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Sexually divergent cortical control of affective-autonomic integration

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Significance

Depression and cardiovascular disease reduce health-related quality of life and increase mortality risk. These conditions commonly co-occur with sex-based differences in incidence and severity. While the biological mechanisms linking the disorders are poorly understood, the ventral medial prefrontal cortex regulates behavioral and physiological responses to stress. Therefore, activity in this region may integrate depression-related behaviors with the cardiovascular burden of chronic stress. In a rodent model, we utilized optogenetics during behavior and *in vivo* physiological monitoring to examine how the ventral medial prefrontal cortex regulates affect, social motivation, neuroendocrine-autonomic stress reactivity, and the cardiac consequences of chronic stress. Our findings identify a sex-specific neurobiological mechanism regulating mood and stress responding, suggesting males and females differentially integrate affective and physiological processes.

Abstract

Major depressive disorder accounts for the most years lived with disability worldwide and cardiovascular diseases are the leading cause of death globally. These conditions are co-morbid and exhibit sexual divergence in prevalence and severity. Furthermore, stress exposure is an environmental risk factor for the onset of both mood and cardiovascular symptoms. However, the neural processes that integrate stress effects on affective and cardiovascular outcomes are unknown. Human imaging studies indicate that both sad stimuli and autonomic processes activate the ventral medial prefrontal cortex (vmPFC). In rodents, the infralimbic (IL) portion of vmPFC modulates physiological stress responses, leading us to hypothesize that IL pyramidal neurons integrate depression-relevant behaviors with cardiovascular and endocrine stress reactivity. In the current study, an optogenetic approach targeted channelrhodopsin-2 expression to IL glutamatergic neurons in male and female rats. Animals were then assessed for stimulation preference and social motivation. Additionally, radiotelemetry and echocardiography were used to examine cardiovascular stress responses and chronic stress effects on cardiac structure and function. Our results indicate that IL glutamate neurons increased place preference and social motivation in males without affecting socio-motivational behaviors in females. IL activation also reduced endocrine and cardiovascular stress responses in males, while increasing reactivity in females. Moreover, prior IL stimulation protected males from subsequent chronic stress-induced sympatho-vagal imbalance and cardiac hypertrophy. In contrast, females were resistant to stress-induced hypertrophy, yet IL stimulation increased cardiac contractility after chronic stress. Collectively, the data suggest that cortical regulation of behavior, physiological stress responses, and cardiovascular outcomes fundamentally differ between sexes.

Keywords: infralimbic cortex, social motivation, corticosterone, chronic stress, ventricular hypertrophy

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Introduction

Major depressive disorder (MDD) and cardio-metabolic conditions including hypertension, glucose intolerance, and heart failure significantly contribute to global disease burden. Epidemiological evidence implicates life stressors as a risk factor for both MDD and cardiovascular disease (CVD) (1–4). Furthermore, sex differences in the incidence of MDD, CVD, and MDD-CVD co-morbidity suggest that sex-specific factors contribute to outcomes (5). However, the biological basis for stress effects on health, particularly the integration of affective and physiological systems, is poorly understood. Human brain imaging studies indicate that ventral medial prefrontal cortex (vmPFC) activity associates with sadness and blood pressure reactivity, suggesting that top-down cortical control may integrate diverse aspects of mood and systemic physiology.

The vmPFC is involved in numerous cognitive and emotional processes (6–8). A subregion of the vmPFC, the subgenual cingulate cortex (BA25), is activated by sadness-provoking stimuli, responds to social isolation, and has reduced volume in MDD patients (9–11). BA25 is also targeted for deep brain stimulation in patients with treatment-resistant depression, where larger volumes predict better treatment outcomes (12, 13). Subgenual regions of vmPFC have also been identified as components of a central autonomic network monitoring visceral functions (14–18). The rodent homolog of BA25, the infralimbic cortex (IL) (19–21), innervates limbic and stress-regulatory nuclei including the amygdala, thalamus, and hypothalamus (22–25). Additionally, IL stimulation reduces passive coping and increases pyramidal neuron spine density in male rodents (26–29). Moreover, knockdown of IL glutamatergic output exacerbates chronic stress effects on hypothalamic-pituitary-adrenal (HPA) axis reactivity and

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vascular function (30, 31). However, the potential sex-specific roles of IL activity to integrate socio-motivational behaviors with physiological stress reactivity and the cardiac outcomes of chronic stress remain to be determined.

In the current study, channelrhodopsin-2 (ChR2) was expressed under the calcium/calmodulin-dependent protein kinase type II α (CaMKIIα) promoter in the IL to permit optogenetic activation of IL pyramidal neurons in both male and female rats (24). This approach was combined with measures of place preference and social behavior to examine affective valence and sociability. Behavioral assessment was followed by measures of physiological stress reactivity, including radiotelemetry and echocardiography over the course of chronic variable stress (CVS). Ultimately, these findings identify the IL as an affective-autonomic integrator that links motivation and stress responding divergently in males and females.

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Methods

Animals

Age-matched adult male and female Sprague-Dawley rats were obtained from Envigo (Denver, CO) with male rat weight ranging from 250-300 g and female from 150-200 g. After stereotaxic surgery, rats were housed individually in shoebox cages with cardboard tubes for enrichment in a temperature- and humidity-controlled room with a 12-hour light-dark cycle (lights on at 07:00h, off at 19:00h) and food and water *ad libitum*. All procedures and protocols were approved by the Colorado State University Institutional Animal Care and Use Committee (protocol: 16-6871A) and complied with the National Institutes of Health Guidelines for the Care and Use of Laboratory Animals. Signs of poor health and/or weight loss ≥ 20% of pre-surgical weight were *a priori* exclusion criteria. These criteria were not met by any animals in the current experiments; however, animals were removed from experimentation if fiber optic or radiotelemetry devices failed.

Microinjections

Rats were anesthetized with isoflurane (1-5%) followed by analgesic (0.6 mg/kg buprenorphine-SR, subcutaneous) and antibiotic (5 mg/kg gentamicin, intramuscular) administration. Rats received bilateral microinjections (0.75-2 μL) of adeno-associated virus (AAV) into the IL (males: 2.7 mm anterior to bregma, 0.6 mm lateral to midline, and 4.2 mm ventral from dura, females: 2.3 mm anterior to bregma, 0.5 mm lateral to midline, and 4 mm ventral from dura). AAV5-packaged constructs (University of North Carolina Vector Core, Chapel Hill, NC) either expressed yellow fluorescent protein

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(YFP) or ChR2 conjugated to YFP under the CaMKIIα promoter to achieve pyramidal cell-predominant expression (24). All micinjections were carried out with a 25-gauge, 2-μL microsyringe (Hamilton, Reno, NV) using a microinjection unit (Kopf, Tujunga, CA) at a rate of 5 minutes/μL. The needle was left in place for 5 minutes before and after injections to reduce tissue damage and allow diffusion. Skin was closed with wound clips that were removed 2 weeks after injections and animals were allowed at least 6 weeks for recovery and ChR2 expression.

