



## Chronic inflammatory pain drives alcohol drinking in a sex-dependent manner for C57BL/6J mice

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### ABSTRACT

Sex differences in chronic pain and alcohol abuse are not well understood. The development of rodent models is imperative for investigating the underlying changes behind these pathological states. In the present study, we investigated whether hind paw treatment with the inflammatory agent Complete Freund's Adjuvant (CFA) could generate hyperalgesia and alter alcohol consumption in male and female C57BL/6J mice. CFA treatment led to greater nociceptive sensitivity for both sexes in the Hargreaves test, and increased alcohol drinking for males in a continuous-access two-bottle choice (CA2BC) paradigm. Regardless of treatment, female mice exhibited greater alcohol drinking than males. Following a 2-h terminal drinking session, CFA treatment failed to produce changes in alcohol drinking, blood ethanol concentration (BEC), and plasma corticosterone (CORT) for both sexes. Two-hour alcohol consumption and CORT was higher in females than males, regardless of CFA treatment. Taken together, these findings have established that male mice are more susceptible to escalations in alcohol drinking when undergoing pain, despite higher levels of total alcohol drinking and CORT in females. Furthermore, the exposure of CFA-treated C57BL/6J mice to the CA2BC drinking paradigm has proven to be a useful model for studying the relationship between chronic pain and alcohol abuse. Future applications of the CFA/CA2BC model should incorporate manipulations of stress signaling and other related biological systems to improve our mechanistic understanding of pain and alcohol interactions.

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### Introduction

Alcohol provides an accessible means of self-medication for pain-suffering populations, with approximately 25% of chronic pain patients consuming alcohol for symptom relief (Riley & King, 2009). Although alcohol can act as a transient pharmacological intervention for pain, excessive drinking can lead to increased risk for addiction and related health complications (Koob & Volkow, 2010). Chronic exposure to alcohol is especially detrimental for pain, with marked increases in sensitivity after drug cessation (Boissoneault, Lewis, & Nixon, 2018; Dhir, Naidu, & Kulkarni, 2005;

Dina et al., 2000; Dina, Gear, Messing, & Levine, 2007; Dodds, Lawson, Simpson, & Williams, 1945; Edwards et al., 2012; Fu et al., 2015; Gatch & Lal, 1999; Jochum, Boettger, Burkhardt, Juckel, & Bar, 2010; Malec, Kotlinska, & Langwinski, 1987; Riley & King, 2009; Roltsch Hellard, Impastato, & Gilpin, 2017; Shumilla, Liron, Mochly-Rosen, Kendig, & Sweitzer, 2005; Smith, Li, & Ryabinin, 2015; Wolff, Hardy, & Goodell, 1942). Clinical observations have suggested important differences in the way men and women consume alcohol and experience the detrimental consequences of alcohol abuse when suffering from pathological pain. Among chronic pain patients, alcohol use is more prevalent in males (Brennan, Schutte, Moos, & Moos, 2011; Egli, Koob, & Edwards, 2012; Riley & King, 2009; Wilsnack, Wilsnack, Kristjanson, Vogeltanz-Holm, & Gmel, 2009). Females that habitually consume alcohol, however, are more susceptible to pathological pain (Boissoneault et al., 2018). To date, preclinical investigations have

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failed to model similar sex-specific patterns in drinking and pain, thus providing a major hurdle to studying the mechanisms of pain-related alcohol consumption (Smith et al., 2015; Yeziarski & Hansson, 2018).

To address this deficit in preclinical models, the present study examines alcohol consumption in male and female C57BL/6J mice treated with Complete Freund's Adjuvant (CFA), an antigen emulsion containing heat-dried *Mycobacterium tuberculosis*. CFA was selected to model chronic inflammatory pain, since it closely mimics the time course of persistent injury (Hargreaves, Dubner, Brown, Flores, & Joris, 1988; Larson, Brown, el-Atrash, & Walser, 1986; Ren & Dubner, 1999). Furthermore, postoperative pain, arthritis, and related inflammatory states have exhibited a close relationship with alcohol abuse (King et al., 2012). Therefore, we hypothesized that CFA-treated mice would show increased alcohol consumption compared to uninjured mice. To test this, we exposed saline- and CFA-treated mice of both sexes to a voluntary drinking paradigm (i.e., CA2BC with 20% ethanol), and measured alcohol consumption across a 3-week timespan. Thermal nociceptive thresholds were assessed to ensure that CFA treatment altered pain sensitivity. Blood ethanol concentration (BEC) and plasma corticosterone (CORT) levels were analyzed to assess pharmacologically relevant drinking and alcohol-related stress signaling, two possible contributors to sex differences in alcohol and pain interactions (Edwards et al., 2012; Egli et al., 2012; Fu & Neugebauer, 2008; Heilig & Koob, 2007; Koob, 2013). Taken together, these experiments aim to successfully model sex differences in pain-related alcohol drinking for mice, with the hope that it can be applied toward mechanistic investigations of pain and alcohol interactions in the future.

## Materials and methods

### Animals

A total of 32 male and female C57BL/6J mice (Jackson Laboratories, Bar Harbor, Maine) arrived at 6 weeks of age and were group-housed for one week to habituate to vivarium conditions. Following habituation, mice were individually housed in ventilated Plexiglas® cages and given 3 days of acclimation in a 12-h reverse light/dark cycle (lights on from 12:00 midnight to 12:00 noon) prior to the start of the experiment. Subjects were provided *ad libitum* access to water and Isopro RMH 3000 chow (Prolab, St. Louis, Missouri) for the duration of the experiment. All procedures were approved by the University of North Carolina at Chapel Hill Institutional Animal Care and Use Committee and were in accordance with the NIH Guide for Care and Use of Laboratory Animals.

### Continuous-access two-bottle choice drinking

Male ( $n = 16$ ) and female ( $n = 16$ ) mice were given continuous access to 20% ethanol (w/v) and tap water for 3 weeks. Ethanol solutions were prepared with tap water and 95% ethanol (Pharmaco-AAPER; Brookfield, Connecticut), and delivered via sipper tubes made from 50-mL plastic tubes (Nalgene), rubber stoppers (Fisher Scientific; Agawam, Massachusetts), and sipper tubes (Ancare Corp.; Bellmore, New York). Prior to ethanol exposure, subjects were given 3 days to adapt to drinking with sipper tubes. Individually housed mice were then given access to two sipper tubes per cage – one containing 20% ethanol and the other containing tap water. For the span of 3 weeks, ethanol and water bottles were weighed daily 3 h into the dark cycle. Bottle placement (left vs. right) was alternated weekly to control for an inherent or developed side preference. To control for non-consumption-related fluid loss, a dummy cage containing identical sipper tubes was used

to subtract weekly dripped fluid values from subject fluid consumption.

### Chronic inflammatory pain

Prior to ethanol exposure, subjects were given a 50- $\mu$ L subcutaneous injection of saline or Complete Freund's Adjuvant (CFA) (Sigma; St. Louis, Missouri) in the plantar surface of the right hind paw ( $n = 8$ ). Drinking experiments started 3 days after paw injections, around the time that CFA exhibits maximum inflammatory hyperalgesia (Pitzer, Kuner, & Tappe-Theodor, 2016). To verify that changes in drinking behavior resulted from differences in pain sensitivity, thermal nociceptive thresholds of saline- and CFA-treated mice were assessed one day after the last 24-h ethanol exposure using the Hargreaves test. Mice were placed into a Plexiglas® chamber elevated on a glass plate (ITC Life Science Inc.; Woodland Hills, California) and habituated to the behavioral apparatus for a minimum of 30 min. The mid-plantar surface of saline/CFA-treated and untreated hind paws was then exposed to three heat trials each and assessed for paw withdrawal latencies (PWL). The beam intensity was set to produce basal PWLs of approximately 4–6 s, with a maximum value of 20 s to prevent excessive tissue damage. All testing was conducted with investigators blinded to the experimental conditions.

