptic connectivity. Potential targets include metabotropic glutamate receptor (mGluR) antagonists, AMPA receptor activation, and modulation of intracellular signaling mechanisms such as mTOR and PAK (Bear *et al*, 2004; Berry-Kravis *et al*, 2006; Dolen *et al*, 2007; Ehninger *et al*, 2008a; Hayashi *et al*, 2007; Lauterborn *et al*, 2000; Meikle *et al*, 2008; Ogier *et al*, 2007; Price *et al*, 2007; Simmons *et al*, 2009; Zhou *et al*, 2009).

Animal models offer opportunities to test genetic hypotheses and evaluate proposed treatments. One strategy utilized with success in mice is the forward genetics approach of identifying inbred strains of mice with phenotypes relevant to the symptoms of a human disease (Bolivar *et al*, 2007; Brodtkin, 2007; McFarlane *et al*, 2008; Moy *et al*, 2004; Moy *et al*, 2008; Moy *et al*, 2007; Nadler *et al*, 2004), conducting biological assays to understand the mechanisms responsible for the phenotypes, and evaluating pharmacological challenges to discover treatments that reverse the phenotypes. Using forward genetics, we and others identified the BTBR T+tf/J (BTBR) strain, which exhibits multiple behavioral traits with face validity for the diagnostic symptoms of autism. BTBR exhibits deficits on juvenile and adult reciprocal social interactions, adult social approach, and social transmission of food preference (Bolivar *et al*, 2007; McFarlane *et al*, 2008; Moy *et al*, 2007; Yang *et al*, 2009; Yang *et al*, 2007a; Yang *et al*, 2007b), unusual patterns of vocalization (Scattoni *et al*, 2008), and high levels of repetitive self-grooming (McFarlane *et al*, 2008; Yang *et al*, 2009; Yang *et al*, 2007a; Yang *et al*, 2007b) as compared to many other inbred strains of mice (Moy *et al*, 2008; Moy *et al*, 2007). Adult social approach deficits and high self-grooming phenotypes, replicated in three laboratories using at least eight independent cohorts of BTBR mice, offer robust behavioral read-outs to evaluate pharmacological compounds, as a first preclinical step towards developing therapeutic interventions for autism.

Our laboratory is interested in the translational application of well-defined mouse models to identify novel pharmacological interventions with efficacy in both autistic children and adults, and in specific subgroups with subsets of symptoms (Betha and Sikich, 2007; King *et al*, 2009). Mouse models of monogenic neurodevelopmental disorders have proven useful as translational tools to evaluate potential treatments (Ehninger *et al*, 2008b). Genetic rescues have been demonstrated in several mouse models of neurodevelopmental disorders,

including Rett syndrome *Mecp2* mutant mice (Guy *et al*, 2007; Jugloff *et al*, 2008) and Fragile X syndrome *Fmr1* mutant mice (Dolen *et al*, 2007; Hayashi *et al*, 2007; Paylor *et al*, 2008; Spencer *et al*, 2008). The pharmacological agent 2-methyl-6-phenylethynyl-pyridine (MPEP), a potent, blood-brain barrier penetrable noncompetitive mGluR5 antagonist, normalized some components of the *Fmr1* phenotype, including seizures, prepulse inhibition, and reduced excessive dendritic spine densities (Bear *et al*, 2008; de Vrij *et al*, 2008; Dolen and Bear, 2008; Yan *et al*, 2005). We therefore chose to investigate the ability of MPEP to modulate the social deficits and repetitive behaviors in BTBR.

Early, intensive behavioral intervention is currently the most effective treatment for the diagnostic symptoms of autism (Landa, 2008; Rao *et al*, 2008; Williams White *et al*, 2007). While a few pharmacological treatments appear to reduce some associated symptoms, none thus far relieve the core symptoms of autism. One drug, the atypical antipsychotic risperidone, has been approved by the US Food and Drug Administration (FDA) for the treatment of autism, specifically for the treatment of irritability, a descriptor that includes self-injury, aggression, upset to change, and tantrums associated with autism spectrum disorders. As a second test compound, we investigated the ability of risperidone to modulate the social deficits and repetitive behaviors in BTBR. The present studies represent the first in a systematic approach to test prototype compounds for efficacy in reversing autism-relevant phenotypes in the BTBR model system.

## Materials and Methods

### Mice

Inbred strains C57BL/6J (B6) and BTBR T+ tf/J (BTBR) were purchased from The Jackson Laboratory (Bar Harbor, ME) and bred in a conventional mouse vivarium at the National Institute of Mental Health (NIMH), Bethesda, MD, using harem breeding trios. After two weeks with a male, females were separated into individual cages before delivery. Pups were kept with the dam until weaning at postnatal day (PND) 21. After weaning, juveniles were housed by sex and strain in standard plastic cages in groups not exceeding four per cage. Cages were housed in ventilated racks in temperature (20°C) and humidity (~55%) controlled colony rooms, on a 12 hour circadian cycle, lights on from 0700 to 1900 hr. Standard rodent chow and tap water were available *ad libitum*. In addition to standard bedding, a Nestlet square, shredded brown paper and a cardboard tube were provided in each cage. Previous studies in our laboratory documented no sex difference in sociability or self-grooming in BTBR and B6 (McFarlane *et al*, 2008; Yang *et al*, 2009). Therefore, male and female mice were used in all studies in approximately equal proportions. Experiments were conducted in dedicated behavioral testing rooms during the standard light phase, usually between 1000 and 1500 hr. All procedures were conducted in strict compliance with the NIH Guidelines for the Care and Use of Laboratory Animals and approved by the National Institute of Mental Health Animal Care and Use Committee.

### Drug Administration

MPEP (0.5, 1.0, 10.0 and 30.0 mg/kg, Sigma Aldrich, St. Louis, MO) was dissolved in saline (0.9% NaCl). Risperidone (0.125, 0.250, and 0.500 mg/kg, Sigma Aldrich, St. Louis, MO) was dissolved in saline (0.9% NaCl) containing 1% acetic acid. Adult male and female B6 and BTBR mice weighing 25-40 grams received an intraperitoneal (i.p.) injection of saline vehicle, MPEP or risperidone 30 minutes before the start of behavioral test sessions for the self-grooming, social approach, and open field behavioral tasks. Behavioral data and *in vivo* receptor occupancy studies determined the post treatment interval for both MPEP and risperidone (Anderson *et al*, 2003; Carvalho *et al*, 2003; Yan *et al*, 2005). Testing began at ages 6-8 weeks. Treatment groups consisted of 6-10 mice per drug dose or vehicle, with

approximately equal numbers of males and females throughout. Each mouse was used only once, for a single behavioral task, receiving a single drug dose. Drug doses were coded to ensure that the raters were blind to the treatment condition.

### Behavioral assays

**Self-Grooming**—Mice were scored for spontaneous grooming behaviors as previously described (McFarlane *et al.*, 2008; Yang *et al.*, 2007b). Each mouse was placed individually into a standard mouse cage, (46 cm length × 23.5 cm wide × 20 cm high), illuminated at ~ 40 lux. A thin (1 cm) layer of bedding reduced neophobia, while preventing digging, a potentially competing behavior. After a 5-minute habituation period in the test cage, each mouse was scored with a stopwatch for 10 minutes for cumulative time spent grooming all body regions. The slightly different fur color markings of B6 (dark brown) and BTBR (dark brown with a light brown ventral patch) prevented fully blind rating in real time for self-grooming. However, the observer sat at a distance of approximately 2 meters from the test cage, and was generally unable to identify the strain while scoring self-grooming (McFarlane *et al.*, 2008; Yang *et al.*, 2007b).

**Open field locomotion**—General exploratory locomotion in a novel open field environment was assessed as previously described (Bailey *et al.*, 2007), as an independent control for direct drug effects on physical activity that could confound the interpretation of results from the self-grooming and social approach tasks. Individual mice were placed in a VersaMax Animal Activity Monitoring System (AccuScan Instruments, Columbus, OH, USA) for a 30-minute test session. The testing room was illuminated with overhead lighting at ~ 200 lux. The chambers consisted of clear Plexiglas sides and floor, approximately 40 × 40 × 30.5 cm. Mice were placed in the center of the open field at the initiation of the testing session. Photocells at standard heights for recording activity were aligned 8 to a side, dividing the chamber into 64 equal squares. Total distance traversed was automatically collected using the Versamax activity monitor and analyzer software system. Test chambers were cleaned with 70% ethanol between test subjects. At least five minutes between cleaning and the start of the next session was allowed for ethanol evaporation and odor dissipation.