Electrophysiology

Adult male rats (n = 8) were injected with AAV constructs as described above and, after 8-12 weeks, exposed to 5% isoflurane prior to decapitation and brain removal. As previously described (32), brains and sections were collected in ice-cold artificial CSF (aCSF) consisting of the following (in mM): 126 NaCl, 2.5 KCl, 1.2 $MgCl_2$ Λ $6H_2O$, 2.4 $CaCl_2$ Λ $2H_2O$, 1.2 NaH_2PO_4, 11.1 glucose, and 21.4 $NaHCO_3$, bubbled with 95% O_2 and 5% CO_2. Coronal slices containing the IL were cut at a thickness of 240 μm using a model VT1200S vibratome (Leica Microsystems, Buffalo Grove, IL). After resting 1 hr at 37°C in aCSF, slices were transferred to the recording chamber and perfused with oxygenated 37° C aCSF at a 2 ml/min flow rate. For whole-cell recordings, the internal recording solution contained the following (in mM): KCL 57.5, K-methyl sulfate 57.5, NaCl 20, $MgCl_2$ 1.5, HEPES 5; EGTA 0.1; ATP 2; GTP 0.5, and phosphocreatine 10. The pH was adjusted to 7.3. Recording electrodes had a resistance of 2 – 4 MΩ when filled with this solution. IL pyramidal neurons were identified for recording based on the expression of ChR2-YFP under the control of

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CaMKIIα. Whole-cell patch-clamp recordings were acquired in voltage-clamp at a holding potential of -60 mV using an Axopatch 200B Amplifier (Molecular Devices, San Jose, CA). Current-clamp recordings were acquired while holding current at 0 pA. Electrophysiological data were collected and analyzed using Axograph X software on a Mac OS X operating system (Apple, Cupertino, CA). Light activation of IL neurons expressing ChR2 was triggered via a 5 ms 470 nm LED (Thorlabs, Newton, NJ) light pulse driven by a LEDD1B driver (Thorlabs, Newton, NJ) triggered through the TTL output on an ITC-18 computer interface board (HEKA Instruments, Holliston, MA). Current-clamp experiments utilized 5, 10, and 20 Hz stimulation frequencies for 5 min bouts. Recordings were excluded if access resistance exceeded 10 Ω during recording.

Radiotelemetry implantation

A subset of rats was instrumented with ECG-enabled radiotelemetry transmitters (HD-S11 F0, Data Sciences International, St. Paul, MN) as previously described (30, 33, 34). Briefly, rats were anesthetized with inhaled isoflurane anesthesia (1-5%) and given a subcutaneous injection of analgesic (0.6 mg/kg Buprenorphine-SR) and an intramuscular injection of antibiotic (5 mg/kg gentamicin). The descending aorta was exposed via an abdominal incision, allowing implantation of a catheter extending from the transmitter. The catheter was secured with tissue adhesive (Vetbond; 3M Animal Care Products, St. Paul, MN) applied over a cellulose patch. ECG leads were passed through abdominal musculature and sutured subcutaneously above the rib cage and pectoral muscles. The transmitter body was then sutured to the abdominal musculature,

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followed by closure of the abdominal musculature and skin with suture and wound clips, respectively. Rats then recovered for 2 weeks before wound clips were removed.

Fiber optic cannulas

Rats were anesthetized (isoflurane 1-5%) and bilateral fiber-optic cannulas (flat tip 400/430 μm, NA = 0.66, 1.1 mm pitch with 4.5 mm protrusion for males and 4.2 mm protrusion for females; Doric Lenses, Québec, Canada) were aligned with the IL injection sites and lowered into place approximately 1 mm dorsal to the injection. Cannulas were secured to the skull with metal screws (Plastics One) and dental cement (Stoelting, Wood Dale, IL). Skin was sutured and rats were given a subcutaneous injection of analgesic (0.6 mg/kg Buprenorphine-SR) and an intramuscular injection of antibiotic (5 mg/kg gentamicin). Following 1 week of recovery, rats were handled daily and acclimated to the stimulation procedure for another week before experiments began. Rat handling and cannula habituation continued daily throughout experiments.

Optogenetic stimulation

Light pulses (1 mW, 5 ms pulses, 10 or 20 Hz) were delivered through a fiber-optic patch cord (240 μm core diameter, NA = 0.63; Doric Lenses) connected to a 473 nm LED driver (Doric Lenses). Optic power was measured with a photodiode sensor (PM160, Thorlabs Inc, Newton, NJ) at the cannula fiber tip. Rats received a single 30-minute session of stimulation (1 min on/1 min off) in their homecage during habituation the week prior to experimentation.

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Estrous cycle cytology

All female rats went through experiment 3 simultaneously, housed in the same room and randomly cycling. Immediately following acute measures of behavior and/or physiology, vaginal cytology was examined to approximate the estrous cycle stage. A damp (deionized water) cotton swab was used to collect cells from the vaginal canal and place them onto a glass slide. When dried, slides were viewed under a 10x objective light microscope by a minimum of two blind observers and were categorized as proestrus, estrus, metestrus, or diestrus (35–37).

Real-time place preference

The real-time place preference (RTPP) assay was used to assess the valence of IL stimulation (38, 39). Cannulas were connected to LEDs for light delivery and rats placed in a custom-made fiberglass arena with two chambers connected by a corridor (chambers: 15 x 15'', corridor: 8 x 6'', 15'' deep). Rats explored the arena for 10 minutes on two consecutive days. The first day was a habituation day and no stimulation was delivered on either side. On the second day, rats received LED-generated 465 nm light pulses upon entry to the assigned stimulation side. Trials were recorded by a camera mounted above the arena and animal position was tracked by Ethovision software (Noldus Information Technologies) for automated optic hardware control. Stimulation side assignment was counterbalanced and animal testing was randomized. The time rats spent in the stimulation side was divided by the total time and multiplied by 100 to generate a percentage of time spent in the stimulation side.

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Social behavior

A modified version of the 3-chambered social behavior assay was used to accommodate optic patch cords (40, 41). To examine social interaction, each rat was connected to a patch cord and placed in a black rectangular fiberglass arena (36 x 23'', 15.8'' deep). Initially, the arena was empty and experimental rats were allowed to explore for 5 minutes without optic stimulation. The experimental rat was then returned to their home cage while an empty enclosure (ventilated with small round openings) was placed on one side of the arena, defined as the object, and an identical enclosure containing an age- and sex-matched conspecific was placed on the other side of the arena, defined as the social cage. The experimental rat was then placed in the middle of the arena and allowed to explore freely for 10 minutes with 5 ms pulsatile stimulation delivered throughout to quantify social motivation. The experimental rat was then placed again into its home cage while the empty enclosure was replaced with a new enclosure containing a novel age- and sex-matched conspecific. The experimental rat freely explored for 10 minutes while receiving optic stimulation to assess social novelty preference. Behavior was recorded with an overhead camera and interactions were defined as nose pokes onto cages and scored by a treatment-blinded observer. The duration of interactions was divided by the total time of each interaction period and multiplied by 100 to give a percent interaction value. Sides for object cage, social cage, and novel cage were counterbalanced and animal order randomized.

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Novel environment

Rats with radiotelemetry implants were exposed to a 30-minute novel environment stressor to assess acute cardiovascular reactivity. Rats were connected to fiber-optic patch cords and placed into a brightly-lit semi-transparent arena. Radiotelemetry receiver pads (Data Sciences International, St. Paul, MN) were arrayed under the arena with 10 Hz optic stimulation during the stressor to record hemodynamics and activity in 1-minute bins. Heart rate (HR), mean arterial pressure (MAP), systolic arterial pressure (SAP), and diastolic arterial pressure (DAP) were collected and analyzed with Ponemah software (Version:6.4x Data Sciences International).

Restraint stress

Restraint was used to examine neuroendocrine responses to acute stress. Rats were placed in plastic film decapicones (Braintree Scientific, Braintree, MA) and connected to fiber-optic patch cords for optic stimulation throughout the 30-minute restraint. Blood samples (approximately 250 μL) were collected by tail clip at the initiation of restraint with additional samples taken 15 and 30 min after (42). At the conclusion of restraint, patch cords were disconnected and rats returned to their homecage with recovery blood samples collected at 60 and 90 min after the initiation of restraint. Blood glucose was determined with Contour Next EZ glucometers (Bayer, Parsippany, NJ) and 2 independent readings for each time point were averaged. Blood samples were centrifuged at 3000 X g for 15 minutes at 4° C and plasma was stored at –20° C until radioimmunoassay (RIA). Plasma corticosterone levels were measured with

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an ^{125}I RIA kit (MP Biomedicals, Orangeburg, NY) as previously described (31). All samples for each sex were run in duplicate and all time points were run in the same assay. RIA intra-assay coefficient of variation was 8.6% and interassay 13.6%.

