Hormones and Behavior 146 (2022) 105260

Contents lists available at ScienceDirect

Hormones and Behavior

journal homepage: www.elsevier.com/locate/yhbeh

Testosterone, cortisol, and criminal behavior in men and women

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ARTICLE INFO

Keywords:
Hormones
Testosterone
Cortisol
Crime
Violence

ABSTRACT

Only two studies to date have considered the joint effects of testosterone and cortisol on direct measures of criminal behavior. The current study extends this earlier work by incorporating the direct and interactive effects of baseline hormone measures and hormone change scores in response to social stress. The current study also extends prior work by considering distinct measures of different criminal behavior types and sex differences. Analyses based on a large sample of undergraduates indicated that testosterone had a positive and statistically significant association with impulsive and violent criminal behavior. The interaction of testosterone with cortisol had a negative association with income generating crime. Simple slopes analyses of this interaction indicated testosterone had a positive association with income generating crime when cortisol was low (−1 SD). Associations between hormones and criminal behavior were not moderated by sex.

1. Introduction

The costs of crime are substantial. For example, a recent estimate placed the cost of personal and property crime in the United States during 2017 at $2.1 trillion (Miller et al., 2021).

These costs demonstrate the need for comprehensive models of the etiology of criminal behavior in support of preventative and treatment efforts. The development of such models would benefit from increased attention to neuroendocrinological influences on criminal behavior. Research has established that testosterone and cortisol are associated with crime (Booth and Osgood, 1993; Brewer-Smyth et al., 2004; Dabbs et al., 1995; Virkkunen, 1985), but to date only two studies have considered the joint effects of testosterone and cortisol on criminal behavior (Cooke et al., 2020; Dabbs et al., 1991).

Testosterone is an androgenic steroid hormone that is a product of the Hypothalamic Pituitary Gonadal (HPG) axis. Testosterone is widely known for its role in male reproductive physiology and behavior, (Mooradian et al., 1987; Wingfield et al., 1990). Models of testosterone's role in human behavior argue that it facilitates status seeking and dominance (Mazur, 1985; Mazur and Booth, 1998). To the extent that crime overlaps with these broad classes of behaviors we may then expect that testosterone would be associated with increased risk for criminal behavior. For example, meta-analyses have established that testosterone is positively associated with aggression (Archer et al., 2005; Book et al., 2001). This positive association extends to self-report measures of aggression which overlap with self-reports of criminal behavior (Geniole et al., 2019). However, not all aggressive or criminal behaviors are enacted to facilitate status seeking or dominance, and the association between testosterone and crime may instead more directly reflect an increased sensitivity to reward through testosterone's influence on the brain's mesolimbic reward system or modulation of other aspects of the brains social behavior network (Carré and Olmstead, 2015; Eisenegger et al., 2011; Newman et al., 2005; Welker et al., 2015). Here, increases in sensitivity to reward may lead to increased risk for the immediate gratification that many criminal behaviors seem to offer (Gottfredson and Hirschi, 1990).

Recently, the relationship between testosterone and behavior is increasingly considered in the context of the action of cortisol, a steroid

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https://doi.org/10.1016/j.yhbeh.2022.105260
Received 10 February 2022; Received in revised form 1 September 2022; Accepted 3 September 2022
Available online 16 September 2022

hormone released as part of the Hypothalamic Pituitary Adrenal (HPA) axis stress response (Chrousos and Gold, 1992; McEwen and Stellar, 1993). As an aspect of the stress response, cortisol has a number of physiological effects, including the mobilization of energy, immune suppression, and cardiovascular changes (Buckingham, 2006; Sapolsky et al., 2000). Cortisol is also secreted as a part of a set of physiological, psychological, and behavioral responses to threats to the social self (Dickerson and Kemeny, 2004). As an indicator of stress system activity, cortisol may be related to psychopathy through blunted or aberrant reactivity to stress (Lykken, 1995; Patrick et al., 1993). Low stress system activity is associated with decreased affect and a lack of concern for distress in others, while increased stress system activity is associated with negative affect including depression and anger (Jonsdottir et al., 2012; Kemeny and Shestyuk, 2008; Lykken, 1995; Patrick et al., 1993).