**Sociability**—Social approach was tested in an automated three-chambered apparatus using methods previously described (Chadman *et al.*, 2008; Crawley, 2007; Yang *et al.*, 2009; Yang *et al.*, 2007a). The apparatus was a rectangular, three-chambered box made from clear polycarbonate. Retractable doorways within the two dividing walls allowed access to the side chambers. Number of entries and time spent in the chambers were automatically recorded from photocells embedded in the doorways. A top mounted CCTV camera (Security Cameras Direct, Luling, TX) was placed over the boxes to record the session, for subsequent scoring of the videos for time spent sniffing the novel mouse and novel object. The apparatus was cleaned with 70% ethanol and water between subjects with at least five minutes between cleaning and the start of the next test session to allow for ethanol evaporation and clearance of ethanol vapor odors. Mice used as the novel stimulus target were 129Sv/ImJ, aged 12–20 weeks old, bred and maintained in the NIMH vivarium from breeding pairs originally obtained from The Jackson Laboratory, and matched to the subject mice by sex and age. Stimulus mice were habituated to the apparatus and to the wire cup enclosure, several days before the start of experiments, for 30 minutes during 3 habituation sessions per day for 2 days. The location (left or right) of the novel object and stranger mouse alternated across subjects. The subject mouse was allowed to acclimate to the apparatus for 20 minutes before the sociability test, 10 minutes in the central chamber with the doors closed, followed by 10 minutes in the entire empty arena with the doors open. The subject was then briefly confined to the center chamber while a novel object (inverted wire

cup, Galaxy Cup, Kitchen Plus, <http://www.kitchen-plus.com>) was placed in one of the side chambers and a novel mouse was placed inside an identical inverted wire cup in the other side chamber. The side containing the novel mouse was alternated across the test session. Novel mice were enclosed in a wire cup to ensure that all social approach was initiated by the subject, and to avoid complications of fighting and sexual activity, while allowing visual, olfactory, auditory, and partial tactile contact through the widely spaced wire bars. A plastic cup (Solo Cup Company, Highland Park, IL) with a lead weight was placed on the top of the inverted wire cups, to prevent climbing and sitting on top of the inverted wire cup during the sociability phase test. Time spent in each chamber and number of entries into each chamber were calculated by the automated software, based on the movements of the subject mouse in sequentially breaking and unbreaking a series of photocell beams embedded in the openings between chambers (Crawley, 2007). Number of entries served as a within-task control for levels of general exploratory locomotion. Lack of innate side preference was confirmed in previous experiments and during the initial 10 minutes of habituation to the entire arena. After both stimuli were positioned, the doors were simultaneously re-opened and the subject was allowed access to all three chambers for 10 minutes. An observer uninformed of the drug treatments scored the videos with a stopwatch for cumulative time in which the subject mouse sniffed the target mouse. At the end of each testing day test chambers were thoroughly cleansed with Alconox (Alconox, White Plains, NY) detergent diluted with warm water, followed by extensive rinsing with hot water and air drying.

### Statistical analysis

Self-grooming was analyzed with a Two-way ANOVA followed by a Newman-Keuls posthoc test, using StatView statistical software (Citewise.com, Acton, MA). Open field locomotion was analyzed with Repeated Measures ANOVA followed by Bonferroni-Dunn or Tukey's post hoc analysis, using SigmaPlot version 11.0 (Systat Inc., San Jose, CA). Social approach was analyzed with a within groups Repeated Measures Analysis of Variance (ANOVA), using StatView software, to compare time spent in the side chambers in the sociability test. Since times spent in each of the three chambers added to 10 minutes, and therefore were not independent, the test condition factor compared time spent only in the right versus left chambers. Center chamber times are shown in the graphs for illustrative purposes. Time spent sniffing the novel object versus the novel mouse and entries into the side chambers were similarly analyzed. In cases where the overall ANOVA was significant, the treatment factor for each strain was further analyzed with a one-way ANOVA followed by a Newman-Keuls posthoc to compare each drug dose group to its vehicle control group.

## Results

### Reductions in repetitive self-grooming behavior in BTBR mice treated with MPEP, at doses that did not decrease locomotion in an open field

Figure 1 illustrates self-grooming scores for B6 and BTBR mice treated with saline vehicle or MPEP doses. Overall two-way ANOVA detected a statistically significant difference for strain ( $F_{(1, 81)} = 17.22, p < 0.0001$ ) and dose ( $F_{(4, 73)} = 2.74, p < 0.05$ ). MPEP had no significant effects on the cumulative self-grooming score of B6 (Panel A;  $F_{(4, 36)} = 0.10, p > 0.05$ ). MPEP significantly reduced repetitive self-grooming scores in BTBR (Panel B;  $F_{(4, 41)} = 4.23, p < 0.05$ ), at treatment doses of 1.0 mg/kg ( $p < 0.05$ ), 10mg/kg ( $p < 0.05$ ) and 30 ( $p < 0.05$ ) mg/kg as compared to saline treatment. As previously described, no sex differences or sex by strain differences were detected in the self-grooming assay at any drug dose treatment.

Figure 2 illustrates the open field exploratory locomotion for both B6 and BTBR following an acute injection of the two highest doses of the MPEP doses that were tested in the self-grooming assay. The time course for total distance traversed in the novel open field over a 30 minute time period was highly significant, as expected, representing habituation to the novel open field by both B6 (Panel A;  $F_{(5, 20)} = 66.92, p < 0.0001$ ) and BTBR (Panel B;  $F_{(5, 21)} = 65.99, p < 0.0001$ ). A significant interaction was detected between strain and total distance traversed ( $F_{(5, 42)} = 8.64, p < 0.001$ ), reflecting the higher initial open field activity of BTBR, as previously reported (McFarlane *et al*, 2008; Moy *et al*, 2007). Of interest is the lack of significant reductions in locomotor activity following MPEP in the strains tested, supporting previously published literature in rats (Spooren *et al*, 2000b; Tatarczynska *et al*, 2001). In fact, slightly higher total distance scores were detected after MPEP administration to B6 (Panel A;  $F_{(2, 21)} = 4.32, p < 0.05$ ) at the 30 mg/kg dose of MPEP, using a stringent Tukey's post-hoc comparison. Similarly, MPEP administration increased total distance scores in BTBR (Panel B;  $F_{(2, 21)} = 6.02, p < 0.01$ ). Tukey's posthoc analysis indicated a significant difference between saline and the 30 mg/kg dose of MPEP ( $q = 4.87, p < 0.05$ ), during the first ( $q = 4.30, p < 0.05$ ), second ( $q = 4.20, p < 0.05$ ), fifth ( $q = 3.73, p < 0.05$ ) and sixth ( $q = 4.14, p < 0.05$ ) 5-minute time bin intervals. Figure S1 and S2 illustrate additional open field parameters following MPEP administration in the B6 and BTBR. Statistical analyses are provided in the Supplementary Materials.