Chronic variable stress

Chronic variable stress was comprised of twice daily (AM and PM) repeated and unpredictable stressors presented in a randomized manner including: exposure to a brightly-lit open field (28.5 x 18'' 13'' deep, 1 hour), cold room (4° C, 1 hour), cage tilt (45°, 1 hour), forced swim (23° to 27° C, 10 minutes), predator odor (fox or coyote urine, 1 hour), restraint (1 hour), and shaker stress (100 rpm, 1 hour). Additionally, overnight stressors were variably included, comprised of damp bedding (400 mL water) and overnight light. During the 2 weeks of CVS, rats were weighed every 3-4 days to monitor body weight.

Spectral analysis of heart rate variability

Throughout CVS, resting homecage recordings of heart rate variability (HRV) were collected and analyzed using Ponemah software (Version:6.4x Data Sciences International, St. Paul, MN). Using guidelines for heart rate variance (43) occurring as a function of frequency, low (LF) and high frequency (HF) components were collected during two-hour periods in the AM and PM and averaged within treatment groups. Recordings were sampled at least one hour after stressors and did not follow overnight stressors, swim, or restraint. Spectral analysis is used to measure autonomic balance as LF predominantly represents sympathetic and HF predominantly parasympathetic

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contributions to HRV (3, 43). Accordingly, LF/HF represents net cardiac sympathetic drive.

Echocardiography

Left ventricle structure and function were assessed before and after CVS via echocardiography. In preparation, rats were anesthetized with inhaled isoflurane (5% induction, 2% maintenance), connected to fiber optic patch cord, and shaved over the ventral thorax. A 12-mHz pediatric transducer connected to a Phillips XD11 ultrasound system was used to image the heart in transverse (parasternal short axis) and 4-chamber angles. M-mode echocardiograms were utilized to measure left ventricular end-systolic and end-diastolic chamber dimensions and anterior/posterior wall thickness (44, 45). Once the measurements were taken for a rat, optics were turned on and a second exam was conducted to investigate acute stimulation-induced changes. Total exam time for each trial was approximately 5 minutes.

Tissue collection

Rats were given an overdose of sodium pentobarbital and perfused transcardially with 0.9% saline followed by 4.0% paraformaldehyde in 0.1 M PBS. Brains were removed and post-fixed in 4.0% paraformaldehyde for 24 h at room temperature, followed by storage in 30% sucrose in PBS at 4 °C. Coronal sections were made on a freezing microtome at 30 μm thickness and then stored in cryoprotectant solution at −20 °C until processing. A subset of rats received optogenetic stimulation prior to tissue collection. Rats were tethered to a fiber optic patch cord and received 5

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minutes of optic stimulation followed by 90 minutes of recovery for immediate-early gene (c-Fos) expression prior to euthanasia, as described above (24).

Immunohistochemistry and microscopy

For fluorescent labeling of c-Fos, coronal brain sections were removed from cryoprotectant and rinsed in PBS (5 x 5 min) at room temperature. Sections were then placed in blocking solution (PBS, 0.1% bovine serum albumin, and 0.2% Triton X-100) for 1 hour. Next, sections were incubated overnight in rabbit anti-c-Fos primary antibody (1:200 in blocking solution, Cell Signaling Technologies, Ab #2250). Following overnight incubation in primary antibody, sections were rinsed in PBS (5 x 5 min) and incubated in donkey anti-rabbit Cy5 secondary (1:1000 in PBS, Jackson ImmunoResearch, AB_234060) for 1 hour. The tissue was then washed (5 x 5 min in PBS), mounted with polyvinyl medium, and cover slipped for imaging. To determine injection placement, YFP was imaged with a Zeiss Axio Imager Z2 microscope using the 10x objective, while YFP and c-Fos fluorescence were acquired as tiled 20x objective images.

Experimental Design

Timelines for *in vivo* experiments are outlined in figure 1. Experiment 1 was comprised of 2 cohorts of male rats (n = 13-14 each) to yield 10 YFP and 17 ChR2. For this experiment, real-time place preference and social behavior were assessed prior to restraint stress with 20 Hz used for all stimulation. Experiment 2 consisted of 3 cohorts of male rats (n = 7-8 each) for a total of 12 YFP and 10 ChR2. A subset of these rats was equipped with radiotelemetry transmitters (YFP n = 7, ChR2 n = 8) and all

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underwent real-time place preference and social behavior prior to novel environment with 10 Hz stimulation. Afterward, rats in experiment 2 underwent echocardiography before and after CVS. Experiment 3 was designed as a single cohort of female rats (n = 29) with 12 YFP and 17 ChR2. A subset of these rats was equipped with radiotelemeters (YFP n = 7, ChR2 n = 8). Real-time place preference and social motivation were followed by novel environment and restraint with 10 Hz stimulation for all measures. Female rats also underwent echocardiography before and after CVS.

Data analysis

Data are expressed as mean ± standard error of the mean. Data were analyzed using Prism 8 (GraphPad, San Diego, CA), with statistical significance set at $p < 0.05$ for rejection of null hypotheses. RTPP stimulation preference was assessed via repeated measure two-way analysis of variance (ANOVA) with virus and day (repeated) as factors. In the case of significant main or interaction effects, Sidak's multiple comparisons were run to determine group differences. Social motivation and novelty preference were assessed with unpaired t-tests to compare virus groups within social, object, novel rat, or familiar rat interactions. Total distance traveled during RTPP and social interaction was assessed with unpaired t-tests comparing virus groups. Stress responses over time (corticosterone, glucose, HR, MAP, SAP, DAP, and HRV spectra) were analyzed using mixed-effects analysis with virus and time (repeated) as factors, followed by Fisher's post-hoc if significant main or interaction effects were present. Mean activity during novel environment was assessed with Mann-Whitney U non-parametric test comparing virus groups. Fractional shortening and ventricular structure

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were assessed with paired Wilcoxon signed-rank tests comparing pre- and post-CVS or optic status within virus groups.

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Results

Validation and design

AAV viral vectors were targeted to the IL for expression of membrane-targeted ChR2-YFP or cytosolic YFP under the pyramidal neuron promoter, CaMKIIα. Fiber optic cannulas implanted in the IL permitted selective stimulation of IL glutamatergic neurons, as previously reported (24, 29). In female rats, c-Fos labeling verified *in vivo* neural activation in response to light-stimulation (10 Hz, 5 ms, 5 min) (**Fig. 1A**). Whole-cell patch-clamp recordings in slice demonstrated light-evoked depolarizing current in male IL neurons expressing ChR2 (**Fig. 1B**). Further, 10 Hz stimulation led to high-fidelity action potential generation. 20-Hz light pulses induced action potential firing, as well as increased resting membrane potential (**Fig. 1C**). These results, combined with our previous studies quantifying a 4.5-fold increase in immediate-early gene expression after 20 Hz stimulation (24), suggest that both 10 Hz and 20 Hz stimulation activate IL CaMKIIα-positive neurons. Although, 10 Hz stimulation is in line with the reported 4-10 Hz intrinsic firing rate of IL pyramidal neurons (46, 47). The experimental design (**Fig. 1D**) is detailed in the methods. Male and female rats received optogenetic stimulation during behavioral and physiological measures in separate experiments. At the conclusion of all experiments, the placement of viral injections and fiber optics was determined. Only animals with cannula placement verified to be within or immediately dorsal to the IL were included in analyses (**Fig. 1E**).

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Real-time place preference

RTPP was used to examine the affective valence of stimulating IL glutamatergic neurons. Group mean heat maps illustrate time spent in the stimulation versus non-stimulation chambers (**Fig. 2A**). Male rats showed a preference for the stimulation chamber (**Fig. 2B**) with 20 Hz (repeated-measures 2-way ANOVA: stimulation x virus $F_{(1, 23)} = 15.04$, $p < 0.001$) and 10 Hz stimulation (repeated-measures 2-way ANOVA: stimulation $F_{(1, 20)} = 6.03$, $p < 0.05$, virus $F_{(1, 20)} = 9.04$, $p < 0.01$, stimulation x virus $F_{(1, 20)} = 6.427$, $p < 0.05$). Specifically, Sidak's *post hoc* indicated a preference for the 20 Hz and 10 Hz stimulation chambers compared to habituation day in the ChR2 groups (n = 10-15, $p < 0.01$). Both ChR2 groups also preferred the stimulation chamber relative to YFP animals on the stimulation day (n = 10-12, $p < 0.01$). In contrast, female rats demonstrated no preference or aversion for the chamber paired with IL stimulation (n = 11-13/group, repeated-measures 2-way ANOVA: stimulation $F_{(1, 22)} = 5.79$, $p < 0.05$, stimulation x virus $F_{(1, 22)} = 0.005$ $p = 0.943$). Additionally, IL stimulation did not affect general locomotor activity in either sex (**Fig. 2C**). Together, these findings indicate that the activity of male IL glutamatergic neurons has a positive affective valance as animals were motivated to seek out the stimulation. However, this cell group does not appear to modify affective state in females.