### Blood ethanol and corticosterone concentrations

Following pain sensitivity testing, mice were given 4 days to recover and re-establish CA2BC drinking behavior in preparation for blood ethanol and corticosterone measurements. On the final drinking day, mice were sacrificed 2 h into the dark cycle, with trunk blood immediately collected in centrifuge tubes following decapitation. Blood samples were centrifuged at 4 °C for 10 min at 3000 RPM, and the plasma was separated for storage at –80 °C until analysis. To measure blood ethanol concentration (BEC; mg/dL), 5- $\mu$ L plasma samples were administered through a Model AM1 Alcohol Analyser (Analox Instruments Ltd.; Lunenburg, Massachusetts). To measure plasma corticosterone (CORT; ng/mL), 5- $\mu$ L plasma samples were processed with a commercially available colorimetric ELISA kit (Arbor Assays; Ann Arbor, Michigan), according to the manufacturer's instructions, with all samples run in duplicate.

### Statistical analysis

All statistical analyses were performed using Prism 6 (GraphPad Software Inc.; La Jolla, California). Analysis of drinking across sessions for saline- and CFA-treated mice (i.e., Treatment  $\times$  Session for ethanol intake, ethanol preference ratio, water intake, and total fluid intake) was performed with a repeated-measures analysis of variance (RM-ANOVA). Drinking values for each mouse were averaged across the 3-week drinking period to compare Treatment  $\times$  Sex with additional two-way ANOVAs. Differences in PWL were determined with a two-way ANOVA comparing Treatment  $\times$  Paw. *Post hoc* analyses with Sidak or Tukey adjustment were performed following significant main group effects. Data are reported as mean plus or minus the standard error of the mean (mean  $\pm$  SEM). Correlational analyses were conducted using linear regressions to assess the predictive relationship of ethanol intake and thermal nociceptive sensitivity, BEC, and CORT levels, with slopes and intercepts assessed for deviation from zero to determine statistical significance. See Fig. 1 for Experimental Timeline.

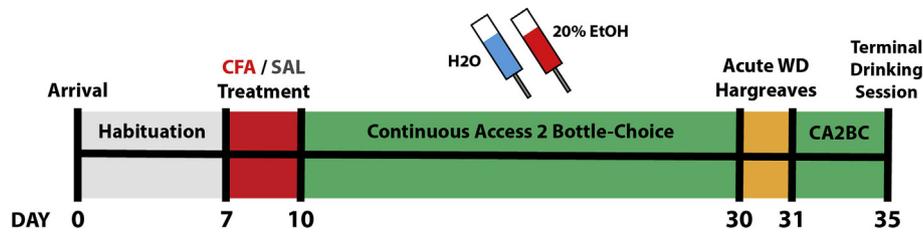


Fig. 1. Experimental timeline of CFA/CA2BC. Days are marked relative to arrival of subjects.

## Results

### CFA-treated mice exhibit greater alcohol drinking in a sex-dependent manner

#### Ethanol intake

Male mice treated with CFA consumed a significantly greater amount of ethanol per day (g/kg/24 h) than saline-treated controls, while females did not exhibit any consumption differences across treatments (Fig. 2). A RM-ANOVA (Treatment  $\times$  Session) revealed a main effect for Treatment [ $F(1,76) = 4.768, p = 0.0465$ ] and Session [ $F(19,266) = 1.656, p = 0.0437$ ] in males (Fig. 2A), and a main effect for Session [ $F(19,266) = 9.470, p < 0.0001$ ] in females (Fig. 2B), but no significant interaction for either sex. Sidak *post hoc* analysis revealed no significant difference in ethanol intake between saline- and CFA-treated mice during individual drinking sessions of males or females. Mean drinking values for individual subjects were averaged across 3 weeks in their respective treatment and sex groupings. A two-way ANOVA (Treatment  $\times$  Sex) revealed a main effect for Treatment [ $F(1,76) = 26.04, p < 0.0001$ ] and Sex [ $F(1,76) = 179.6, p < 0.0001$ ], and a significant interaction between Treatment and Sex [ $F(1,76) = 16.45, p = 0.0001$ ], where female mice exhibit greater ethanol intake than males, regardless of paw treatment (Fig. 2C). Tukey *post hoc* analysis revealed a significant difference in ethanol intake between saline- and CFA-treated mice for males, but not females (Fig. 2C).

#### Ethanol preference ratio

Preference for ethanol exhibited similar results, with CFA-treated male mice showing a significantly greater ethanol preference ratio than their saline-treated counterparts, while females did not exhibit a preference difference across treatments (Fig. 3). A RM-ANOVA (Treatment  $\times$  Session) revealed a main effect for Treatment [ $F(1,14) = 6.777, p = 0.0208$ ] in males (Fig. 3A) and Session [ $F(19,266) = 5.297, p < 0.0001$ ] in females (Fig. 3B), but no

significant interaction for either sex. Sidak *post hoc* analysis showed no significant difference in ethanol preference ratio between saline- and CFA-treated mice during individual drinking sessions of males or females. A two-way ANOVA (Treatment  $\times$  Sex) revealed a main effect for Treatment [ $F(1,76) = 29.88, p < 0.0001$ ] and Sex [ $F(1,76) = 128.6, p < 0.0001$ ], and a significant interaction between Treatment and Sex [ $F(1,76) = 48.43, p < 0.0001$ ], where ethanol preference ratio was greater in females than males for both treatments (Fig. 3C). Tukey *post hoc* analysis showed a significant difference in ethanol preference ratio between saline- and CFA-treated mice for males, but not females (Fig. 3C).

#### Water intake

CFA-treated mice showed sex-specific effects for water intake, with CFA-treated males consuming less water than saline-treated controls, and CFA-treated females consuming more water than controls (Fig. 4). A RM-ANOVA (Treatment  $\times$  Session) revealed a main effect for Session [ $F(19,266) = 5.661, p \leq 0.0001$ ] in males (Fig. 4A), no main effect for Treatment or Session in females (Fig. 4B), and no significant interaction for either sex. Sidak *post hoc* analysis showed no significant difference in water intake between saline- and CFA-treated mice during individual drinking sessions of males or females. A two-way ANOVA (Treatment  $\times$  Sex) revealed a main effect for Sex [ $F(1,76) = 37.04, p < 0.0001$ ] but not Treatment [ $F(1,76) = 0.8203, p = 0.3680$ ], and a significant interaction between Treatment and Sex [ $F(1,76) = 27.19, p < 0.0001$ ] (Fig. 4C). Tukey *post hoc* analysis showed a significant difference in water intake between saline- and CFA-treated mice for both males and females (Fig. 4C).