### No change in sociability after MPEP treatment

Figure 3 illustrates the sociability scores from the automated three-chambered social approach task following a single dose of MPEP or saline in B6. Sociability, defined as spending more time in the chamber with the novel mouse than in the chamber with the novel object, was not significantly different among doses of MPEP and saline for B6 (Panel A;  $F_{(3, 35)} = 38.02, p < 0.001$ ). Time spent in the chamber with the novel mouse was significantly greater for all treatment groups (saline,  $F_{(1, 8)} = 7.29, p < 0.05$ ; MPEP 1.0 mg/kg,  $F_{(1, 9)} = 8.42, p < 0.05$ ; MPEP 10 mg/kg,  $F_{(1, 9)} = 35.26, p < 0.05$ ; MPEP 30 mg/kg,  $F_{(1, 8)} = 11.42, p < 0.05$ ). Similarly, time spent sniffing the novel mouse was greater than time spent sniffing the novel object for all treatment groups (Panel B;  $F_{(3, 35)} = 112.90, p < 0.001$ ). Time spent sniffing the novel mouse was significantly greater than time sniffing the novel object after saline treatment ( $F_{(1, 8)} = 18.98, p < 0.05$ ), MPEP 1.0 mg/kg ( $F_{(1, 9)} = 22.18, p < 0.05$ ), 10 mg/kg ( $F_{(1, 9)} = 157.83, p < 0.05$ ) and 30 mg/kg ( $F_{(1, 8)} = 17.70, p < 0.05$ ). Entries into the side chambers were not affected by MPEP (Panel C;  $F_{(3, 35)} = 0.05, p > 0.05$ ), indicating that the drug treatment had no direct effect on exploratory locomotion during the social approach task. No innate side preference was present in B6 during the task, as shown by similar amounts of time in the left and right side chambers during the 10 minute habituation session before the start of social testing (Panel D;  $F_{(3, 35)} = 0.01, p > 0.05$ ). No sex differences were exhibited in the B6 ( $F_{(1, 37)} = 0.41, p > 0.05$ ) in the social approach task at any drug dose treatment.

Figure 4 illustrates a replication of previous findings (McFarlane *et al*, 2008; Yang *et al*, 2007a; Yang *et al*, 2007b), showing that BTBR did not exhibit sociability, defined as no difference between time spent in the side chamber with the novel mouse as compared to time spent in the side chamber with the novel object. MPEP did not improve sociability in BTBR (Panel A;  $F_{(3, 34)} = 1.43, p > 0.05$ ). Time in the chamber with the novel mouse was similar to time in the chamber with the novel object for each treatment (saline,  $F_{(1, 9)} = 0.29, p > 0.05$ ; MPEP 1.0 mg/kg  $F_{(1, 9)} = 2.17, p > 0.05$ ; MPEP 10 mg/kg,  $F_{(1, 9)} = 2.08, p > 0.05$ ; MPEP 30 mg/kg,  $F_{(1, 7)} = 3.51, p > 0.05$ ). Time spent sniffing the novel mouse versus the novel object was also not significant in the BTBR for vehicle (Panel B;  $F_{(1, 6)} = 6.30, p > 0.05$ ), MPEP 1.0 mg/kg ( $F_{(1, 8)} = 0.46, p > 0.05$ ), or MPEP 10 mg/kg ( $F_{(1, 7)} = 0.08, p > 0.05$ ). However, increased sniffing in BTBR was detected for the 30 mg/kg dose of

MPEP ( $F_{(1, 7)} = 59.58, p < 0.05$ ). Entries into the side chambers were not affected by MPEP, indicating that the drug treatment had no direct effect on exploratory locomotion during the social approach task (Panel C;  $F_{(3, 34)} = 0.39, p > 0.05$ ). No innate side preference was present in BTBR during the task, as shown by similar amounts of time in the left and right side chambers during the 10 minute habituation session, before the start of social testing (Panel D;  $F_{(3, 37)} = 0.53, p > 0.05$ ). Replicating previous reports (McFarlane *et al*, 2008; Yang *et al*, 2007a; Yang *et al*, 2007b), no sex differences were detected in BTBR during the social approach task ( $F_{(1, 36)} = 0.26, p > 0.05$ ).

### Reductions of repetitive self-grooming behavior in BTBR mice treated with risperidone, confounded by reductions in open field

Figure 5 illustrates self-grooming scores for B6 and BTBR treated with vehicle or risperidone. An overall ANOVA detected a statistical difference in strain ( $F_{(1, 45)} = 7.98, p < 0.01$ ) on repetitive self-grooming, consistent with previous publications and with the findings described above for the MPEP experiment. Risperidone has no significant effects on the cumulative self-grooming score of the B6 mice (Panel A;  $F_{(2, 20)} = 0.49, p > 0.05$ ). Risperidone produced a significant reduction in the high level of repetitive self-grooming in BTBR (Panel B;  $F_{(2, 21)} = 4.47, p < 0.05$ ), at treatment doses 0.125 mg/kg ( $p < 0.05$ ) and 0.25 mg/kg ( $p < 0.05$ ).

Figure 6 illustrates open field locomotion following an acute injection of risperidone. The time course for total distance traversed in the novel open field over a 30 minute time period was highly significant, as expected, representing habituation to the novel open field for both B6 ( $F_{(5, 40)} = 9.04, p < 0.0001$ ) and BTBR ( $F_{(5, 33)} = 9.55, p < 0.0001$ ). A significant effect of drug was detected for B6 (Panel A;  $F_{(3, 40)} = 27.20, p < 0.05$ ) and BTBR (Panel B;  $F_{(3, 33)} = 11.31, p < 0.001$ ). The interaction of drug x distance traversed was significant for B6 ( $F_{(3, 15)} = 4.49, p < 0.01$ ) and BTBR ( $F_{(3, 15)} = 4.29, p < 0.01$ ). Tukey's posthoc comparisons reveal significant reductions in total distance scores after risperidone treatment in B6, at each dose compared to vehicle (0.125 mg/kg,  $q = 8.01, p < 0.05$ ; 0.25 mg/kg,  $q = 7.90, p < 0.05$ ; 0.5 mg/kg,  $q = 12.15, p < 0.05$ ) during the 30 minute test session, and at each of the 5-minute time bins. Similarly, significant reductions in open field locomotion were detected in BTBR at each dose of risperidone (0.125 mg/kg,  $q = 3.84, p < 0.05$ ; 0.25 mg/kg,  $q = 4.69, p < 0.05$ ; 0.5 mg/kg,  $q = 8.19, p < 0.05$ ). Additional Tukey's posthoc comparisons in BTBR revealed that the 0.5 mg/kg dose differed from vehicle at the first ( $q = 10.70$ ), second ( $q = 7.40$ ), third ( $q = 5.602$ ), fourth ( $q = 5.327$ ) and sixth ( $q = 3.739$ ) 5-minute intervals. In the BTBR, the two lower doses of risperidone reduced locomotion during the first (0.125 mg/kg,  $q = 4.18$ ; 0.25 mg/kg,  $q = 9.16$ ) and second 5-minute intervals (0.125 mg/kg,  $q = 4.35$ ; 0.25 mg/kg,  $q = 4.88$ ). Figure S3 and S4 illustrate additional open field parameters following risperidone administration in the B6 and BTBR. Statistical analyses are provided in the Supplementary Materials.

### No improvement in sociability after risperidone treatment

Figure 7 illustrates the automated social approach scores following risperidone or vehicle in B6 mice. Normal sociability, as defined above, was displayed by B6 mice following vehicle treatment for time spent in the chamber with the novel mouse (Panel A;  $F_{(1, 9)} = 16.50, p < 0.01$ ). Absence of sociability was seen in B6 mice after treatment with risperidone (0.125 mg/kg,  $F_{(1, 9)} = 2.37, p > 0.05$ ; 0.25 mg/kg,  $F_{(1, 9)} = 1.08, p > 0.05$ ; 0.5 mg/kg,  $F_{(1, 10)} = 1.00, p > 0.05$ ). Moreover, risperidone had a significant effect on the time spent in the chamber with either the novel mouse or novel object ( $F_{(3, 78)} = 39.27, p < 0.01$ ). Between groups ANOVA followed by Bonferroni-Dunn posthoc analysis indicates the B6 group treated with risperidone 0.5 mg/kg spent less time in the two side chambers as compared to the vehicle group ( $p < 0.001$ ). Time spent sniffing the novel mouse was significantly greater

than time spent sniffing the novel object for vehicle treatment (Panel B;  $F_{(1, 9)} = 50.36$ ,  $p < 0.001$ ), and 0.25 mg/kg risperidone ( $F_{(1, 9)} = 4.99$ ,  $p < 0.05$ ) but not for risperidone at 0.125 mg/kg ( $F_{(1, 9)} = 4.10$ ,  $p > 0.05$ ) and 0.5 mg/kg ( $F_{(1, 10)} = 1.00$ ,  $p > 0.05$ ). Entries into the side chambers were reduced by risperidone treatment (Panel C;  $F_{(3, 75)} = 64.33$ ,  $p < 0.05$ ). Between groups ANOVA revealed significant reductions in entries in B6 ( $F_{(3, 78)} = 70.36$ ,  $p < 0.001$ ). Bonferroni-Dunn posthoc analysis indicated significant differences in number of entries between vehicle and each risperidone dose 0.125 mg/kg ( $p < 0.001$ ), 0.25 mg/kg ( $p < 0.001$ ) and 0.5 mg/kg ( $p < 0.001$ ), indicating a sedating effect of all three doses of risperidone in B6. No innate side preference was present in B6 during the 10 minute habituation session before the start of social testing following vehicle or risperidone (Panel D;  $F_{(1, 40)} = 3.46$ ,  $p > 0.05$ ). Bonferroni-Dunn posthoc analysis indicated significantly less time in the left and right side chambers in the risperidone groups at doses 0.25 mg/kg ( $p < 0.001$ ) and 0.5 mg/kg ( $p < 0.001$ ). No sex differences in B6 ( $F_{(1, 39)} = 1.101$ ,  $p > 0.05$ ) were detected in the social approach task at any drug dose treatment.