Social behavior

The three-chamber social interaction assay was used to determine the influence of IL glutamatergic neurons on sociability. During the social motivation test (**Fig. 3A**), there was no difference in social interactions with 20 Hz stimulation in males (n = 9-

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10/group, unpaired t-test: ChR2 vs YFP $t_{(17)} = 0.77$, $p = 0.452$). However, 10 Hz stimulation in males increased social interactions (**Fig. 3B**; n = 10-12/group, unpaired t-test: ChR2 vs YFP $t_{(18)} = 3.00$, $p < 0.01$). In contrast, 10 Hz stimulation in females did not impact social interaction (n = 12-16/group, unpaired t-tests: ChR2 vs YFP $t_{(24)} = 1.01$, $p = 0.321$). Furthermore, neither male nor female IL stimulation affected preference for novel vs. familiar interactors (**Table 1**). Overall, these results indicate that IL glutamatergic activity increases male social motivation in a frequency-dependent manner; however, this cell population does not alter female social motivation.

Endocrine reactivity

To study the effect of stimulating IL pyramidal neurons on neuroendocrine responses, blood glucose and plasma corticosterone were monitored during restraint stress. In males, optic stimulation decreased corticosterone (n = 10-17/group, mixed-effects: time $F_{(4,81)} = 139.4$, $p < 0.0001$, virus $F_{(1,25)} = 8.93$, $p < 0.01$) at the 30-minute timepoint (**Fig. 4A**; $p < 0.01$). Additionally, corticosterone was decreased post-stimulation in the ChR2 group during stress recovery (90 min; $p < 0.05$). Stimulation also decreased blood glucose (mixed-effects: time $F_{(4,90)} = 62.86$, $p < 0.0001$, time x virus $F_{(4,90)} = 3.43$, $p < 0.05$) in male rats during restraint (**Fig. 4B**; 15 min, $p < 0.01$; 30 min, $p < 0.05$). In contrast, stimulation did not alter plasma corticosterone in female rats (**Fig. 4C**; n = 10-17/group, mixed-effects: time $F_{(4,93)} = 62.94$, $p < 0.0001$) with effects of time limited to within treatment. Additionally, stimulation increased glucose responses to stress in female rats (n = 10-17/group, mixed effects: time $F_{(4,90)} = 24.96$, $p < 0.0001$) specifically at the 15-min timepoint (**Fig. 4D**; $p < 0.05$). Collectively, these results

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suggest that IL activity in males reduces HPA axis activation as well as glucose mobilization. In females, IL activity does not appear to alter HPA axis response to stress. However, IL stimulation in females increases glucose, possibly through sympathetic mobilization of epinephrine and/or glucagon.

Cardiovascular reactivity

Exposure to a brightly-lit novel environment was used as a psychogenic stimulus to examine IL glutamatergic effects on cardiovascular reactivity. Over the course of the stressor, there were no differences in activity between male YFP (n = 7) and ChR2 (n = 8) rats (**Fig. 5A**; Mann-Whitney: U = 407, $p = 0.53$). In terms of hemodynamic responses, stimulation decreased HR reactivity in male ChR2 rats (mixed-effects: time $F_{(30,280)} = 19.61$, $p < 0.0001$, time x virus $F(_{30,280}) = 2.06$, $p < 0.01$), an interaction present at the 8-minute timepoint (**Fig. 5B**; $p < 0.05$). After the first minute of stimulation, arterial pressures including mean (mixed-effects: time $F_{(30,172)} = 25.99$, $p < 0.0001$, time x virus $F(30,172) = 1.86$, $p < 0.01$), systolic (mixed-effects: time $F_{(30,213)} = 27.61$, $p < 0.0001$), and diastolic (mixed-effects: time $F_{(30,189)} = 20.56$, $p < 0.0001$, virus $F_{(1,12)} = 8.05$, $p < 0.05$, time x virus $F_{(30,189)} = 2.38$, $p < 0.01$) were decreased in male ChR2 rats. Post-hoc analysis indicated these effects were present across numerous timepoints (**Fig. 5C-E**; 7-28 minutes; $p < 0.05$). In contrast, stimulation increased MAP and DAP in minute 1 ($p < 0.05$). For females, there was no effect of virus on activity in the novel environment (**Fig. 5F**; n = 7-8, Mann-Whitney: ChR2 vs YFP U = 352, $p = 0.15$). However, IL activation increased female HR responses (mixed effects: time $F_{(30,390)} = 25.83$, $p < 0.0001$) early in the stressor (**Fig. 5G**; 1-9 min; $p < 0.05$) as well as

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at 25 min ($p < 0.05$). Mixed effects analysis of arterial pressure found main effects of time for MAP (**Fig. 5H**; time $F_{(30,390)} = 31.96$, $p < 0.0001$) and SAP (**Fig. 5I**; time $F_{(30,390)} = 35.01$, $p < 0.0001$) without virus-specific effects. Taken together, these results indicate activation of male IL glutamate neurons decreases HR and arterial pressure responses to psychological stress. In contrast, activation in females increases HR.

Effects of chronic stress on cardiac function

Resting homecage LF/HF of HRV was recorded via radiotelemetry to assess how prior optic stimulation affected circadian autonomic balance and net cardiac sympathetic drive during CVS. In the absence of ongoing stimulation, ChR2 (n = 8) males had lower LF/HF than YFP (n = 7) rats (**Fig. 6A**; mixed-effects: time $F_{(5,62)} = 4.45$, $p < 0.01$, virus $F_{(1,13)} = 5.33$, $p < 0.05$). In the AM the day prior to CVS, ChR2 males had lower baseline LF/HF ($p < 0.05$) leading to decreased sympathetic drive the morning of CVS day 14 ($p < 0.05$). In females, there were circadian effects on LF/HF (**Fig. 6B**; n = 5-6/group, mixed-effects: time $F_{(5,45)} = 5.98$, $p < 0.01$) but no differences due to virus (mixed-effects: virus $F_{(1,9)} = 1.28$, $p > 0.05$).

Left ventricle echocardiography was performed before and after CVS to examine the *in vivo* cardiac consequences of chronic stress and the effects of IL stimulation on cardiac contractility. Fractional shortening (FS) was measured as the portion of diastolic dimension lost in systole. In male rats treated with YFP (n = 8), CVS increased FS (**Fig. 6C**; Wilcoxon: Post vs Pre W = 30.0, $p < 0.05$). In contrast, there was no effect of CVS on FS in ChR2 (n = 8) males (Wilcoxon: Post vs Pre W = -4.0, $p = 0.84$). To determine whether post-CVS FS was affected by acute stimulation, measurements were taken

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with optics off and then on (**Fig. 6D**). Here, a cohort of males showed no effect of acute optic status on FS (n = 3-4/group, Wilcoxon: YFP On vs Off W = 4.0, $p = 0.13$; ChR2 On vs Off W = 2.0, $p = 0.75$). In females there was no effect of CVS on FS (**Fig. 6E**; n = 10, YFP Post vs Pre W = -21.0, $p = 0.25$; n = 17, ChR2 Post vs Pre W = 53.0, $p = 0.07$). However, optic stimulation increased post-CVS FS in ChR2 animals (**Fig. 6F**; Wilcoxon: On vs Off W = 87.0, $p < 0.01$). In aggregate, these findings indicate that a history of IL stimulation limits net cardiac sympathetic drive during chronic stress in males, an effect that may protect against CVS-increased FS. Conversely, neither CVS nor prior IL stimulation affected autonomic balance or cardiac function in females. However, acute IL stimulation after CVS increased female cardiac contractility.