#### Total fluid intake

CFA-treated mice exhibited significantly greater total fluid intake than their saline-treated counterparts in both sexes (Fig. 5). A RM-ANOVA (Treatment  $\times$  Session) revealed a main effect for Session in males [ $F(19,266) = 13.35, p < 0.0001$ ] (Fig. 5A) and

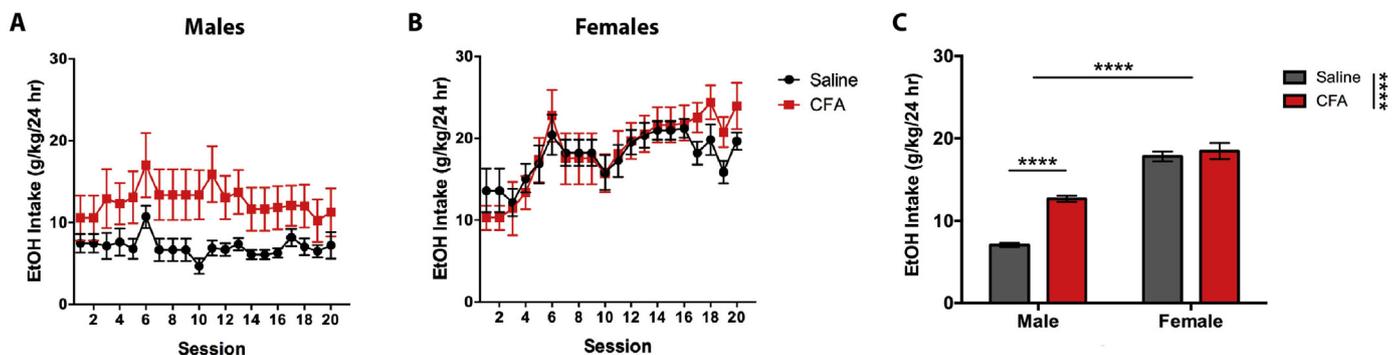
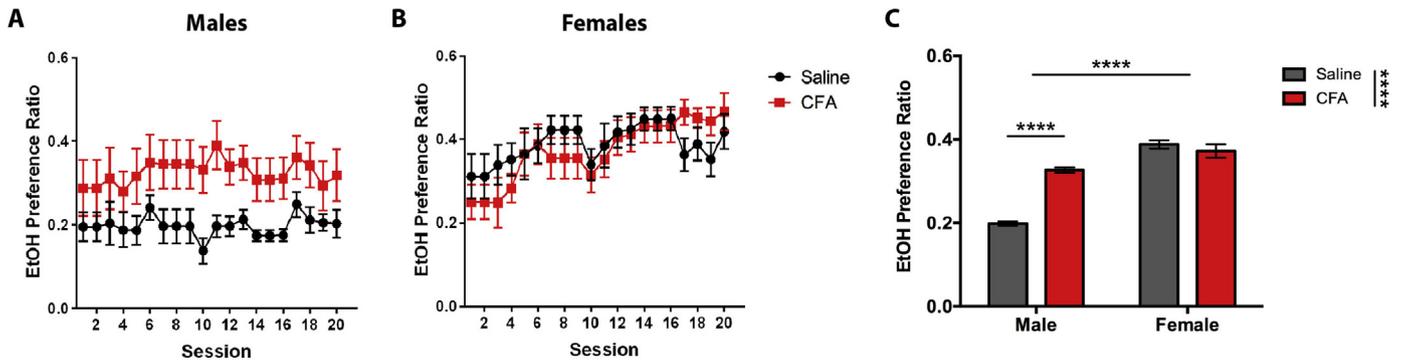
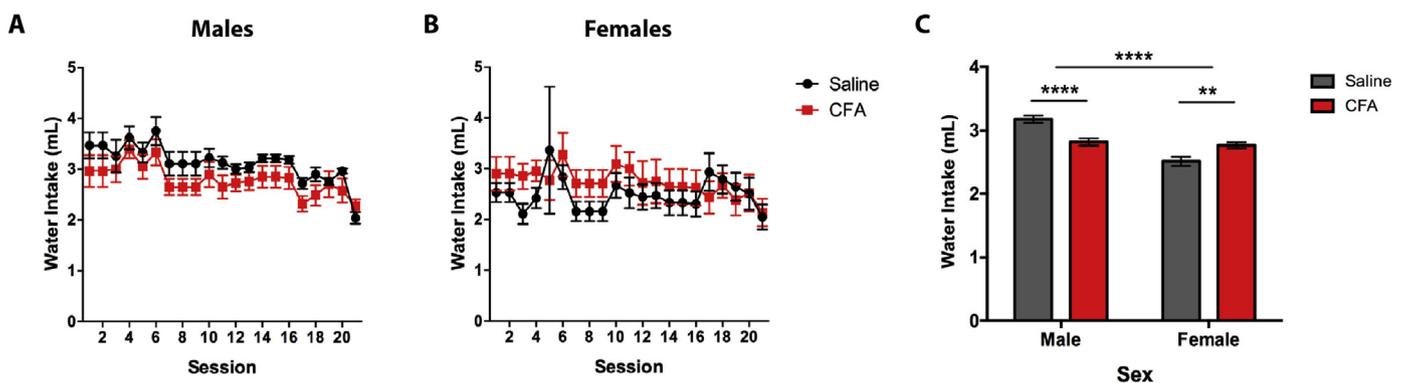


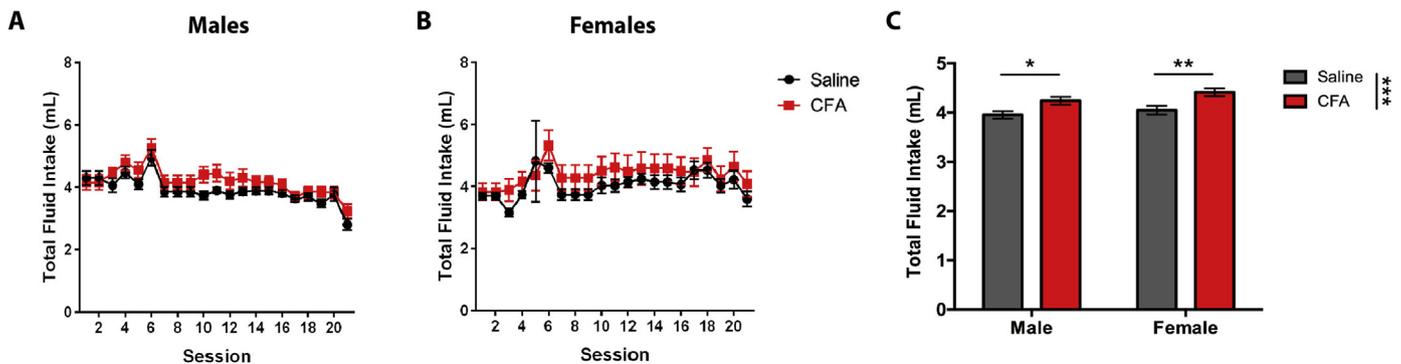
Fig. 2. Daily alcohol intake (g/kg/24 h) of saline- or CFA-treated C57BL/6J mice over a 3-week continuous-access regimen. Pain-related consumption of 20% ethanol (w/v) was assessed for (A) males ( $n = 8$ ) and (B) females ( $n = 8$ ) in 20 consecutive sessions. (C) Averages of daily intake were compared between saline- and CFA-treated males and females. Data are mean alcohol intake  $\pm$  SEM. \*\*\*\* $p < 0.0001$  difference between groups.