A series of studies utilizing samples of male prisoners gathered during the 1990s demonstrated a positive association between testosterone and aspects of criminality and criminal behavior among males including recidivism, the length and severity of criminal history, the likelihood of serious and violent crime relative to petty crime, and prison misconduct (Dabbs et al., 1995; Dabbs et al., 1987; Dabbs et al., 1991). Other work with male samples has found increased testosterone among aggressive prisoners relative to non-aggressive prisoners (Ehrenkranz et al., 1974), greater testosterone among juvenile prisoners with a violent criminal history relative to juvenile prisoners without (Kreuz and Rose, 1972), and no difference across groups of adult psychiatric patients charged with murder, assault, or property offenses (Bain et al., 1987). Positive associations between testosterone and crime are also present in non-forensic samples (Booth and Osgood, 1993; Dabbs and Morris, 1990) and extend to women (Dabbs and Hargrove, 1997; Dabbs et al., 1988).

The majority of studies examining the association between cortisol and both criminal and antisocial behavior suggest that decreased cortisol is associated with increases in problem behavior (Fairchild et al., 2018; van Goozen et al., 2007). However, there are null findings in this area, and studies showing a positive association between cortisol and antisocial behavior (Gerra et al., 1997; McBurnett et al., 2005; Van Bokhoven et al., 2005). This bifurcated pattern of association is also present in work with a specific focus on the association between cortisol and crime. Studies using criminal justice system-involved samples have shown that violent offenders have lower cortisol than non-violent offenders among both men and women (Brewer-Smyth et al., 2004; Virkkunen, 1985). In addition, young adult male offenders whose cortisol levels declined during the Trier Social Stress Test (TSST) were incarcerated for longer periods of time and more frequently relative to those whose cortisol levels increased during the TSST (Johnson et al., 2015). Negative associations between cortisol and crime within forensic samples may not extend to comparisons between forensic and community samples. Inmates with psychopathy have lower cortisol concentrations than offenders without psychopathy, but not community controls (Cima et al., 2008). In addition, work contrasting male violent offenders with community controls found higher cortisol concentrations in the incarcerated sample (Soderstrom et al., 2004). Positive associations between cortisol and antisocial behavior are also present in research reporting increased cortisol response to aggression induction in aggressive men from the community but not community controls (Gerra et al., 1997), and in research reporting an association between increased cortisol response to stress and conduct problems among at-risk adolescent males (McBurnett et al., 2005).

Growing research indicates that a full understanding of the role of hormones in the explanation of criminal behavior will require a consideration of both direct and interactive effects for testosterone and cortisol. The interactive effects of testosterone and cortisol are implied by reciprocal interconnections between the HPA- and HPG-axes (Salvador, 2012; Viau, 2002). In general, HPA-axis stress response dampens HPG-axis activity (Burnstein et al., 1995; Johnson et al., 1992; Tilbrook et al., 2000). However, there is also evidence that the HPA-axis is inhibited by testosterone at both the hypothalamus and the adrenal gland (Rubinow et al., 2005; Williamson and Viau, 2008).

Two studies have tested the joint contribution of testosterone and cortisol to risk for criminal behavior. In a sample of late adolescent (17–18 years old) male offenders, Dabbs et al. (1991) found cortisol moderated the direct association between testosterone and violent crime, with low cortisol levels strengthening the positive association between testosterone and violent criminal behavior. Using data that the current analyses are also based on, Cooke et al. (2020), examined the joint effects of testosterone and cortisol on associations between life stress, negative emotions and antisocial behavior. Cooke et al. (2020) found the ratio of testosterone to change in cortisol had a positive association with an antisocial behavior index including indicators of criminal behavior. This pattern of association is roughly parallel to Dabbs et al. (1991)'s findings. Larger testosterone to change in cortisol ratios occur when testosterone is high and change in cortisol is low. While informative, Cooke et al. (2020) did not consider direct associations between hormones and antisocial behavior or the potential moderating role of sex. In addition, the use of hormone ratios rather than interactions to explore the joint influence of hormones on behavior is somewhat controversial (Sollberger and Ehlert, 2016).