Figure 8 illustrates automated social approach in the BTBR following risperidone. An overall Repeated Measures ANOVA indicated that BTBR did not display sociability (Panel A;  $F_{(1, 41)} = 0.73$ ,  $p > 0.05$ ), after vehicle treatment ( $F_{(1, 9)} = 0.43$ ,  $p > 0.05$ ), risperidone 0.125 mg/kg ( $F_{(1, 10)} = 0.06$ ,  $p > 0.05$ ), risperidone 0.25 mg/kg ( $F_{(1, 9)} = 0.53$ ,  $p > 0.05$ ), and risperidone 0.5 mg/kg ( $F_{(1, 10)} = 2.66$ ,  $p > 0.05$ ). A between groups ANOVA indicated a significant effect of risperidone ( $F_{(3, 80)} = 5.08$ ,  $p < 0.01$ ) on the repeated measure factor of sociability, defined as the time spent in the either the side chamber containing the novel mouse or the side chamber containing the novel object, in BTBR during the sociability phase of testing. Bonferroni-Dunn posthoc analysis detected risperidone at dose 0.5 mg/kg significantly differs from vehicle ( $p < 0.005$ ). Time spent sniffing the novel mouse versus the novel object was not significant for vehicle or any doses of risperidone tested (Panel B; vehicle,  $F_{(1, 9)} = 1.87$ ,  $p > 0.05$ ; 0.125 mg/kg;  $F_{(1, 10)} = 0.01$ ,  $p > 0.05$ ; 0.25 mg/kg;  $F_{(1, 9)} = 1.08$ ,  $p > 0.05$ ; 0.5 mg/kg;  $F_{(1, 10)} = 1.24$ ,  $p > 0.05$ ). Reduction in entries into the side chambers was detected by an overall Repeated Measures ANOVA for entries in BTBR (Panel C;  $F_{(3, 80)} = 39.32$ ,  $p < 0.001$ ). Between groups ANOVA followed by a Bonferroni-Dunn posthoc analysis detected reduced entries into the left and right side chambers after risperidone at 0.25 mg/kg ( $p < 0.01$ ) and 0.5 mg/kg ( $p < 0.01$ ), indicating sedative effects of the drug treatments. No innate side preference was present in BTBR during habituation before the start of social testing following vehicle or risperidone (Panel D;  $F_{(1, 41)} = 1.78$ ,  $p > 0.05$ ). Bonferroni-Dunn indicated a significant effect of risperidone during the habituation period by reduced time in the left and right chambers in BTBR after the risperidone dose 0.5 mg/kg ( $\#p < 0.001$ ). No sex differences were detected in BTBR ( $F_{(1, 39)} = 0.04$ ,  $p > 0.05$ ).

## Discussion

Robust phenotypes in mouse models of autism offer powerful translational tools for discovering effective treatment interventions. Mutant mouse models of monogenic neurodevelopmental disorders, including Fragile X syndrome, Rett syndrome, and tuberous sclerosis, have provided valuable leads in demonstrating symptom reversal by mGluR5 antagonists, rapamycin, and gene rescue (Dolen *et al.*, 2007; Ehninger *et al.*, 2008a; Guy *et al.*, 2007; Kwon *et al.*, 2006; Meikle *et al.*, 2008; Paylor *et al.*, 2008; Spencer *et al.*, 2008; Zhou *et al.*, 2009). MPEP is a prototypical antagonist of the metabotropic glutamate receptor mGluR5, with an *in vitro* inhibitory potency  $IC_{50}$  value of 36 nM and an *in vivo* half life of 45 minutes (Anderson *et al.*, 2003; Gasparini *et al.*, 1999; Yan *et al.*, 2005). MPEP effectively reversed several phenotypes in the *Fmr1* mutant mouse model of Fragile X syndrome, including hyperactivity, seizures, prepulse inhibition deficits, and remarkable rescues in synaptic plasticity and spine morphology (Bear *et al.*, 2008; de Vrij *et al.*, 2008; Dolen *et al.*,



2008; Dolen *et al*, 2007; Yan *et al*, 2005). Further, behavioral actions of MPEP included anxiolytic-like effects in standard mice and rats on the elevated plus-maze, stress induced hyperthermia, marble burying assay, conflict drinking test and four plate anxiety assessment (Nordquist *et al*, 2007; Pilc *et al*, 2002; Spooren *et al*, 2000b; Tatarczynska *et al*, 2001) and analgesic actions in the formalin test, inflammatory pain models, paw pressure, Freund's adjuvant induced thermal hypersensitivity and partial sciatic nerve ligation (Montana *et al*, 2009; Walker *et al*, 2001a; Walker *et al*, 2001b). Ligands of the mGluR5 and mGluR2/3 antagonist class may have therapeutic potential for a variety of psychiatric and neurologic disorders and are in clinical trials for Fragile X treatment (Berry-Kravis *et al*, 2009; Patil *et al*, 2007; Rorick-Kehn *et al*, 2007).

Our results demonstrate that MPEP effectively reduced a prominent repetitive behavior in the BTBR mouse model of autism. Doses of 1, 10, and 30 mg/kg i.p. reduced repetitive self-grooming by approximately 50%. Levels of self-grooming in BTBR treated with MPEP were not significantly different than baseline self-grooming in the B6 control strain. Open field exploratory locomotion was in the normal to high range for these doses of MPEP, indicating the absence of gross motor deficits following MPEP administration in the present study, consistent with previous published literature using similar dose ranges on motor assessments including the open field and rotarod tasks (Spooren *et al*, 2000a; Tatarczynska *et al*, 2001). The efficacy of MPEP in reducing repetitive behavior is a novel finding, adding to the potential therapeutic indications for MPEP, and directly relevant to the third diagnostic symptom of autism.

Repetitive behaviors in autism encompass a variable range of motor stereotypies, self-injurious behavior, compulsions, persistent occupation with parts of objects, preoccupations/restricted patterns of interest and inflexible adherence to nonfunctional routines/rituals (Bodfish *et al*, 2000; Lewis *et al*, 2007; Moy *et al*, 2008; Richler *et al*, 2007). Previous indications that MPEP may have anxiolytic-like and analgesic actions (Brodkin *et al*, 2002; Montana *et al*, 2009; Spooren *et al*, 2000b; Tatarczynska *et al*, 2001; Walker *et al*, 2001a; Walker *et al*, 2001b) hold additional promise for mGluR5 antagonist strategies, since associated symptoms of autism include anxiety and elevated pain tolerance in autistic individuals engaged in self-injurious behaviors (Dawson *et al*, 1998; Towbin *et al*, 2005; White *et al*, 2009).