**Fig. 3.** Daily alcohol preference ratio of saline- or CFA-treated C57BL/6J mice over a 3-week continuous-access regimen. Pain-related alcohol preference was assessed for (A) males ( $n = 8$ ) and (B) females ( $n = 8$ ) in 20 consecutive sessions. (C) Averages of daily intake were compared between saline- and CFA-treated males and females. Data are mean alcohol preference  $\pm$ SEM. \*\*\*\* $p < 0.0001$  difference between groups.



**Fig. 4.** Daily water intake (mL) of saline- or CFA-treated C57BL/6J mice over a 3-week continuous-access regimen. Pain-related consumption of water was assessed for (A) males ( $n = 8$ ) and (B) females ( $n = 8$ ) in 20 consecutive sessions. (C) Averages of daily intake were compared between saline- and CFA-treated males and females. Data are mean alcohol preference  $\pm$ SEM. \*\* and \*\*\*\* correspond to  $p < 0.005$  and  $p < 0.0001$  difference between groups.

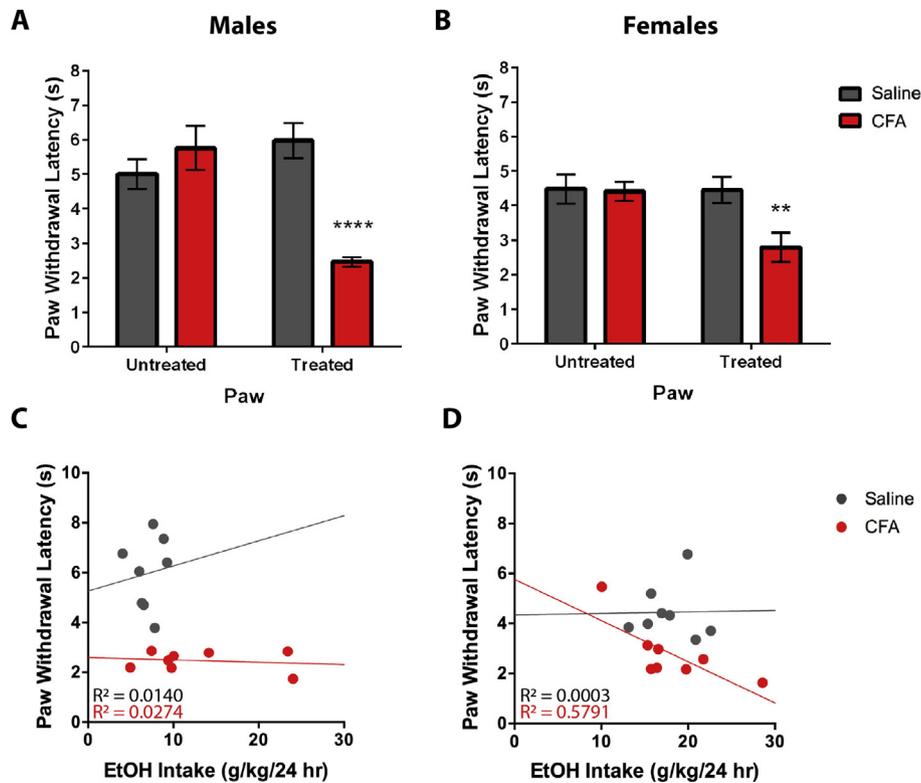


**Fig. 5.** Daily alcohol and water intake (mL) of saline- or CFA-treated C57BL/6J mice over a 3-week continuous-access regimen. Pain-related consumption of fluids was assessed for (A) males ( $n = 8$ ) and (B) females ( $n = 8$ ) in 20 consecutive sessions. (C) Averages of daily intake were compared between saline- and CFA-treated males and females. Data are mean fluid intake  $\pm$ SEM. \*, \*\*, and \*\*\* correspond to  $p < 0.05$ ,  $p < 0.005$ , and  $p < 0.0005$  difference between groups.

females [ $F(19,266) = 4.514$ ,  $p < 0.0001$ ] (Fig. 5B), but no significant interaction for either sex. Sidak *post hoc* analysis demonstrated no significant difference in total fluid intake between saline- and CFA-treated mice during individual drinking sessions of males or females. A two-way ANOVA (Treatment  $\times$  Sex) revealed a main effect for Treatment [ $F(1,76) = 16.38$ ,  $p = 0.0001$ ], but no main effect for Sex [ $F(1,76) = 2.742$ ,  $p = 0.1018$ ] or significant interaction between Treatment and Sex [ $F(1,76) = 0.2358$ ,  $p = 0.6287$ ] (Fig. 5C). Tukey *post hoc* analysis showed a significant difference in total fluid intake between saline- and CFA-treated mice for both males and females (Fig. 5C).

#### CFA-treated mice exhibit higher sensitivity to thermal nociception in both sexes

Male and female mice treated with CFA exhibit higher sensitivity to thermal nociception, as indicated by lower PWLs, when compared to saline-treated mice (Fig. 6). A RM-ANOVA (Treatment  $\times$  Paw) exhibited a main effect for Treatment [ $F(1,14) = 7.010$ ,  $p = 0.0191$ ] and Paw [ $F(1,14) = 8.155$ ,  $p = 0.0127$ ], and a significant Treatment  $\times$  Paw interaction [ $F(1,14) = 27.46$ ,  $p = 0.0001$ ] in males (Fig. 6A), whereas a RM-ANOVA (Treatment  $\times$  Paw) exhibited a main effect for Paw



**Fig. 6.** Pain sensitivity of saline- and CFA-treated C57BL/6J mice was tested 24 h after last alcohol exposure. Using the Hargreaves test, paw withdrawal latency (s) was measured in response to a thermal nociceptive stimulus for substance-treated and untreated paws of (A) male and (B) female mice. Pain sensitivity was correlated with average daily alcohol intake in (C) males and (D) females. Data are mean paw withdrawal latency  $\pm$ SEM. \*\* and \*\*\*\* correspond to  $p < 0.005$  and  $p < 0.0001$  difference between groups, respectively.