In an effort to parse the role of hormones in the explanation of criminal behavior, the current work tests associations between testosterone, cortisol, and measures of criminal behavior in a large sample of University students. This study extends prior work by 1) incorporating baseline hormone measures and measures of change in hormones in response to a social stressor, 2) considering interactions between hormone measures and sex, and 3) using multiple measures of criminal behavior derived from iterative factor analyses.

2. Methods

2.1. Study subjects

Data were gathered from a convenience sample of undergraduate students at a University in the Southern United States as part of a larger study on the etiology of antisocial and criminal behavior. Measures of criminal behavior were collected with a self-report survey that was administered during regularly scheduled classes after participants provided informed consent. Subjects were offered extra credit for study participation, at the discretion of class instructors. After the survey, subjects were referred to a separate laboratory measurement protocol where hormone measures were collected. Subjects then scheduled the laboratory measurement protocol using signupgenius.com, an online scheduling website. Of the 862 subjects who completed the self-report survey, 567 also participated in the laboratory measurement protocol. Of these, 10 declined to provide saliva samples for analysis, and four did not complete the protocol. A single subject reporting that they were a transgender female was also omitted from analyses, leaving a final analysis sample of 552. Participants were 32.5 % male and 66.5 % female and averaged 20.34 years of age (SD = 3.02). Self-identified race/ethnicity of participants was 13.4 % African American, 36.9 % Caucasian, 39.3 % Hispanic, and 10.4 % other.

2.2. Criminal behavior measures

A set of 38 self-report items captured the past years occurrences of a broad range of criminal activities including violent, property, drug, fraud, weapon, sex, and disorderly conduct crimes. The use of self-report measures to capture criminal behavior is widespread in research on the etiology of crime (Krohn et al., 2010). While such measures are not without their limitations, the validity of self-report measures of criminal behavior is well established with work showing self-reports are associated with a variety of different types of official crime measures including arrest and court referrals (Brame et al., 2004; Hindelang et al., 1981; Jolliffe et al., 2003). Self-report criminal behavior items were factor

analyzed in order to assess potential differences in associations between hormones and criminal behavior types. Potential differences in the etiology of criminal behavior types are implied by work showing differences in the genetic, temperamental, socio-environmental, and developmental correlates of types of antisocial and aggressive behaviors (Baker et al., 2008; Connell and Goodman, 2002; Leadbeater et al., 1999; Miller and Lynam, 2006; Oldehinkel et al., 2004). The potential for differences in associations between hormones and criminal behavior types are also more directly indicated by work showing associations between hormones and antisocial behaviors vary according to antisocial behavior type (Armstrong et al., 2021; Denson et al., 2013; Geniole et al., 2011; van Bokhoven et al., 2005).

Factor analyses resulted in a 10-item *impulsive and violent crime* measure and an 8-item *income-generating crime* measure. A description of the factor analyses and the specific items in each of the respective measures are presented in the Supplementary Materials. Criminal behavior measures were estimated as variety scores increasing by one for each different type of criminal behavior that a respondent had engaged in during the past year. Estimated in this way criminal behavior variety scores are equal to the number of different types of criminal behavior that a participant engaged in during the past year. Variety scores are preferable to scales based on the average frequency of criminal behaviors, as variety scores are not heavily influenced by the frequency of less serious offenses (Sweeten, 2012). For the impulsive and violent crime variety score, four non-continuous outliers were rescored as the highest continuous score (Wilcox, 2010). There were no outliers among the income-generating crime variety scores. Descriptive statistics for criminal behaviors and hormone measures, along with tests for sex differences are included in Table 1.

2.3. Laboratory measurement protocol and hormone assays

Hormones were measured with assays of samples gathered both before and during a social stressor. Laboratory measurements were administered between the hours of 0800 and 1830. The protracted window of data collection supported the collection of a large number of samples but may impact associations given diurnal cortisol and testosterone cycles and evidence for between individual variation in the magnitude of variation in cortisol (Faiman and Winter, 1971; Rose et al., 1972; Zhang et al., 2017). Sensitivity analyses assessed the potential impact of the data collection window on results by re-estimating tests of the association between hormones with the sample restricted to those participating between 0800 and 1200, and again with the sample restricted to those participating between 1200 and 1830.