Absence of sociability in BTBR was not reversed by treatment with MPEP. Failure to rescue sociability was not due to a reduction in overall activity, as number of chamber entries during the social task and locomotor activity in an open field were within normal ranges. One report suggested that social exploration was significantly improved with MPEP administration (Spooren *et al*, 2000b) in rats, using a resident intruder task that measures male-male aggression. Another report demonstrated MPEP rescue of courtship behavior in a *Drosophila* model of Fragile X (McBride *et al*, 2005). It is interesting to note that our highest dose MPEP, 30 mg/kg, significantly increased time spent sniffing the novel mouse versus the novel object in BTBR. This preliminary finding suggests that MPEP may have a positive effect on social approach, and highlights the need to test higher doses, multiple injections, or more potent, selective mGluR5 antagonist analogues. MPEP has non-selective effects on NMDA receptors and monoamine oxidase-A (Cosford *et al*, 2003; Lea and Faden, 2006; Montana *et al*, 2009; Movsesyan *et al*, 2001; O'Leary *et al*, 2000), which may contribute to its actions in mediating neuroprotection in cortical neurons and rats (Movsesyan *et al*, 2001; O'Leary *et al*, 2000) and inflammatory pain (Montana *et al*, 2009). Therefore, the significant increase in sniff time in the BTBR at the 30 mg/kg dose could be the result of NMDA modulated non-selective actions of MPEP. Our future directions include assessing the more recently developed 3-[(2-methyl-1,3-thiazol-4-yl) ethynyl] pyridine (MTEP), which has minimal NMDA inhibition, and is active at lower doses in

anxiety-related and pain sensitivity behavioral tasks including the Geller-Seifter conflict test, formalin test, conditioned lick suppression and the Vogel conflict drinking test (Anderson *et al*, 2003; Busse *et al*, 2004; Lea *et al*, 2006; Varty *et al*, 2005), and newer mGluR antagonists in the experimental design described herein.

In contrast to MPEP, risperidone reduced repetitive behavior in BTBR only at doses that were sedating. Risperidone is an atypical antipsychotic, approved specifically to treat irritability associated with autistic disorder in children and adolescents ages 5 to 16 years, including symptoms of aggression towards others, deliberate self-injuriousness, temper tantrums, and quickly changing moods (McCracken *et al*, 2002; McDougle *et al*, 1997; McDougle *et al*, 2005). Our experiments assessed the efficacy of acute administration of risperidone at doses shown to block marble burying, hyperlocomotion, prepulse inhibition deficits, and aggressive behaviors in rats and mice (Bruins Slot *et al*, 2008; Duncan *et al*, 2006; Rodriguez-Arias *et al*, 1998). Risperidone at intraperitoneal doses of 0.125 and 0.25 mg/kg significantly reduced repetitive self-grooming in BTBR, to approximately 40-50% of vehicle control levels, and only slightly higher than B6 control levels. However, at these doses, risperidone reduced activity in the open field test for exploratory locomotion, and produced major reductions in number of entries into the side chambers of the social approach apparatus, due to mice remaining inactive in the center chamber. Significant reductions in general locomotor activity following risperidone in BTBR mice are consistent with previous reports in B6 and BALB/c mouse strains (Cope *et al*, 2009; Wagner *et al*, 2004). Thus, an interpretation of improvement by risperidone in reducing repetitive behaviors in BTBR is confounded by sedation in the present paradigm. In contrast, the clinical literature suggests efficacious and safe use of risperidone for irritability, aggression, hyperactivity, and stereotypy in autism spectrum disorders (McCracken *et al*, 2002; Wagner *et al*, 2004). Experimental design for preclinical studies of risperidone in mouse models of autism may require a wider dose range, a different route of administration, and/or a chronic dose regimen. Further, the autism literature describes considerable variability in the clinical benefits of risperidone treatment in improving social or communication skills. Improvements in eye contact and other measures related to social behavior have been reported (Barnard *et al*, 2002; Chavez *et al*, 2006; McDougle *et al*, 1997; McDougle *et al*, 2000; Posey *et al*, 2008). Minimal or no improvements were reported in social relatedness using the Ritvo Freeman Real Life Rating Scale (Chavez *et al*, 2006; McDougle *et al*, 2005). In the present study, risperidone failed to improve sociability in the BTBR mouse model. Since BTBR mice generally display very low levels of aggression (unpublished observations), low anxiety-like behaviors (McFarlane *et al*, 2008; Yang *et al*, 2009), and do not develop any apparent health problems related to their high self-grooming, they do not present a specific model of obsessive compulsive disorder (Welch *et al*, 2007), self-injurious behavior (Jinnah *et al*, 1999; Wu and Melton, 1993), or other components of irritability relevant to autism.

At present there is no gold standard, and in fact no active compound, that improves sociability in autism, presenting a major challenge to designing predictive validity into translational testing of compounds in mouse models of autism. A goal of this study was to develop a useful experimental design for testing compounds on sociability in mice. We are generating a prototypical screen, towards discovering active compounds in the social approach task, that reverse phenotypes from lack of sociability to sociability in mouse models of autism.

The experimental design presented herein employs two simple behavioral tasks relevant to the first and third diagnostic symptoms of autism, along with a rapid assessment of adverse locomotor side effects. We are beginning to apply this strategy to assess the therapeutic potential of proposed treatments for autism spectrum disorders. Positive findings with the

mGluR5 antagonist MPEP indicate the possibility that this class of compounds may have potential for treating preservative, repetitive behaviors. The strong autism-relevant behavioral phenotypes in the BTBR inbred strain, which is genetically homogenous, commercially available, and easy to breed and maintain, offer a first model system, as a prelude to the future use of hypothesis-driven candidate gene mutation mouse models of autism for testing evidence-based pharmacological interventions.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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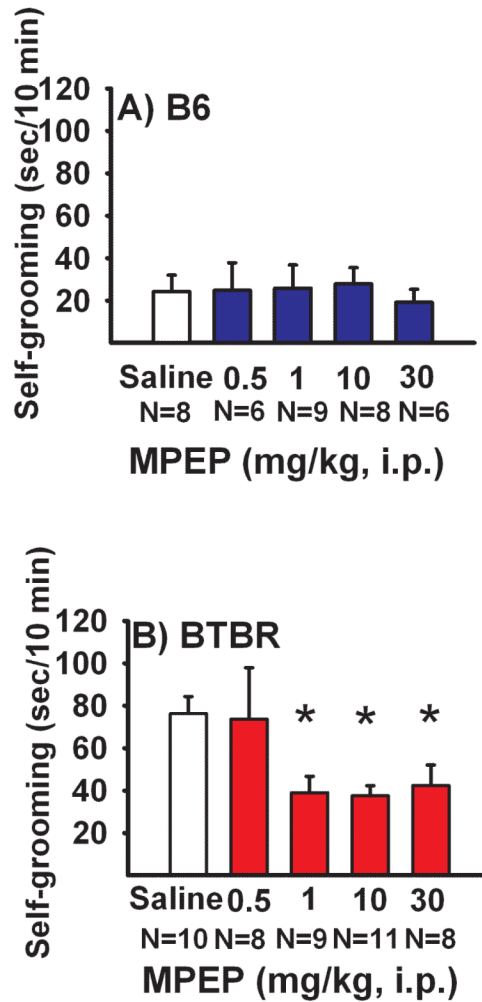
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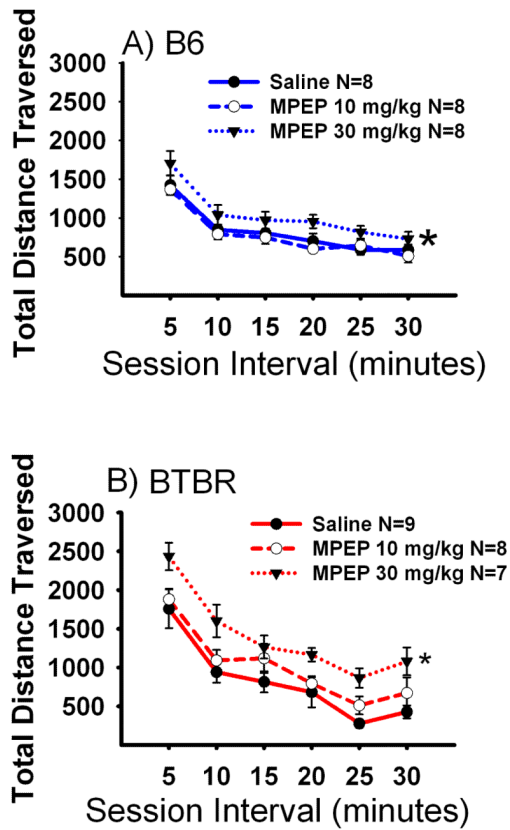
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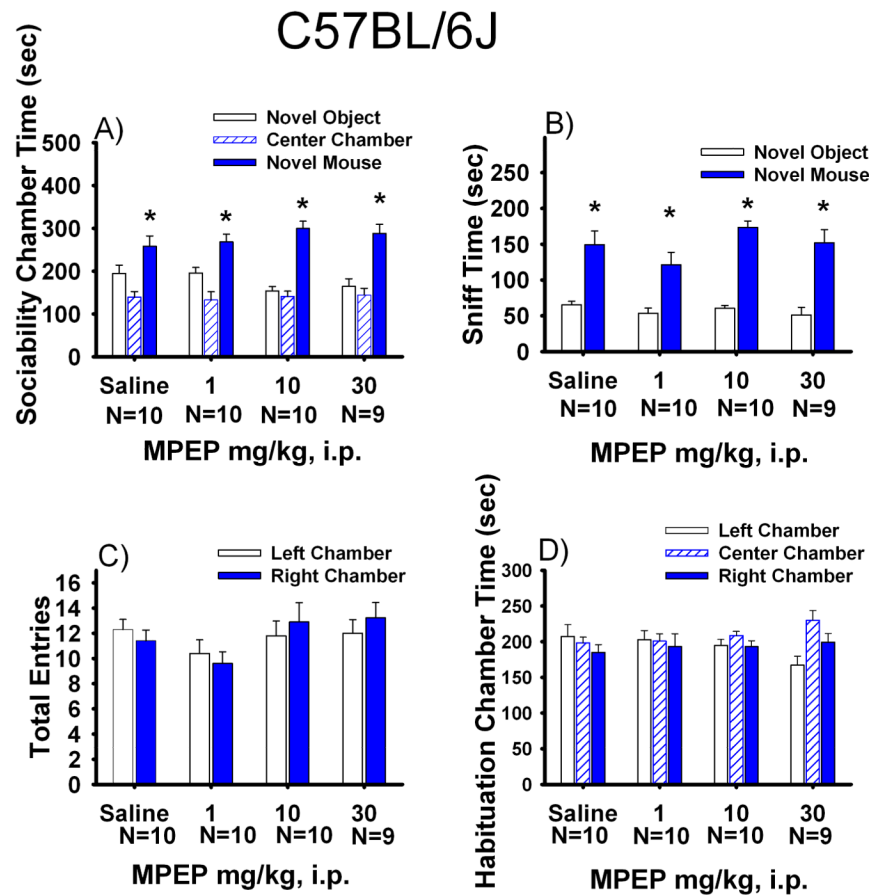
**Figure 1. MPEP reduced self-grooming behavior in BTBR**