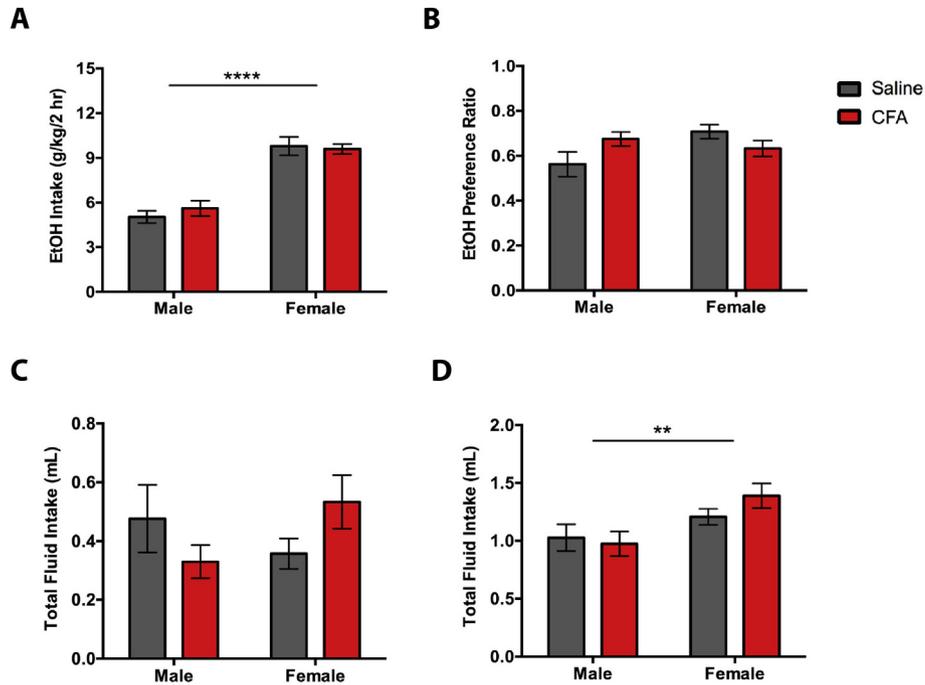
[ $F(1,14) = 11.00, p = 0.0051$ ], but not Treatment [ $F(1,14) = 3.276, p = 0.0918$ ], and a significant Treatment  $\times$  Paw interaction [ $F(1,14) = 10.15, p = 0.0066$ ] in females (Fig. 6B). Sidak *post hoc* analysis revealed a significant difference in PWLs between saline- and CFA-treated mice for treated paws, but not untreated paws, of both males (Fig. 6A) and females (Fig. 6B). To assess the relationship between pain and drinking, a linear regression was conducted for thermal nociceptive sensitivity of the treated paw as a predictor of ethanol intake. For males, saline-treated mice exhibited a non-significant regression equation of [ $F(1,6) = 0.0855, p = 0.7798$ ] with  $R^2$  of 0.0140 (Fig. 6C), whereas CFA-treated mice exhibited a non-significant regression equation of [ $F(1,6) = 0.1691, p = 0.6952$ ] with  $R^2$  of 0.0274 (Fig. 6C). For females, saline-treated mice exhibited a non-significant regression equation of [ $F(1,6) = 0.0018, p = 0.9674$ ] with  $R^2$  of 0.0003 (Fig. 6D), whereas CFA-treated mice exhibited a significant regression equation of [ $F(1,6) = 8.254, p = 0.0283$ ] with  $R^2$  of 0.5791 (Fig. 6D).

#### CFA does not alter blood ethanol concentration and plasma corticosterone

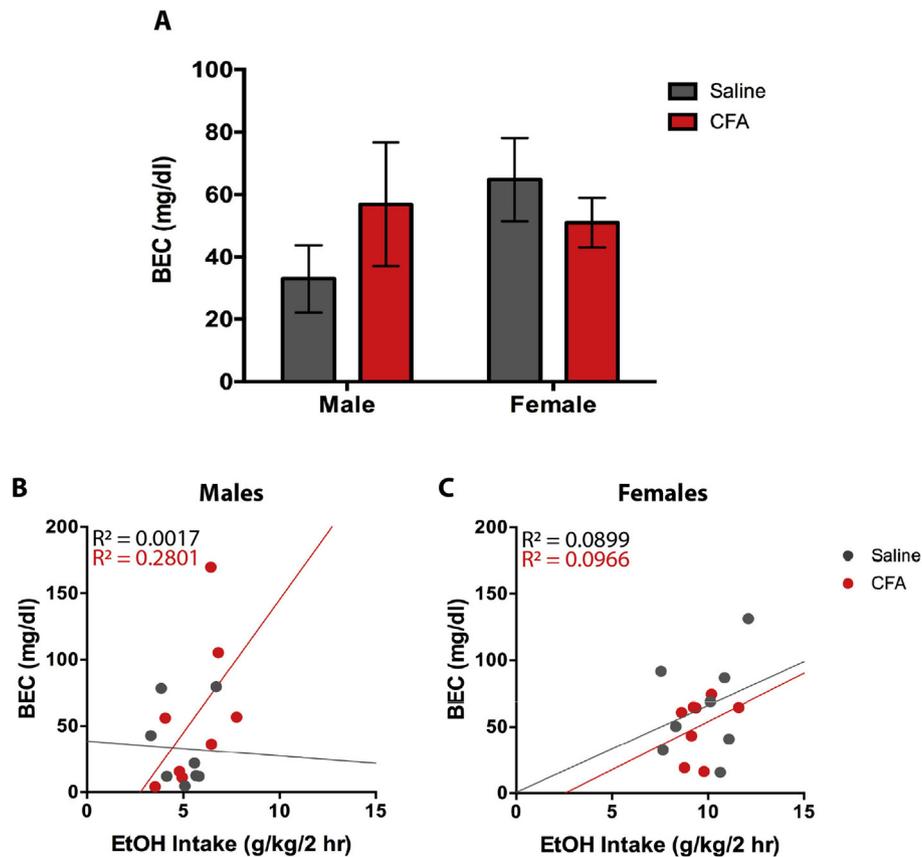
Female mice given 2-h access to ethanol exhibit greater alcohol and total fluid consumption than males (Fig. 7). A two-way ANOVA (Treatment  $\times$  Sex) for 2-h ethanol intake revealed a main effect for Sex [ $F(1,28) = 83.19, p < 0.0001$ ], but not Treatment [ $F(1,28) = 0.1574, p = 0.6945$ ], and no significant Treatment  $\times$  Sex interaction [ $F(1,28) = 0.6611, p = 0.4230$ ] (Fig. 7A). Tukey *post hoc* analysis showed greater 2-h ethanol intake in female mice, but no significant difference in drinking between saline- and CFA-treated mice (Fig. 7A). A two-way ANOVA (Treatment  $\times$  Sex) for 2-h ethanol preference ratio revealed no main effect for Treatment [ $F(1,28) = 0.2239, p = 0.6397$ ] or Sex [ $F(1,28) = 1.673, p = 0.2064$ ],

and a significant Treatment  $\times$  Sex interaction [ $F(1,28) = 5.599, p = 0.0251$ ] (Fig. 7B). Tukey *post hoc* analysis showed no significant difference in ethanol preference ratio between treatments or sex (Fig. 7B). A two-way ANOVA (Treatment  $\times$  Sex) for 2-h water intake revealed no main effect for Treatment [ $F(1,28) = 0.0328, p = 0.8574$ ] or Sex [ $F(1,28) = 0.2640, p = 0.6114$ ], and no significant Treatment  $\times$  Sex interaction [ $F(1,28) = 3.800, p = 0.0613$ ] (Fig. 7C). Tukey *post hoc* analysis showed no significant difference in ethanol preference ratio between treatments or sex (Fig. 7C). A two-way ANOVA (Treatment  $\times$  Sex) for 2-h total fluid intake revealed a main effect for Sex [ $F(1,28) = 8.726, p = 0.0063$ ], but not Treatment [ $F(1,28) = 0.4069, p = 0.5288$ ], and no significant Treatment  $\times$  Sex interaction [ $F(1,28) = 1.341, p = 0.2566$ ] (Fig. 7D). Tukey *post hoc* analysis showed higher 2-h total fluid intake in female mice, but no significant difference in drinking between saline- and CFA-treated mice (Fig. 7D).