Chronic stress effects on cardiac structure

Left ventricular morphological analysis was carried out to examine potential structural contributions to altered function. In YFP males (**Fig. 7A**; n = 8), CVS increased wall thickness of the posterior wall in systole (**Fig 7B**; Wilcoxon: Post vs Pre W = 28, $p < 0.05$) and the anterior wall in both systole (Wilcoxon: Post vs Pre W = 36, $p < 0.01$) and diastole (Wilcoxon: Post vs Pre W = 28, $p < 0.05$). Furthermore, increased wall thickness was sufficient to decrease ventricle size in systole (**Fig. 7C**; Wilcoxon: Post vs Pre W = -30, $p < 0.05$). Critically, male rats that had previously received IL stimulation (ChR2, n = 8) were protected from the effects of CVS on cardiac hypertrophy (**Fig 7D-E**; Wilcoxon: Post vs Pre W = -9 to 20, $p > 0.05$). In contrast to males, female rats (**Fig. 7F**) showed minimal effects of CVS on cardiac remodeling as YFP rats (n = 10) had decreased posterior wall thickness in diastole (**Fig. 7G**; Wilcoxon:

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Post vs Pre W = -37.0, $p < 0.05$) with no other structural changes (**Fig. 7H**; $p > 0.05$). Additionally, there were no significant changes in cardiac structure in the female ChR2 group (**Fig. 7I-J**; n = 16, Wilcoxon: Post vs Pre W = -45 to 25, $p > 0.05$). Overall, CVS-induced inward hypertrophic remodeling was prevented by prior IL activation in males. In contrast, female rats were generally resistant to the hypertrophic effects of chronic stress.

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Discussion

In the current study, optogenetic stimulation of glutamatergic IL pyramidal neurons was combined with behavioral, endocrine, and cardiovascular assessments. Our results show that, in males, IL pyramidal neuron activity was preferred, increased social motivation, and reduced acute physiological stress reactivity. Intriguingly, prior IL activation lowered net cardiac sympathetic drive and protected against subsequent myocardial remodeling after chronic stress. However, IL activity had fundamentally different regulatory effects in females. Stimulation did not have motivational valence or alter social behavior but increased acute physiological stress reactivity and cardiac contractility following chronic stress. Collectively, these findings identify sexual divergence in the cortical integration of affective and physiological systems, suggesting that vmPFC output signaling may differentially impact health outcomes in males and females.

The comorbidity of CVD and MDD shows sexual divergence with females at twice the risk (5, 48, 49). Given the interactions between stress, mood disorders, and CVD, stress-reactive neural populations are well positioned to regulate affective and cardiovascular outcomes. Crucially, chronic stress exposure in male rats reduces IL pyramidal neuron dendritic arborization and increases local GABAergic signaling, suggesting reduced glutamatergic output (50–52). Further, long-term reduction of male IL glutamatergic output increases HPA axis activity and impairs vascular function (30, 31). Collectively, IL output neurons represent a target for modulating behavioral and physiological responses to stress. Thus, we sought to test this hypothesis through real-time *in vivo* assessments of behavior, physiology, and organ function. Altogether, we

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found that the neurobiology of emotional behaviors, endocrine-autonomic integration, and cardiovascular outcomes differed substantially between sexes.

The RTPP test was used to assess the affective state of experimental animals by measuring preference or aversion for IL neural activity. Here, male rats preferred the chamber paired with either 10 Hz or 20 Hz stimulation, but the valence of female IL activation was neither positive nor negative. Previous work indicates that male mPFC stimulation reduces social avoidance after social defeat (53), yet relatively few studies have examined IL function in females. Although social interaction induces less IL immediate early-gene expression in females than males (54, 55), the current study is, to our knowledge, the first examination of IL regulation of female social behavior. IL activity did not alter social behavior in females, indicating a significant sexual divergence in the neural regulation of sociability. However, males exhibited frequency-dependent increases in social motivation. These results suggest that stimulation near the intrinsic pyramidal neuron firing rate (4-10 Hz) (46, 47) is required to increase male social motivation.

Activation of IL glutamatergic neurons also reduced male glucose and corticosterone responses to stress. Conversely, female IL glutamatergic stimulation increased glucose mobilization without affecting corticosterone, suggesting a role in sympatho-excitation. Female IL activity also increased tachycardic responses to stress, while male IL stimulation reduced cardiovascular stress responses including HR and arterial pressures. These experiments indicate that IL activity has opposing effects on endocrine-autonomic integration in males and females whereby male glutamatergic IL

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neurons cause widespread inhibition of the stress response and female IL neurons facilitate sympathetic responses.

Chronic stress exposure induced ventricular hypertrophy and increased endocardial FS in males, suggesting that increased wall thickness likely accounted for the increase in FS. This effect was prevented by a history of IL stimulation in males, likely arising from a reduction in symaptho-vagal imbalance throughout CVS. In fact, previous IL stimulation limited resting net sympathetic drive, a major risk for CVD (56, 57). Given that rats received no optic stimulation during CVS and that acute optic status did not impact male FS, this effect was likely driven by stimulation-induced IL plasticity. IL stimulation has been shown to induce persistent morphological changes in males including increased excitatory synapses onto pyramidal neurons, suggesting a prolonged state of enhanced excitability (29, 58). Thus, lower resting net sympathetic tone and/or reduced sympathetic activity during stressors may have prevented the consequences of chronic stress to induce inward hypertrophic remodeling of the myocardium. These effects were not present in females as hypertrophic remodeling was not evident and acute stimulation increased FS. Collectively, these results indicate that prior male IL glutamatergic activity is sufficient to restrain responses to chronic stress while female IL activity increases cardiac contractility independent of structural changes.

The IL does not directly innervate the neurons that govern endocrine and autonomic stress responses. Accordingly, downstream glutamate signaling from IL synaptic terminals requires intermediary synapses. The exact circuits engaged by IL pyramidal cells to bring about the observed effects remain to be determined. However, anterograde mapping studies indicate that IL projections widely innervate the forebrain

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and brainstem (24, 59). We previously found that, in males, stress-activated IL neurons innervate local inhibitory GABAergic neurons in the posterior hypothalamus (PH) (22). Furthermore, blocking GABAergic tone in the PH reduces social behavior and increases HPA axis reactivity suggesting inhibition of the PH may be important for limiting behavioral and physiological stress responses (22). Additionally, IL inputs to the amygdala are critical for fear extinction and reducing anxiety-like behavior (60, 61). Interestingly, amygdala-projecting IL neurons are both resistant to stress-induced dendritic retraction as well as sensitive to estrogen (62, 63). Thus, the IL-amygdala circuit could play a key role in sex differences in behavioral regulation. Although the downstream mechanisms of IL cardiovascular regulation are unknown, male IL projections target pre-autonomic cell groups in the brainstem and give rise to multi-synaptic pathways that innervate the adrenal medulla (23, 64). Further sex-specific analysis of IL synaptic signaling in forebrain and brainstem nuclei is necessary to determine the basis of divergent behavioral and physiological integration.

While ovarian hormones have far-reaching effects on behavior and physiological systems, we did not control for estrous cycle phase. Instead, we used a single cohort of randomly cycling females. Cycle phase was reported for each treatment, but statistical power was insufficient to examine phase as a factor. Future studies employing ovariectomy and replacement strategies would be needed to determine a potential role for ovarian hormones in cortical stress integration. Additionally, the neuroplastic responses induced by IL stimulation in males could merit further investigation as the specific cellular changes contributing to subsequent stress resilience may represent novel targets for intervention.

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The current study identified a cortical node integrating mood-related behaviors with cardiovascular outcomes. Moreover, activity in this vmPFC cell population produced sex-specific effects on behavior and physiology. In addition to highlighting the necessity of sex-based investigation, these data point to a neurochemical basis for sex differences in stress-related health determinants. Ultimately, further investigation of brain-body interactions in the face of prolonged stress may provide a better understating of disease risk and resilience factors.