Participants were instructed to refrain from a variety of activities that may have affected testosterone and cortisol levels (e.g., smoking, eating, exercise) for at least one hour prior to reporting to the lab. When subjects arrived at the laboratory informed consent was reaffirmed and subjects were seated comfortably. After a 30 s rest period, baseline saliva samples were gathered via passive drool using Salimetrics LLC Saliva Collection Aids. Subjects were then instructed that they had two minutes to prepare a two-minute speech addressing their principal faults and weaknesses. Subjects were notified that their speech would be recorded with a digital camera and analyzed. If the subject's attempted to continue delivering their speech past the two-minute mark they were instructed to stop. Post-stress saliva samples were gathered approximately 15 min after the conclusion of the recording of the speech and (Mean = 22.26; SD = 2.18). The time between initiation of the stressor and collection of the post-stress sample is consistent with the time between onset of stress and peak cortisol response (Dickerson and Kemeny, 2004). Each sample contained at least 1.5 mL of saliva. Prior to analysis, samples were stored in a freezer at −20 degrees Celsius. Samples were then analyzed using materials from and following established protocols for Salimetrics testosterone and cortisol enzyme immunoassay kits. All samples were tested in duplicate. The mean intra-assay coefficient of variation for testosterone and cortisol were 5.98 % and 11.01 % respectively and the mean inter-assay coefficients of variation for testosterone and cortisol were 7.95 % and 5.91 % respectively. Values for hormone measures and tests of differences in hormone values across sex are presented Table 1.

Table 1
Descriptive statistics and sex differences across criminal behavior and hormone measures.

	Full Sample M/(SD)	Females M/(SD)	Males M/(SD)	T-test for Sex Differences
Criminal Behavior				
IV	0.33 (0.76)	0.24(0.51)	0.52(0.89)	$t(240) = 3.97, p < 0.01$
IG	0.66 (1.24)	0.61(1.20)	0.77(1.31)	$t(539) = 1.35, p = 0.18$
Hormones				
T1	72.83(53.34)	46.78(21.23)	124.09 (60.00)	$t(209) = 17.04, p < 0.01$
T2	66.64(51.05)	41.58(21.36)	115.95 (56.35)	$t(212) = 17.38, p < 0.01$
ΔT	−6.42 (22.45)	−5.54 (11.85)	−8.17(34.91)	$t(207) = -1.00, p = 0.32$
C1	0.22(0.16)	0.22(0.17)	0.22(0.16)	$t(550) = -0.02, p = 0.98$
C2	0.23(0.18)	0.21(0.16)	0.25(0.21)	$t(297) = 1.83, p = 0.07$
ΔC	0.00(0.23)	−0.01(0.22)	0.03(0.25)	$t(334) = 2.01, p = 0.05$

Note: Testosterone concentrations are pg/mL and cortisol concentrations are μg/dL. Hormone values are based on raw scores. Degrees of freedom vary when equal variances cannot be assumed. IV = impulsive and violent, IG = income-generating, T1 = baseline testosterone, T2 = post-stress testosterone, ΔT = change in testosterone, C1 = baseline cortisol, C2 = post-stress cortisol, ΔC = change in cortisol.

2.4. Analytic strategy

To account for skewness, cortisol concentrations were log 10 transformed after the addition of a constant of 1. Outliers for both cortisol and testosterone scores were winsorized to 3 SD from the mean (Wilcox, 2010). After transformation there was one univariate outlier in pretest cortisol scores and two univariate outliers in posttest cortisol scores. Due to large and statistically significant sex differences in testosterone concentrations, testosterone scores were evaluated separately within sex and outliers winsorized to 3 SD from the mean.[1] Testosterone concentrations were not skewed in either men or women. Preliminary analyses assessed change in hormones from baseline to post-stress with paired samples *t*-tests. To account for sex differences, all subsequent analyses were based on standardized hormone z-scores, with hormone scores for testosterone standardized within sex. For example, to create the standardized testosterone z-score for women, the mean of testosterone scores among women was subtracted from a participants testosterone score and then divided by the standard deviation of testosterone scores among women. Associations between hormones and measures of criminal behavior were tested with negative binomial regression models estimated with StataMP 15 (StataCorp, 2017). Negative binomial models are uniquely suited to over-dispersed count variables such as the criminal behavior variety scores used in the current study (Hilbe, 2011). Models sequentially tested associations between criminal behavior measures and: 1) baseline hormone and hormone change score direct effects; 2) interactions between baseline hormone measures and between hormones changes scores; 3) interactions between sex and both baseline hormone measures and hormone changes scores; 4) three-way interactions between sex and the interaction of baseline hormone measures and between sex and the interaction of hormone changes