Following 2-h access to ethanol, plasma samples were collected to measure BEC and CORT levels. For BEC, a two-way ANOVA (Treatment  $\times$  Sex) revealed no main effect for Treatment [ $F(1,28) = 0.1365, p = 0.7146$ ] and Sex [ $F(1,28) = 0.8967, p = 0.3518$ ], and no Treatment  $\times$  Sex interaction [ $F(1,28) = 1.890, p = 0.1801$ ] (Fig. 8A). Tukey *post hoc* analysis revealed no significant difference in BEC between treatments or sex (Fig. 8A). To assess the relationship between drinking and BEC among paw treatment groups, a linear regression was conducted for 2-h ethanol intake as a predictor of BEC. For males, saline-treated mice exhibited a non-significant regression equation of [ $F(1,6) = 0.0104, p = 0.9220$ ] with  $R^2$  of 0.0017 (Fig. 8B), whereas CFA-treated mice exhibited a non-significant regression equation of [ $F(1,6) = 2.334, p = 0.1774$ ] with  $R^2$  of 0.2801 (Fig. 8B). For females, saline-treated mice exhibited a non-significant regression equation of [ $F(1,6) = 0.5927, p = 0.4706$ ] with  $R^2$  of 0.0899 (Fig. 8C), whereas CFA-treated mice



**Fig. 7.** Averages of (A) alcohol intake (g/kg/2 h), (B) preference ratio, (C) water intake (g/kg/2 h), and (D) total fluid intake (mL) in saline- or CFA-treated C57BL/6J mice during a final 2-h drinking session. Pain-related consumption of fluids was assessed for males ( $n = 8$ ) and females ( $n = 8$ ) on the 25th session of a continuous-access regimen. Data are mean fluid intake/preference ratio  $\pm$ SEM. Data are mean fluid intake/preference ratio  $\pm$ SEM. \*\* and \*\*\*\* correspond to  $p < 0.005$  and  $p < 0.0001$  difference between groups, respectively.



**Fig. 8.** (A) Blood ethanol content (mg/dL) of saline- and CFA-treated C57BL/6J mice was measured 2 h into the final alcohol exposure day in male and female mice. BEC was correlated with average daily alcohol intake in (B) males and (C) females. Data are mean BEC  $\pm$  SEM.

exhibited a non-significant regression equation of  $[F(1,6) = 0.6417, p = 0.4536]$  with  $R^2$  of 0.0966 (Fig. 8C).

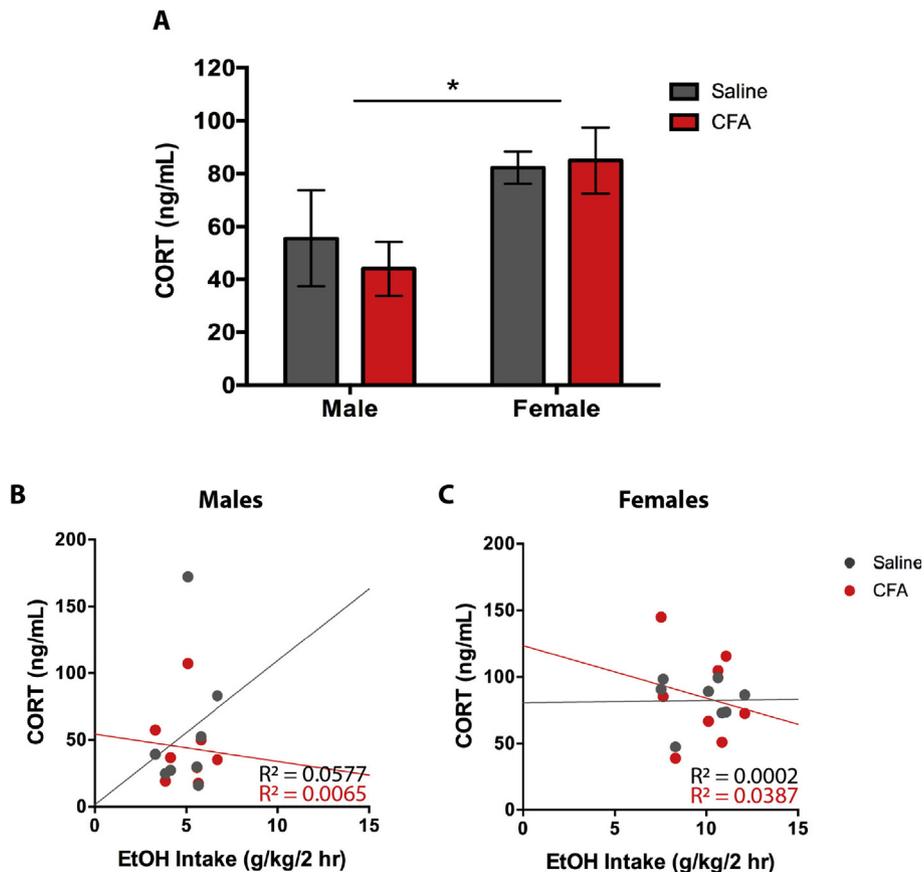
For CORT, a two-way ANOVA (Treatment  $\times$  Sex) revealed a main effect for Sex  $[F(1,28) = 7.298, p = 0.0116]$ , but not Treatment  $[F(1,28) = 0.1243, p = 0.7270]$ , and no Treatment  $\times$  Sex interaction  $[F(1,28) = 0.3202, p = 0.5760]$  (Fig. 9A). Tukey *post hoc* analysis revealed greater CORT levels in female mice, but no significant difference between saline- and CFA-treated mice (Fig. 9A). To assess the relationship between drinking and CORT among paw treatment groups, a linear regression was conducted for 2-h ethanol intake as a predictor of CORT. For males, saline-treated mice exhibited a non-significant regression equation of  $[F(1,6) = 0.3674, p = 0.5666]$  with  $R^2$  of 0.0577 (Fig. 9B), whereas CFA-treated mice exhibited a non-significant regression equation of  $[F(1,6) = 0.0396, p = 0.8487]$  with  $R^2$  of 0.0065 (Fig. 9B). For females, saline-treated mice exhibited a non-significant regression equation of  $[F(1,6) = 0.0016, p = 0.9691]$  with  $R^2$  of 0.0002 (Fig. 9C), whereas CFA-treated mice exhibited a non-significant regression equation of  $[F(1,6) = 0.2297, p = 0.6487]$  with  $R^2$  of 0.0387 (Fig. 9C). Taken together, these findings suggest a weak relationship between 2-h ethanol intake and BEC/CORT.

## Discussion

In this study, we describe sex differences in alcohol drinking following the induction of inflammatory pain. Male CFA-treated mice consumed more alcohol and exhibited higher preference for the drug than saline-treated controls, while female CFA-treated mice only showed greater water intake than controls. Characteristic of C57BL/6j mice with continuous access to high

concentrations of alcohol (Jury, DiBerto, Kash, & Holmes, 2017; Middaugh, Kelley, Bandy, & McGroarty, 1999; Smith et al., 2015), drinking levels differed between sexes, with female mice exhibiting greater ethanol consumption and preference than male mice, regardless of saline or CFA treatment. These findings suggest that chronic inflammatory pain increases alcohol drinking in males, despite higher overall drinking in females. Similar clinical observations have been made in chronic pain patients, with men more commonly self-medicating with alcohol than women (Riley & King, 2009). This pain-related alcohol consumption is greater in males throughout the lifetime, with its peak at early adulthood (Brennan et al., 2011; Riley & King, 2009; Wilsnack et al., 2009). By pairing CFA treatment and CA2BC drinking, our model was able to replicate these human patterns of voluntary drinking in injured young adult male mice, providing evidence that chronic inflammatory pain can potentiate alcohol drinking in a sex-specific manner for rodents.