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Figure Legends

Figure 1: Approach validation and experimental design. (**A**) Injection of AAV-packaged constructs led to expression of cytosolic YFP or membrane-targeted ChR2-YFP under the CaMKIIα promoter. Blue light stimulation in ChR2 females (5 min, 1 mW, 10 Hz, 5 ms pulse) led to robust expression of the immediate-early gene marker c-Fos. White arrows indicate representative c-Fos-positive nuclei. Scale bar: 200 µm and 40 µm for combined. (**B**) Voltage-clamp recordings from male IL-containing slices illustrated light-evoked depolarizing current. (**C**) Current-clamp recordings found stimulation-locked spiking with 10 and 20 Hz stimulation. (**D**) Experimental timelines. RTPP: real-time place preference, SI: social interaction, RS: restraint stress, NE: novel environment, CVS: chronic variable stress. (**E**) Optic fiber placements (YFP: yellow, ChR2: blue) were mapped within or immediately dorsal to the IL (red outline). Coronal sections adapted from Swanson Rat Brain Atlas (3rd edition).

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Table 1: Social novelty preference.
Time spent interacting with novel and familiar rats. Stimulation of IL pyramidal neurons did not affect preference for social novelty in males or females.

Experiment	Virus	Novel interaction (% time)	Novel interaction (SEM)	Familiar interaction (% time)	Familiar interaction (SEM)	n
Male 20 Hz	YFP	16.63	1.27	13.06	2.81	7
	ChR2	12.84	1.72	9.73	0.94	10
Male 10 Hz	YFP	16.43	2.07	13.13	2.17	12
	ChR2	18.19	1.81	16.32	2.47	10
Female 10 Hz	YFP	24.84	2.61	16.56	1.62	12
	ChR2	21.58	1.55	16.96	1.51	16

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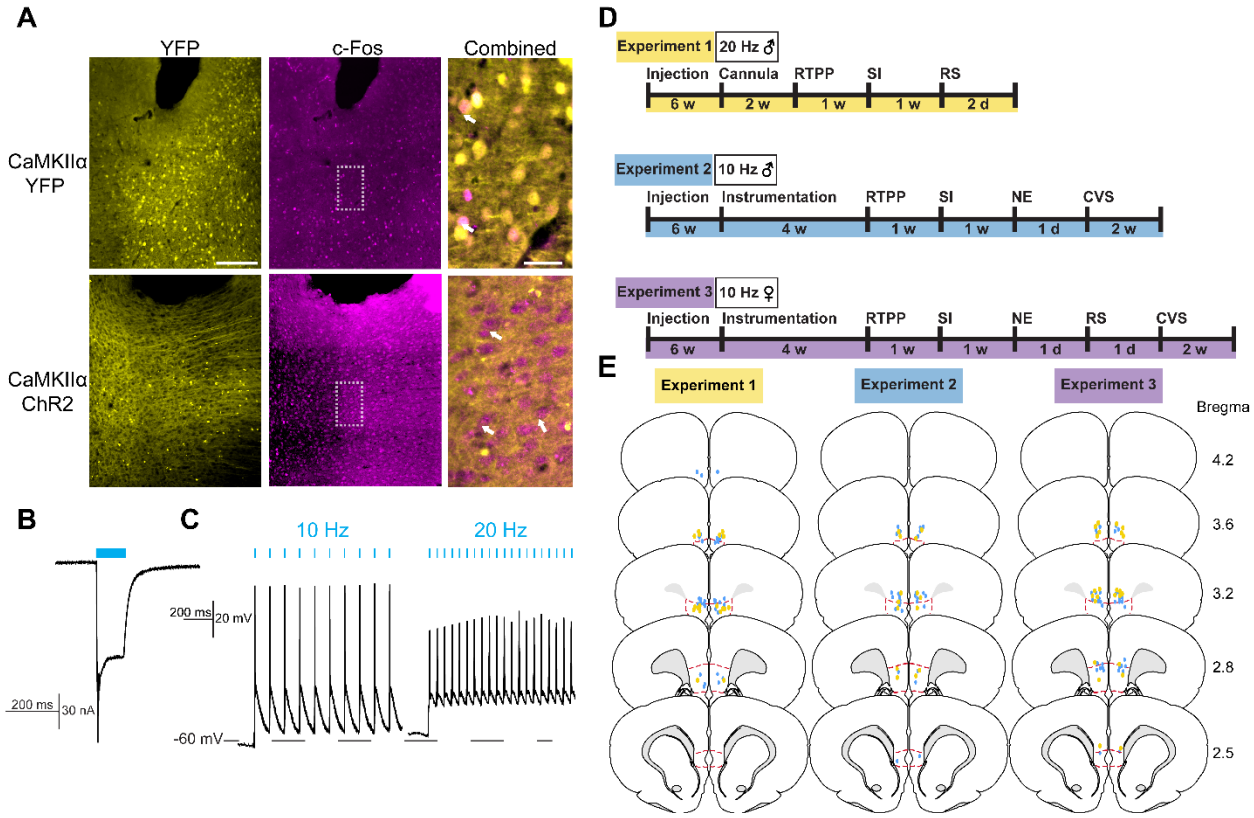

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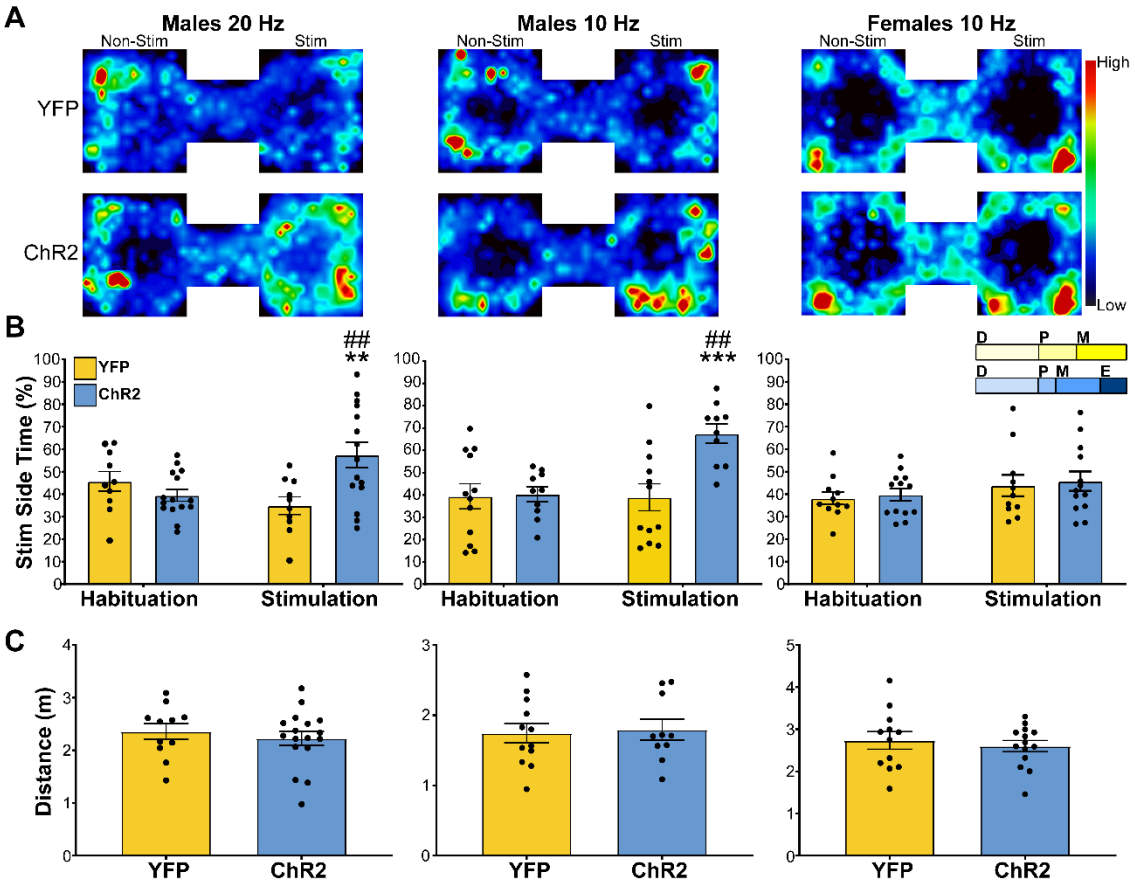