Cumulative time spent self-grooming was scored over a 10 minute session, for the data shown in Figures 1 and 5. A) B6 mice did not display any significant differences in the amount of time spent self-grooming after treatment with saline vehicle or MPEP at doses of 0.5 mg/kg, 1.0 mg/kg, 10 mg/kg or 30 mg/kg i. p. B) BTBR displayed significant reductions in their innately high levels of repetitive self-grooming after treatment with MPEP at doses of 1.0 mg/kg, 10 mg/kg and 30 mg/kg, \* $p < 0.05$  as compared to saline.  $N = 6-10$  per dose for each strain. Data are shown as  $\pm$  SEM in all figures. Significant differences are as compared to vehicle treatment in all figures. Please see Results for individual posthoc comparisons and statistics for all figures.



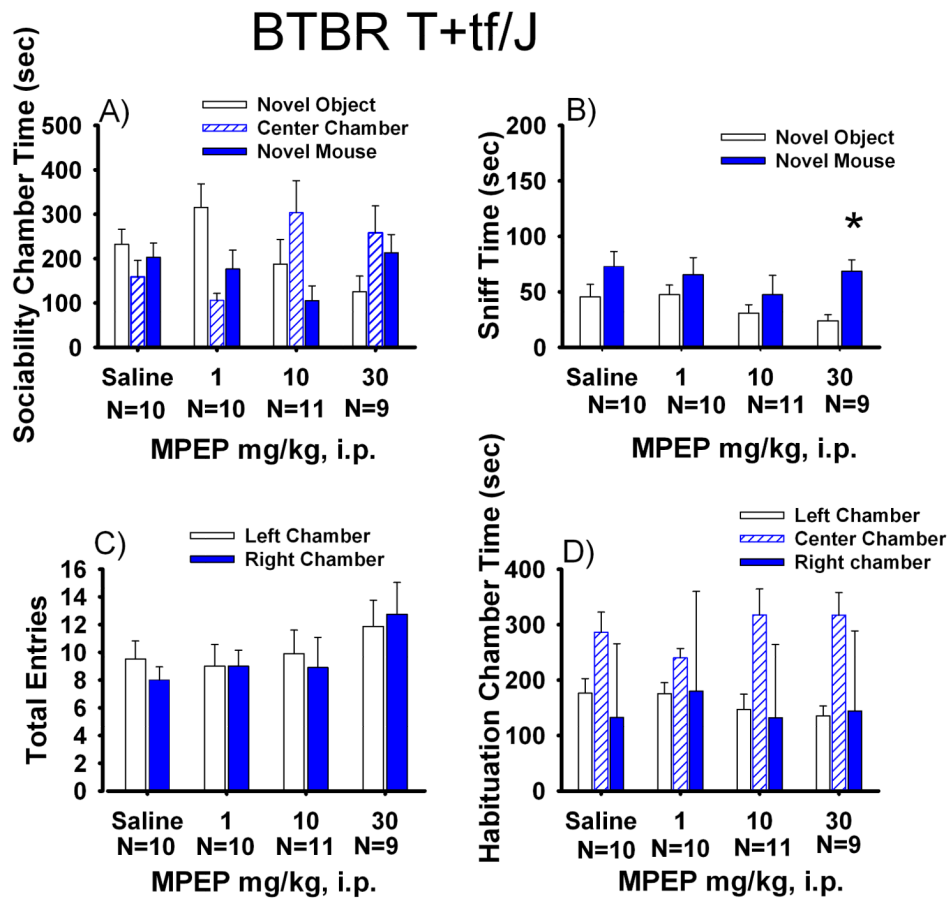
**Figure 2. MPEP did not reduce exploratory locomotion**

Total distance traversed was assayed in 5-minute time bins across a 30 minute session in a novel open field arena, for the data shown in Figures 2 and 6. A) B6 displayed no significant reductions in locomotor activity after administration of MPEP at doses of 10 mg/kg. An overall significant increase in activity compared to vehicle was observed for the 30 mg/kg treatment group  $*p < 0.05$ . Significant increases in total distance during the first and fourth time 5-minute interval were observed compared to the 10 mg/kg dose. B) BTBR displayed no significant reductions in locomotor activity after administration of MPEP at doses of 10 mg/kg and 30 mg/kg. MPEP increased locomotion at the 30 mg/kg dose, during the first, second, fifth and sixth 5-minute time bins  $*p < 0.05$ .  $N = 7-9$  per dose for each strain.