Although this finding is reflective of clinical reports, it is notably inconsistent with another study on CFA-treated mice that found no effect on pain-related alcohol consumption (Smith et al., 2015). The discrepancy between findings may be due to differences in experimental design. For example, escalating concentrations of alcohol were utilized in Smith et al. (2015), while fixed concentrations were used in the present study. Mice given escalating concentrations had CFA administered while being exposed to a lower percentage of alcohol (10%), so consumption may not have produced comparable analgesia to that of a fixed high concentration of alcohol (20%). Theoretically, this would result in a higher dynamic range of alcohol consumption for the fixed concentration paradigm, which could explain why there are more pronounced effects of pain-induced drinking in the present study. Alternatively, the use of differently



**Fig. 9.** (A) Plasma corticosterone (CORT [ng/mL]) of saline- and CFA-treated C57BL/6j mice was measured 2 h into the final alcohol exposure day in male and female mice. CORT levels were correlated with average daily alcohol intake in (B) males and (C) females. Data are mean CORT  $\pm$  SEM. \* $p < 0.05$  difference between groups.

aged mice (i.e., 30–33 weeks old in Smith et al., [2015] versus 7–10 weeks old in the present study) could have altered alcohol consumption as well, since younger rodents drink more than fully developed adults (Holstein, Spanos, & Hodge, 2011; Schramm-Sapota et al., 2014; Vetter-O'Hagen, Varlinskaya, & Spear, 2009). Divergences in pain severity following CFA treatment could also explain the inconsistency in findings. Male mice treated with a high volume of CFA (i.e., 50  $\mu$ L in the present study) exhibited increased alcohol consumption relative to saline-treated controls, while low volume exposure (i.e., 10  $\mu$ L in Smith et al., [2015]) did not alter consumption relative to pre-CFA levels. This suggests that high and low volumes of CFA treatment result in different severities of pain, which can then determine the extent of changes observed with alcohol drinking. If pain severity were to contribute to these consumption differences, a comparison of nociceptive sensitivity should reveal higher pain sensitivity in CFA-treated mice from the present study compared to those in Smith et al. (2015). The use of different behavioral assays at non-parallel time points and a lack of parallel control groups (i.e., Pre-CFA mice in Smith et al., [2015] versus saline-treated mice in the present study), however, makes it difficult to make a direct comparison. Future studies should examine how the severity of chronic inflammatory pain contributes to sex-specific patterns of drinking with more uniform measures of thermal and mechanical nociception and control groups. Determining the extent that alcohol concentration and age can alter pain-related drinking may further clarify any remaining drinking differences between the two studies.

We additionally showed that female C57BL/6J mice exhibit greater alcohol consumption than males, an observation that is common among female rodents exposed to voluntary drinking paradigms (Blanchard & Glick, 1995; Cailhol & Mormède, 2001; Chester, Rausch, June, & Froehlich, 2006; Doremus, Brunell, Ragendran, & Spear, 2005; Jury et al., 2017; Lancaster, Brown, Coker, Elliott, & Wren, 1996; Lê, Israel, Juzysch, Quan, & Harding, 2001; Middaugh et al., 1999; Smith et al., 2015; Truxell, Molina, & Spear, 2007). Moreover, our female drinking data match the maximal average consumption values previously reported in C57BL/6J mice undergoing continuous access to  $\geq 10\%$  alcohol (Jury et al., 2017; Middaugh et al., 1999; Smith et al., 2015). With such high baseline alcohol consumption, it is possible that saline-treated females have already reached maximal drinking in our study, so the addition of pain would not increase drinking in females. Although this ceiling effect is possible, it is unlikely, considering that daily ethanol intake in females was around 10–12 g/kg during the first four sessions and escalated to 20–25 g/kg by the last session. If pain were able to drive alcohol drinking in females, early session ethanol intake should have increased up to two times in CFA-treated mice, but that is not the case. Therefore, sex differences in basal alcohol consumption were not likely to prevent pain-related drinking increases for females.

Differences in inflammatory response and alcohol analgesia may provide a better explanation for sex-specific patterns in drinking. CFA and related inflammatory agents cause female rodents to develop hyperalgesia more rapidly than males, with females being less prone to attenuation of inflammation by alcohol and other analgesic drugs (Alfonso-Loeches, Pascual, & Guerri, 2013; Coleman & Crews, 2018; Cook & Nickerson, 2005; Pascual et al., 2017). Thus, it is possible that CFA-treated females are less susceptible to escalated alcohol consumption relative to saline-treated controls because the drug provides inadequate analgesia to promote further drinking. Although not measured in the present study, ongoing investigations with this model should assess the potential impact of sex differences in alcohol analgesia and its effects on pain-related drinking.

Sex-specific patterns in pain-driven consumption were observed for water as well. CFA-treated males and females exhibited divergent

water consumption patterns, with CFA-treated males reducing intake and CFA-treated females increasing intake relative to their saline-treated counterparts. The consumption of more alcohol and less water by CFA-treated males likely reflects increases in alcohol preference following repeated drug exposure. Although reductions in water intake are not characteristic for escalations in voluntary alcohol consumption (Griffin, 2014; Hwa et al., 2011; Tordoff & Bachmanov, 2003), it has been reported that mice treated with pro-inflammatory agents exhibit increased alcohol intake and reduced water intake when given access to CA2BC (Biesmans et al., 2013; Blednov et al., 2011; Stein, Millan, & Herz, 1988). This is consistent with parallel studies showing that the impairment of pro-inflammatory cytokines reduces alcohol preference (Blednov et al., 2005). In agreement with the literature, our findings show that increases in alcohol intake and decreases in water intake are expected outcomes of heightened inflammatory states.

Inflammation-driven changes in alcohol and water consumption were previously reported for both male and female mice (Blednov et al., 2011), in contrast to the CFA-treated females in the present study that consumed comparable amounts of alcohol and more water than saline-treated controls. This increase in water intake following CFA treatment may be due to alterations in body water composition, a major contributor to sex differences in alcohol consumption (Ely, Hardy, Longford, & Wadsworth, 1999). Considering the high level of alcohol consumption in females, it is possible that inflammation enhances the diuretic properties of alcohol and that the higher rate of fluid loss is compensated for by consuming greater quantities of water (Crow, 1968; Strauss, Rosenbaum, & Nelson, 1950). This effect may be restricted to CFA and other long-lasting inflammatory agents, since acute inflammation reduces water intake, but attenuates over time in female mice (Melgar et al., 2007). The time course of water intake from acute to chronic inflammation has yet to be investigated for both sexes, but this knowledge will likely be important for understanding how relative fluid intake determines alcohol-drinking behavior.

Sex differences in gustation may also explain the observed drinking patterns, since intake profiles differ by fluid type. It has been theorized that C57BL/6J mice are more motivated to consume alcohol for its sweet-tasting components (Bachmanov, Reed, Tordoff, Price, & Beauchamp, 1996; Blednov et al., 2008), but sex does not appear to influence preference for saccharin or alcohol (Bachmanov, Tordoff, & Beauchamp, 1996). However, it is still possible that inflammation alters the gustatory components of alcohol relative to water in a sex-specific manner (Kumarhia, He, & McCluskey, 2016; Steen, Shi, He, & McCluskey, 2010). More research assessing the relationship of sex, inflammation, gustation, and fluid intake is required to understand CFA-mediated effects on alcohol and water intake in CA2BC.