[1] There were two univariate outliers among pretest testosterone scores for women, and one outlier among pretest testosterone scores for men. At posttest testosterone scores there were three univariate outliers among testosterone scores for women and five among testosterone scores for men.

scores. To investigate the potential influence of time of day of hormone sample collection, all models were re-estimated with the sample restricted to those with hormone measures taken between 0800 and 1200, and again with the sample restricted to those with hormone measures taken between 1200 and 1830. Statistically significant interactions were probed using simple slopes analyses (Bauer and Curran, 2005) and visualized with Johnson-Neyman plots generated with the tidyverse package (Wickham et al., 2019) in RStudio 4.0.3 (R Core Team, 2020). All regression models included control variables representing the two largest race/ethnic groups in the sample (1 = Caucasian, 0 = other; 1 = Hispanic, 0 = other), age in years, and time of data collection represented with a whole number for hours on the 24 h clock and fraction of minutes within an hour to two decimal places.

3. Results

3.1. Change in hormones with stress

Decreases in testosterone from baseline to post-stress (results not shown in Table 1) were statistically significant in the full sample ($t(551) = 6.07$, $p < 0.001$), among women ($t(365) = 6.37$, $p < 0.001$), and among men ($t(185) = 3.18$, $p = 0.002$).[2] There was a slight increase in cortisol scores in the full sample that lacked statistical significance ($t(551) = 0.91$. $p = 0.365$), and a statistically significant increase in cortisol scores among men ($t(185) = -2.17$, $p = 0.031$). The small decrease in cortisol scores in women lacked statistical significance ($t(365) = 0.63$, $p = 0.538$).

3.2. Bivariate associations

Baseline hormone scores had a positive correlation with each other (testosterone with cortisol) and a negative correlation with change scores (Table 2). The strong negative association between baseline values and change scores is consistent with the law of initial values (Wilder, 1958). This correlation also indicates the association between change in hormones and traits and behaviors should be considered in the context of baseline measures. Bivariate associations between hormones and crime were specific to impulsive and violent criminal behavior with both baseline testosterone and baseline cortisol positively associated with impulsive and violent behavior. There was also a strong correlation between impulsive and violent criminal behavior and income-generating crime.

Table 2
Bivariate correlations between hormones and criminal behavior.

	T1	ΔT	C1	ΔC	IV	IG
T1	–					
ΔT	−0.47**	–				
C1	0.31**	−0.26**	–			
ΔC	−0.08	0.23**	−0.34**	–		
IV	0.10*	−0.01	0.09*	−0.05	–	
IG	−0.01	−0.06	0.03	−0.03	0.81**	–

Notes: IV = impulsive and violent, IG = income-generating, T1 = baseline testosterone, T2 = post-stress testosterone, ΔT = change in testosterone, C1 = baseline cortisol, C2 = post-stress cortisol, ΔC = change in cortisol.
* $p < 0.05$.
** $p < 0.01$.

[2] These changes are consistent with an earlier study showing decreases in testosterone with the anticipation of stress and social-evaluative threat (Schulz et al., 1996), but are inconsistent with studies showing increases in testosterone in response to status-threat (Chichinadze and Chichinadze, 2008; Kim et al., 2018; Knight and Mehta, 2017; Scheepers and Knight, 2020; Wingfield and Sapolsky, 2003).