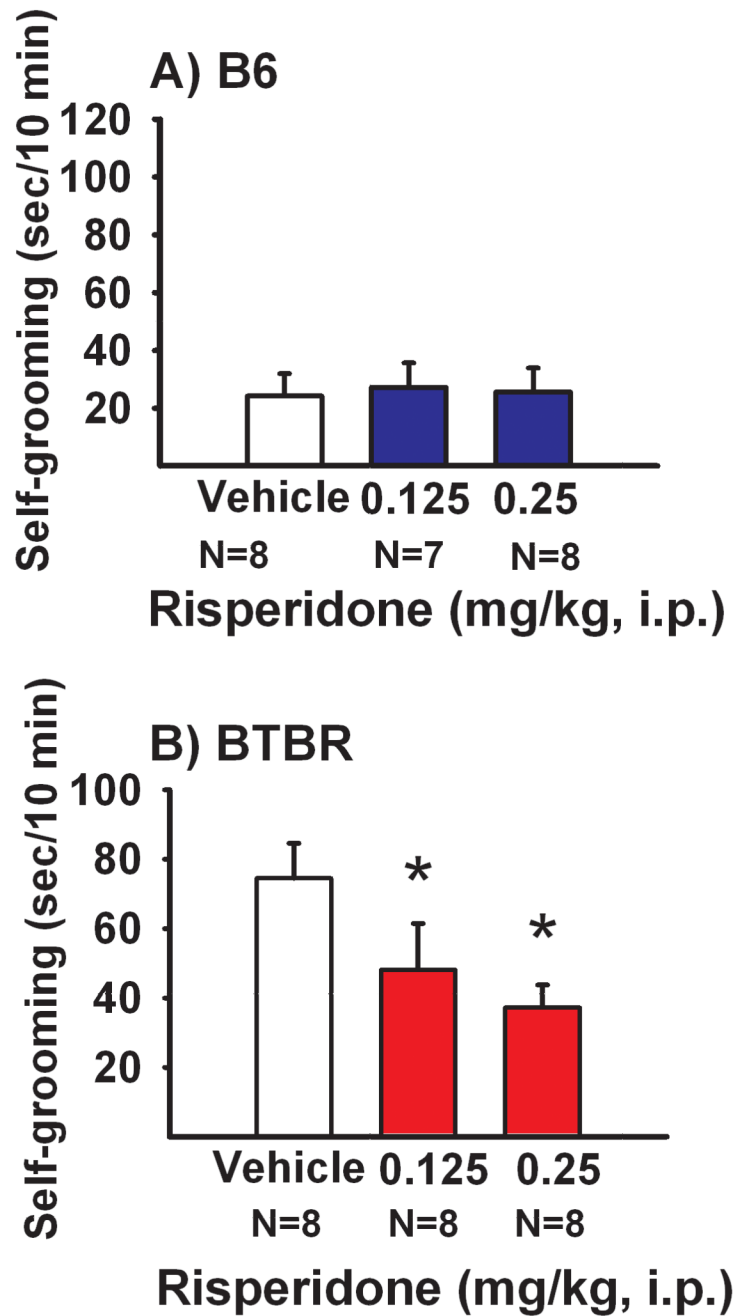
**Figure 3. B6 sociability was unaffected by MPEP administration**

Social approach was assayed in an automated photocell-equipped three-chambered arena, along with observer scoring of direct sniffing interactions from videotapes of the social approach session, in Figures 3, 4, 7, and 8. A) B6 displayed normal sociability as expected, defined as more time in the side chamber with the novel mouse than in the side chamber with the novel object, following saline and MPEP treatments. B) B6 displayed significantly more time spent sniffing the novel mouse than the novel object, following saline and MPEP treatments. C) B6 displayed no difference in number of entries into the side chambers after MPEP treatment, indicating no drug effect on general exploratory activity during the social approach task. D) B6 displayed no innate chamber side bias during the 10 minute habituation phase before the start of the sociability test. N = 8-10 per dose.



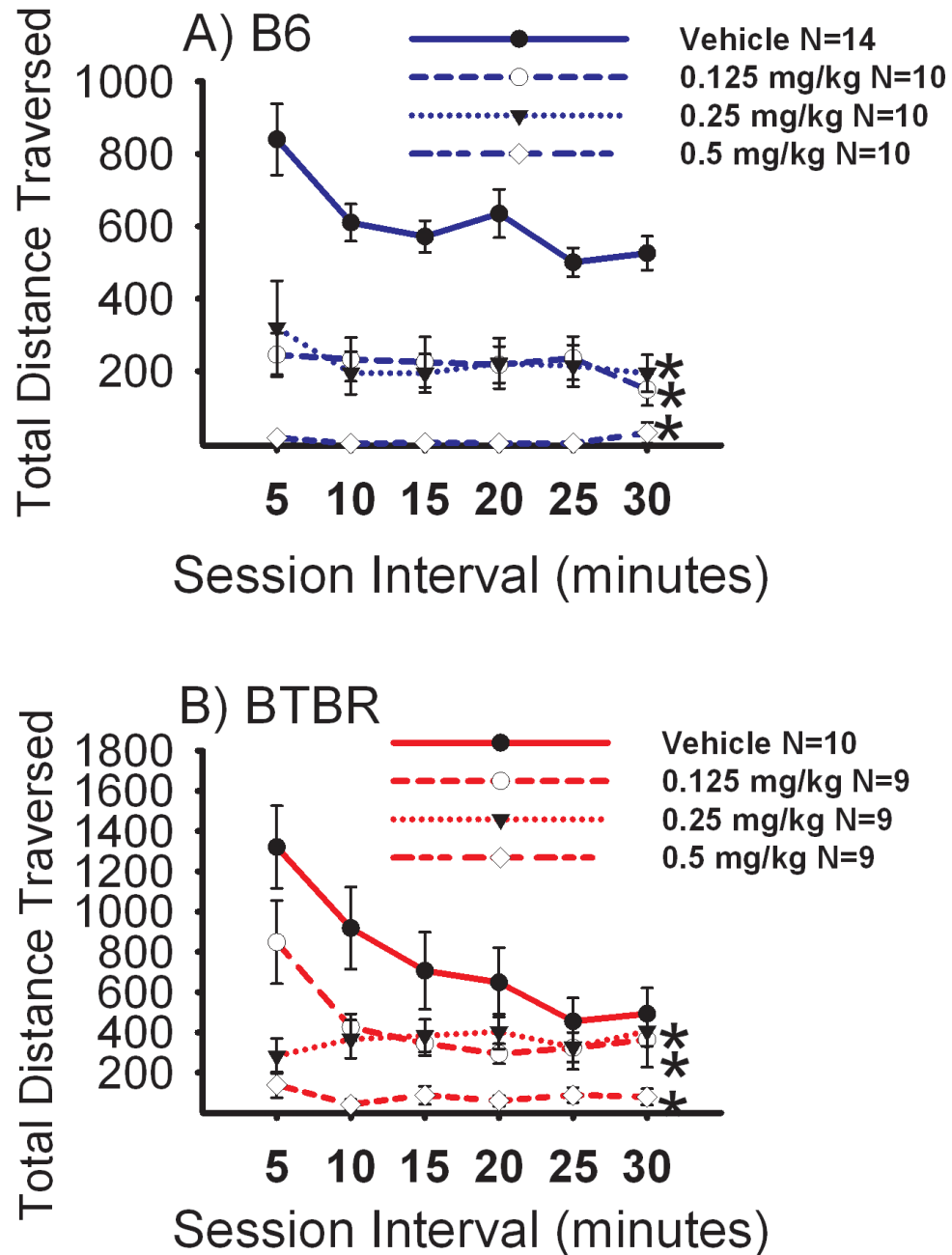
**Figure 4. BTBR lack of sociability was unaffected by MPEP administration**

A) BTBR failed to display sociability as expected, spending similar amounts of time in the novel mouse chamber as compared to the novel object chamber following saline treatment. Lack of sociability in BTBR was similarly seen in each MPEP treatment group. B) BTBR generally did not display significantly more time spent sniffing the novel mouse than the novel object following MPEP treatments. However, increased time spent sniffing was detected in the BTBR group treated with the 30 mg/kg dose of MPEP (\* $p < .05$ ), indicating a trend towards improvement in social interactions. C) No difference in number of entries into the side chambers was detected after MPEP treatments, indicating no drug effects on general exploratory activity during the sociability task. D) BTBR displayed no innate chamber side bias during the 10 minute habituation phase before the start of the sociability task. N = 9-11 per dose.