Three weeks after paw treatment, pain testing revealed that CFA-treated mice had higher thermal nociceptive sensitivity than saline-treated controls for both males and females. Considering the timing of the test, it is unclear whether this difference in sensitivity reflects the contributions of pain to drinking or drinking to pain. This is an important distinction, as cessation of alcohol intake following repeated drug exposure can exacerbate pain sensitivity. This phenomenon, commonly referred to as ethanol withdrawal-induced hyperalgesia (EIH), has been reported in mice (Dhir et al., 2005; Smith, Hostetler, Heinricher, & Ryabinin, 2016), as well as rats (Dina et al., 2007, 2000; Edwards et al., 2012; Fu et al., 2015; Gatch & Lal, 1999; Roltsch Hellard et al., 2017; Malec et al., 1987; Shumilla et al., 2005) and humans (Boissoneault et al., 2018; Dodds et al., 1945; Jochum et al., 2010; Riley & King, 2009; Wolff et al., 1942), using a variety of alcohol exposure models. In our CA2BC paradigm, it is unclear whether there were pathological shifts in sensitivity following 3 weeks of alcohol exposure. The lack

of sensitivity differences following increased drinking in CFA-treated males, along with the non-significant regression of Drinking  $\times$  Pain suggests that the extent of alcohol consumption had little effect on predicting pain sensitivity (and vice versa) in all groups. This result is similar to that of other continuous-access experiments in mice, which also failed to produce EIH (Smith et al., 2015). The exception to this finding is CFA-treated females – despite comparable drinking patterns to saline-treated controls, CFA-treated females exhibited a significant negative correlation for Drinking  $\times$  Pain, whereas injured females that drink more alcohol experience higher pain sensitivity. This result is reminiscent of clinical data showing that there is higher EIH severity and prevalence in females, with women being more likely to report significant recurrent pain and concurrent chronic pain conditions (Boissoneault et al., 2018). Despite our findings closely following predicted results from the literature, not having nociceptive sensitivity measures prior to ethanol exposure makes it impossible to conclude whether or not these data indicate a causal null effect of alcohol consumption on pain. Although a limitation in the study, it does not change our interpretation that male-specific increases in alcohol consumption follow the induction of chronic inflammatory pain. However, future experiments should be mindful of establishing baseline nociceptive sensitivity prior to the start of alcohol exposure when studying pain-related alcohol use.

Following 2 h of CA2BC, females consumed more alcohol than males. Contrary to the increased drinking phenotype seen in CFA-treated males during 24-h alcohol access, no treatment effects were observed. These results suggest that the terminal drinking session did not last long enough to capture peak alcohol consumption (i.e., 4 + hours into the dark cycle) (Smith et al., 2015). Although increases for alcohol drinking in the 2-h CA2BC were specific to females, no sex effects were found for BEC. By contrast, a previous evaluation of BEC showed no sex differences for alcohol consumption after 30-min access to 12% ethanol, but showed higher BECs in females (Middaugh et al., 1999). Although this is a common result for humans when both sexes are allowed an equal dosing of orally administered ethanol (Ammon, Schafer, Hofmann, & Klotz, 1996; Sutker, Tabakoff, Goist, & Randall, 1983), such results are less common in rodents (Ho, Chin, & Dole, 1989). This difference may be due to feeding manipulations coinciding with BEC measurements after drinking, as suggested in Middaugh et al. (1999). Although caloric mediation of alcohol consumption is well established in the literature (Rodgers, 1966; Rodgers, McClearn, Bennett, & Hebert, 1963; Thiele, Koh, & Pedrazzini, 2002), sex differences in prandial metabolism and alcohol consumption are thought to be negligible, as thirst is more strongly motivating for alcohol drinking than caloric need in both sexes (Middaugh et al., 1999). Paradoxically, higher BECs in females are accompanied by enhancements in alcohol metabolism (Baraona et al., 2001; Collins, Yeager, Lebsack, & Panter, 1975; Mumenthaler, Taylor, O'Hara, & Yesavage, 1999), and may explain why female mice that consume a greater amount of alcohol do not produce higher BECs than males.

Similar to alcohol consumption patterns in the 2-h CA2BC paradigm, CORT was not affected by CFA, but differed by sex. Specifically, female CORT levels were found to be higher than that of males. Higher CORT release following alcohol exposure has previously been observed in female rodents, with deletion of circulating sex steroids attenuating the difference (Rivier, 1993). However, increased levels of CORT in female mice may not be the result of the drug, as alcohol drinking does not produce differences in CORT relative to consumption of water in males or females (Finn et al., 2004). Although CFA-treated males did not drink more in the 2-h terminal drinking session, the literature would predict that an increase in drinking after 24-h access would still not potentiate CORT release in the males, despite showing pain-related increases in

alcohol consumption. This suggests that CORT is basally higher in females, and not susceptible to changes following CFA treatment in both sexes. Previous work has found that inflammatory pain increases CORT, but this phenotype has only been observed in male rats and has yet to be investigated in combination with drinking (Butkevich et al., 2013; Harper, Kerins, McIntosh, Spears, & Bellinger, 2001; Pitcher, Tarum, Lehmann, & Bushnell, 2019), suggesting that our findings for CORT are specific to CFA/CA2BC-exposed C57BL/6J mice.

Without pre-treatment CORT levels, it is difficult to determine whether these female-specific elevations in stress are entirely due to sex differences in basal CORT. It is important to consider the alternate possibility that these changes are driven by differences in stress reactivity. It is well established that maladaptive responses to stress promote alcohol drinking and relapse behavior (Becker, Lopez, & Doremus-Fitzwater, 2011; Keyes, Hatzenbuehler, Grant, & Hasin, 2012; Koob & Kreek, 2007; Koob & Le Moal, 2001). Previous studies have linked these behaviors to the sex-dependent expression of stress markers, with females exhibiting higher glucocorticoid levels and alcohol consumption following exposure to various stressors (Cozzoli, Tanchuck-Nipper, Kaufman, Horowitz, & Finn, 2014; Haleem, Kennett, & Curzon, 1988; Heinsbroek, Van Haaren, Feenstra, Endert, & Van de Poll, 1991; Kudielka & Kirschbaum, 2005; Yoshimura et al., 2003). Considering that female mice exhibit a more sensitive and sustained stress response compared to males (Blanchard & Glick, 1995; Brown & Grunberg, 1995; Hermes, Rosenthal, Montag, & McClintock, 2006; Palanza, Gioiosa, & Parmigiani, 2001), it is possible that early experimental stressors such as isolated housing and paw injections increased CORT levels and alcohol consumption for female mice in the present study (Hermes et al., 2006; Lopez, Doremus-Fitzwater, & Becker, 2011; Moriya et al., 2015). This would be contingent on early experimental stressors upregulating CORT responses for over 3 weeks in female mice, an improbable but untested concept. Future studies using CFA/CA2BC should more closely investigate this relationship between sex differences in stress reactivity and alcohol drinking.

In conclusion, male and female mice exhibit distinct alcohol drinking behavior when undergoing pain. Compared to saline-treated controls, CFA-treated males show greater alcohol consumption, while CFA-treated females show a closer relationship between alcohol consumption and pain sensitivity. Regardless of pain state, females exhibited higher levels of total alcohol drinking and corticosterone compared to males. These findings reflect sex-specific trends in alcohol use reported by chronic pain populations and may speak to the validity of our CFA/CA2BC model in mice. Mechanistic contributions to sex differences in pain-related alcohol drinking will be required in future applications of the model, with special attention reserved for the role of stress signaling in pain and alcohol interactions.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.alcohol.2018.10.002>.

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