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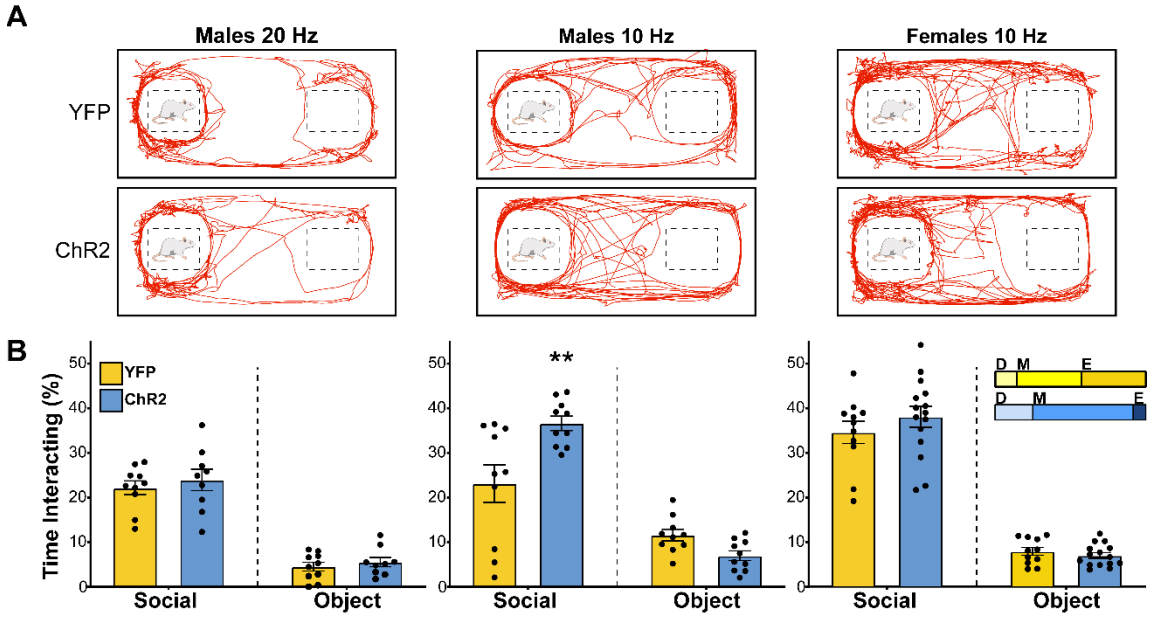

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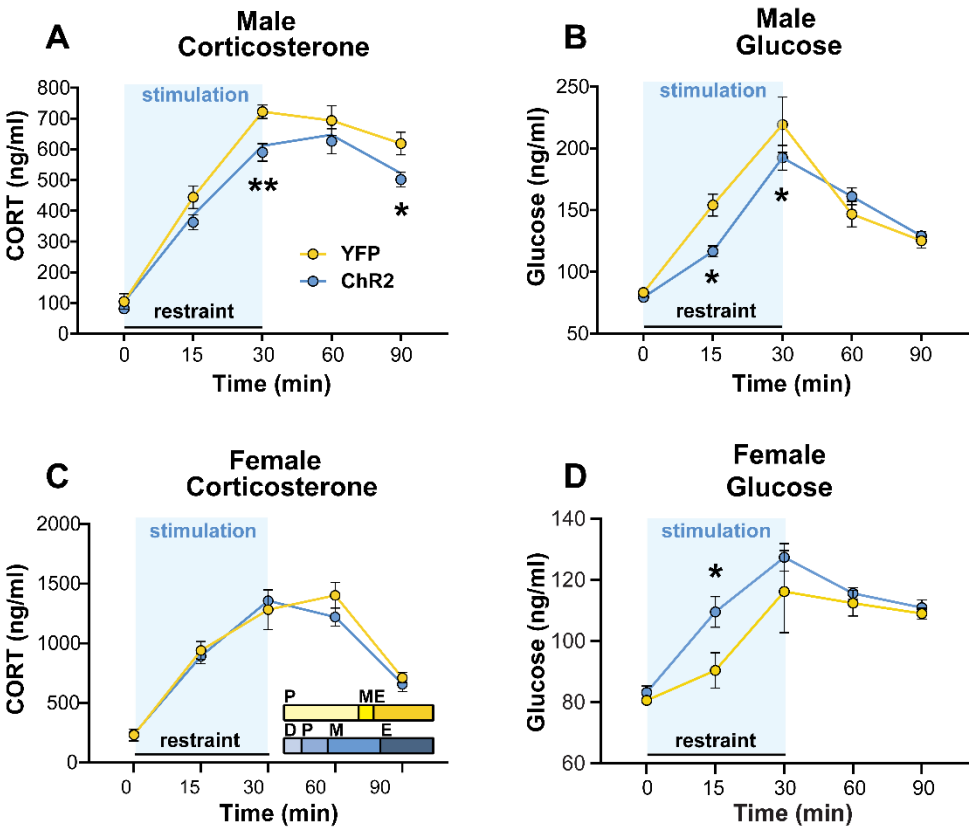

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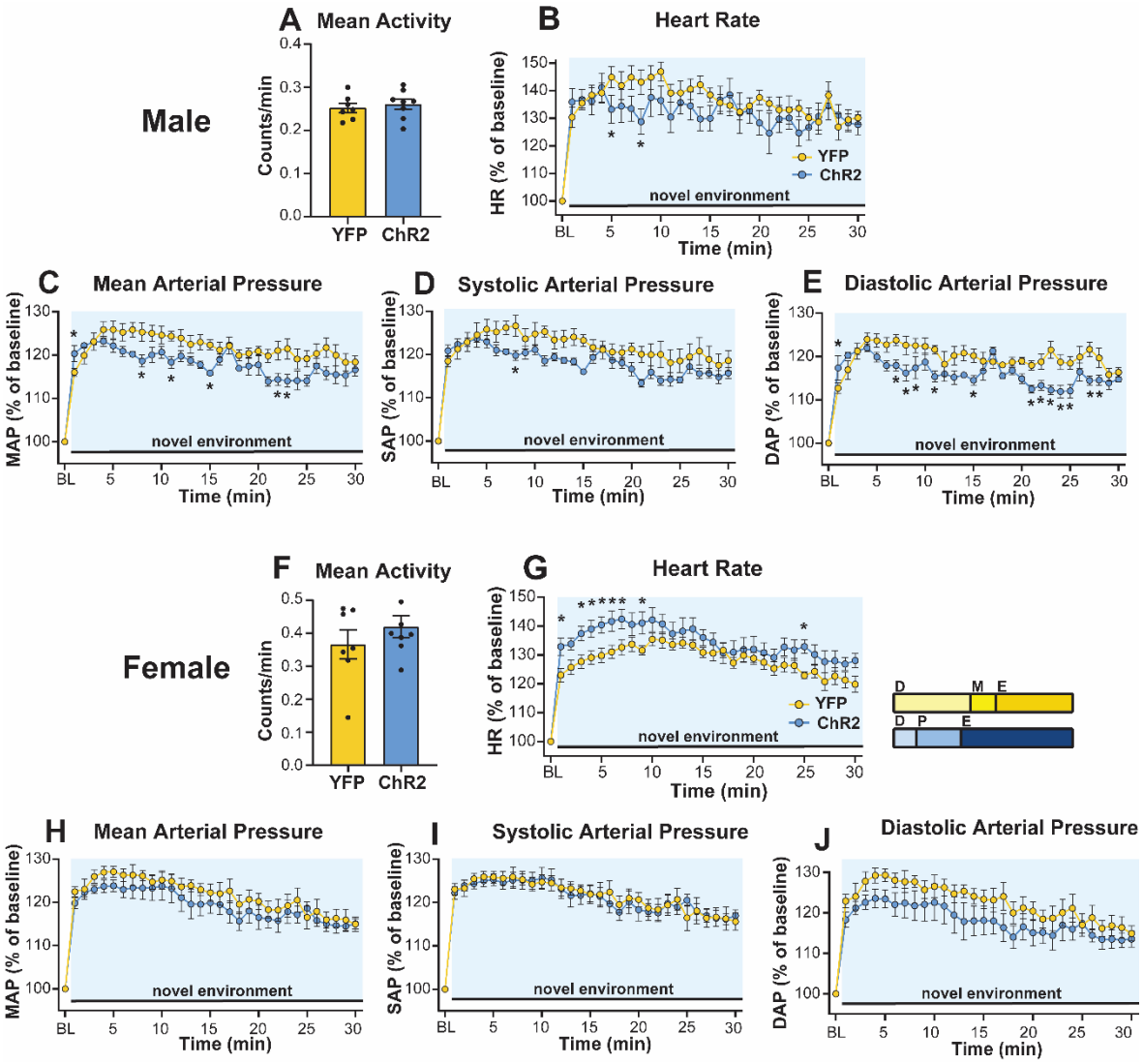