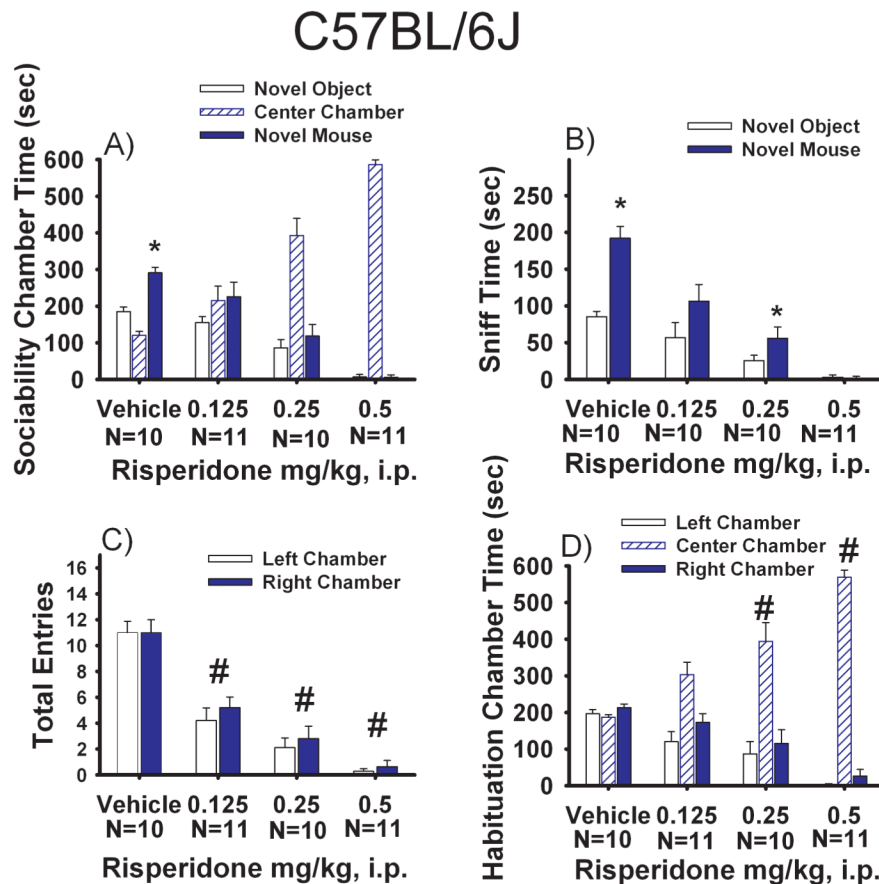
**Figure 5. Risperidone reduced self-grooming behavior in BTBR**

A) B6 mice did not exhibit any significant differences in the amount of time spent self-grooming following treatment with risperidone at doses 0.125 mg/kg and 0.25 mg/kg. B) BTBR displayed significant reductions in their innately high levels of repetitive self-grooming after treatment with risperidone at doses 0.125 mg/kg and 0.25 mg/kg, as compared to vehicle, \* $p < 0.05$ . N = 7-8 mice per dose.



**Figure 6. Risperidone reduced exploratory locomotion in an open field**

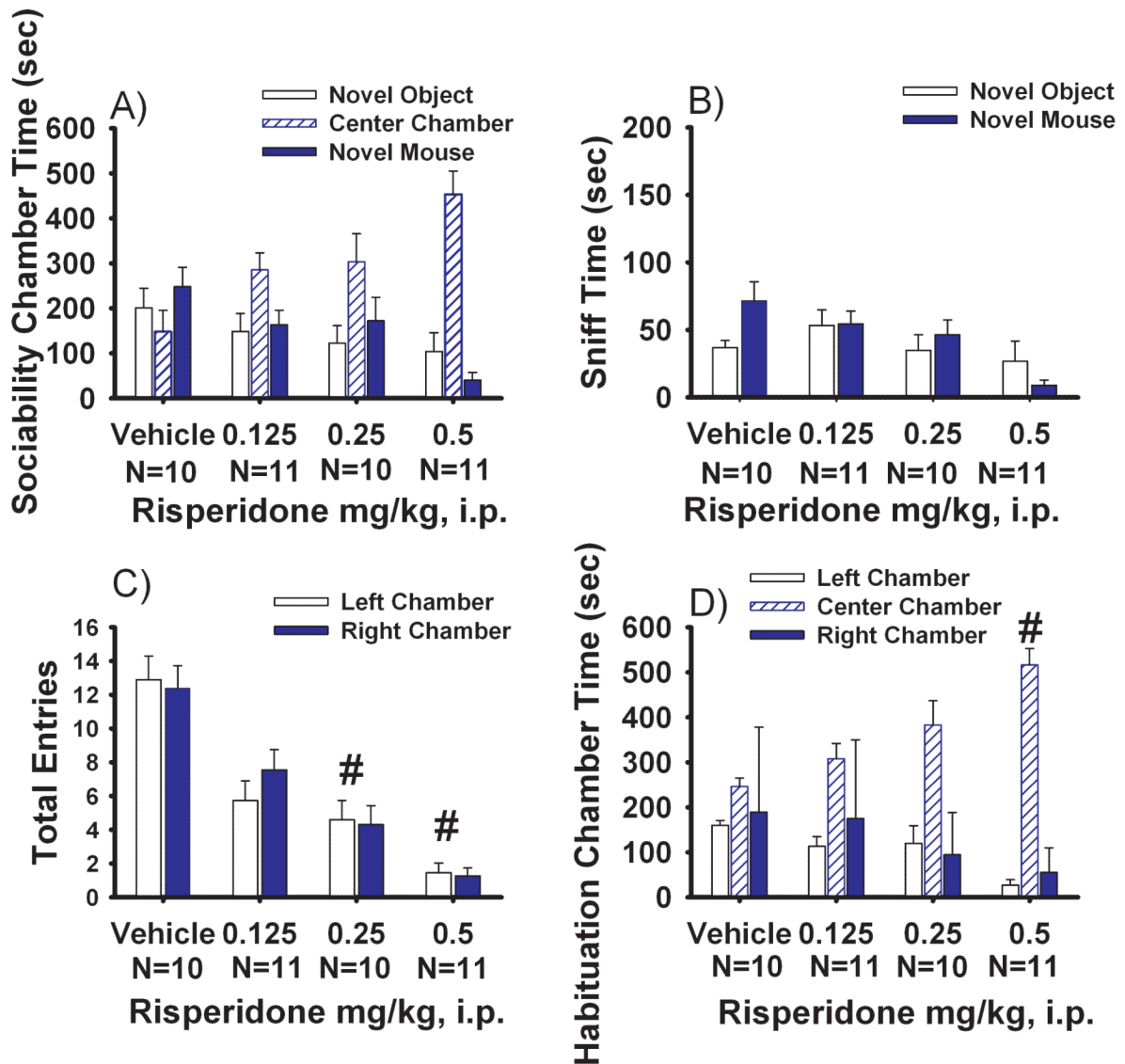
A) B6 displayed significant reductions in locomotor activity after administration of risperidone at doses of 0.125 mg/kg, 0.25 mg/kg and 0.5 mg/kg. B) BTBR displayed significant reductions in locomotor activity after administration of risperidone at doses of 0.125 mg/kg, 0.25 mg/kg and 0.5 mg/kg, during the first and second 5-minute time bins \*  $p < 0.05$ . Risperidone treatment at a dose of 0.5 mg/kg reduced locomotion across 5 of the 6 assessed 5-minute time bins \*  $p < 0.05$ . N = 9-14 per dose for each strain.



**Figure 7. B6 sociability was reduced by risperidone administration**

A) B6 displayed significant sociability, as expected, following vehicle treatment,  $*p < 0.05$ . Risperidone reduced normal sociability in B6, resulting in approximately equal low amounts of time spent in the two side chambers, concomitant with more time spent in the center chamber. B) B6 displayed significantly more time spent sniffing the novel mouse than the novel object after vehicle and 0.25 mg/kg risperidone treatments,  $*p < 0.05$ , but did not following 0.125 mg/kg and 0.5 mg/kg risperidone treatments. C) B6 displayed a reduction in the number of entries into the side chambers, indicating a sedating effect of risperidone during the sociability task  $^{\#}p < 0.05$ . D) B6 displayed no innate chamber side bias during the 10 minute habituation phase before the start of the sociability test.  $N = 8-10$  per dose  $*p < 0.05$ .

## BTBR T+tf/J



**Figure 8. BTBR lack of sociability was unaffected by risperidone administration**

A) BTBR did not display sociability following vehicle or risperidone treatment. B) BTBR did not display significantly more time spent sniffing the novel mouse than the novel object, following vehicle and risperidone administration. C) BTBR displayed a reduction in the number of entries into the side chambers, indicating a sedating effect of risperidone during the sociability task at doses 0.25 mg/kg and 0.5 mg/kg, # $p < .05$ . D) BTBR displayed the normal lack of innate chamber side bias during the 10 minute habituation phase before the start of the sociability test. N = 10-11 per dose.