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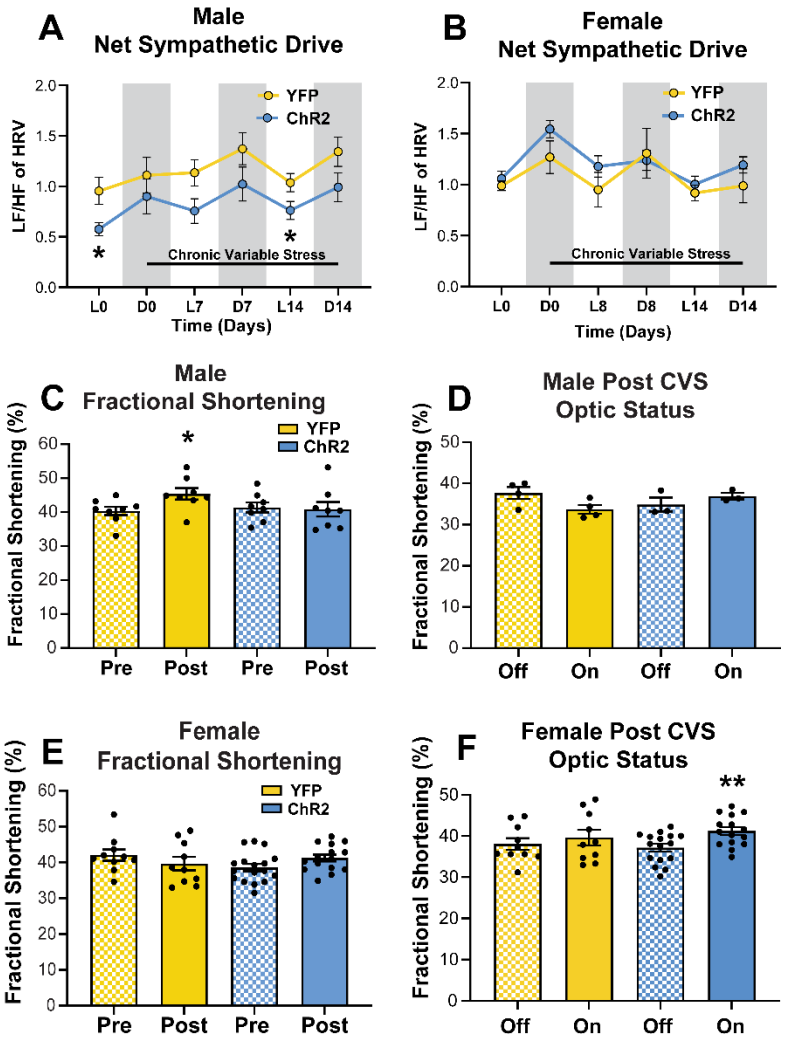

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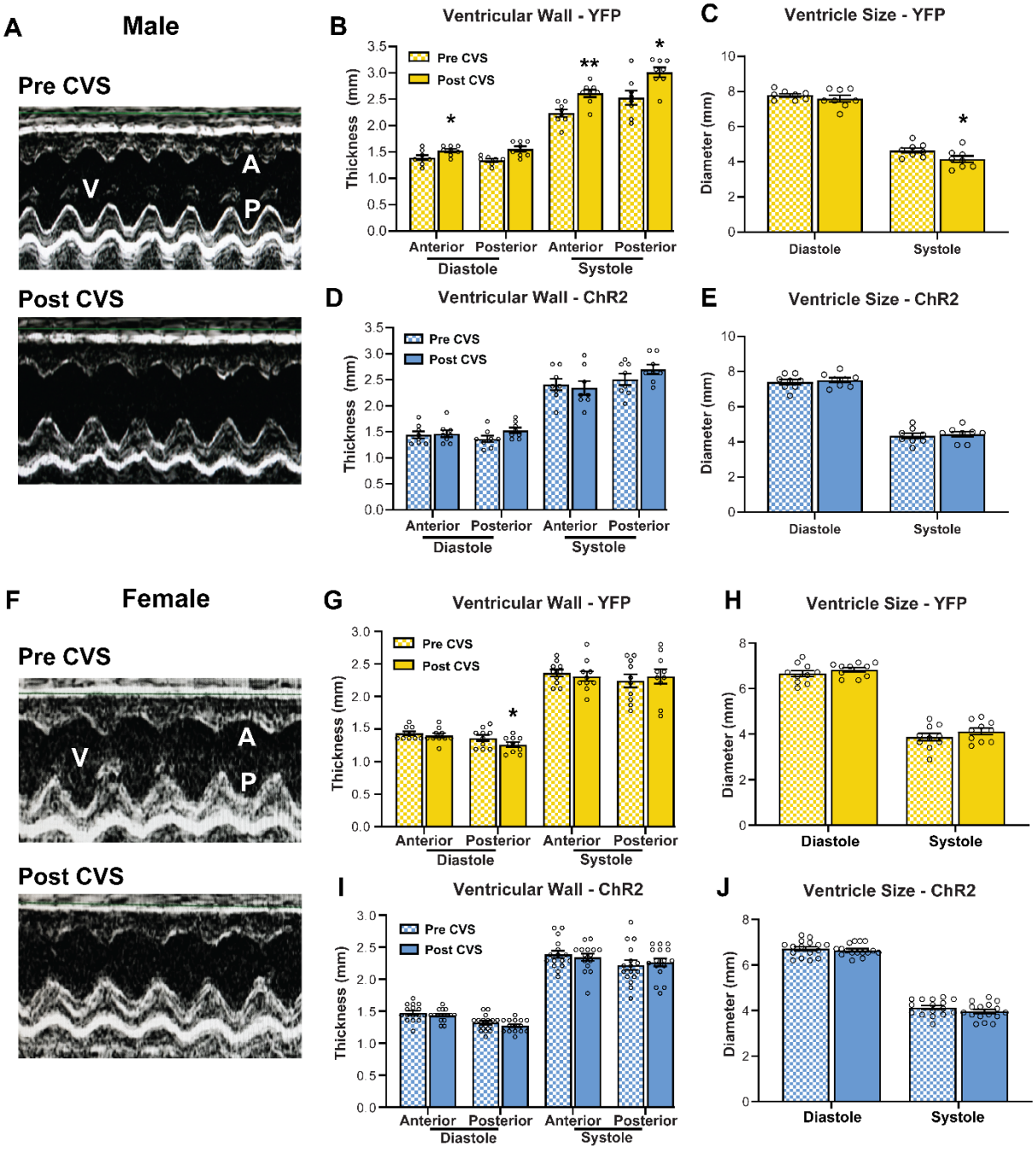

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