3.3. Associations between hormones and crime

Results for regression models testing the multivariate associations between hormones and impulsive and violent criminal behavior are presented in Table 3. For ease of presentation, Tables 3 and 4 only include the unique regression coefficients from Models 2–4. Testosterone was positively associated with impulsive and violent crime ($b = 0.22$, $SE = 0.09$, $p = 0.016$, *95 % CI* [0.04, 0.41]) and a positive association between cortisol and impulsive and violent crime showed a trend towards statistical significance ($b = 0.18$, $SE = 0.10$, $p = 0.069$, *95 % CI* [−0.01, 0.37]). Interactions between hormone measures and between hormone measures and sex were not associated with impulsive and violent criminal behavior.

There were no direct associations between hormones and income-generating crime (Table 4). The interaction between baseline testosterone and baseline cortisol had a negative and statistically significant association with income-generating crime ($b = -0.25$, $SE = 0.09$, $p = 0.007$, *95 % CI* [−0.43, −0.07]). The association between income-generating crime and the interaction of testosterone and cortisol is visualized in Fig. 1. Fig. 1 shows that the conditional effect of testosterone on income generating crime is positive and statistically significant when cortisol is below −0.70 under the mean, and negative statistically significant when cortisol is above 1.669 over the mean. Results also show the three-way interaction between change in testosterone, change in cortisol, and sex was associated with income-generating crime ($B = 0.68$, $SE = 0.31$, $p = 0.027$, 95 % CI [0.08, 1.29]). The plots presented in Fig. 2 show that this three way interaction indicates that change in cortisol moderated the association between change in testosterone in men (Panel A) but not women (Panel B). Among men the conditional effect of change in testosterone on income generating crime is positive and statistically significant when change in cortisol is below −0.87 standard deviations under the mean. Chi-square likelihood ratio tests for the initial income generating crime models lacked statistical significance. However, the difference between Model 1 and Model 2 was statistically significant (χ^2 difference = 7.69(2), $p <$

Table 3
Negative binomial regression of impulsive and violent crime on hormone measures and controls ($n = 526$).

	β	*SE*	*p*	*95 % CI*
Model 1 LR χ^2 (9) = 32.62, $p < 0.001$, $R^2 = 0.043$				
Time	0.07	0.03	**0.035**	[0.01, 0.14]
Caucasian	−0.07	0.23	0.762	[−0.51, 0.38]
Hispanic	0.02	0.22	0.943	[−0.42, 0.45]
Age	−0.00	0.03	0.946	[−0.06, 0.06]
Sex(Female)	−0.76	0.17	**0.000**	[−1.09, −0.42]
T	0.22	0.09	**0.016**	[0.04, 0.41]
C	0.18	0.10	0.069	[−0.01, 0.37]
ΔT	0.13	0.10	0.182	[−0.06, 0.31]
ΔC	−0.08	0.10	0.382	[−0.27, 0.10]
Model 2 LR χ^2 (11) = 33.94, $p < 0.001$, $\Delta R^2 = 0.044$				
TxC	−0.05	0.08	0.516	[−0.21, 0.11]
ΔTxΔC	0.09	0.08	0.269	[−0.07, 0.24]
Model 3 LR χ^2 (13) = 34.38, $p = 0.001$, $R^2 = 0.045$				
TxSex	0.00	0.19	0.981	[−0.36, 0.15]
CxSex	0.16	0.19	0.422	[−0.22, 0.54]
ΔTxSex	−0.14	0.19	0.462	[−0.52, 0.24]
ΔCxSex	0.06	0.19	0.753	[−0.31, 0.43]
Model 4 LR χ^2 (17) = 37.01, $p = 0.003$, $R^2 = 0.048$				
TxCxSex	−0.02	0.16	0.913	[−0.24, 0.30]
ΔTxΔCxSex	0.23	0.19	0.226	[−0.14, 0.60]

Note: T = Testosterone, C = Cortisol, Δ = change; R^2 based on pseudo R^2 reported for negative binomial model; $p < .05$ in bold.

Table 4
Negative binomial regression of income generating crime on hormone measures and controls ($n = 520$).

	β	*SE*	*p*	*95 % CI*
Model 1 LR χ^2 (9) = 9.05, $p = 0.432$, $R^2 = 0.008$				
Time	0.02	0.04	0.658	[−0.05, 0.09]
Caucasian	−0.08	0.23	0.719	[−0.53, 0.37]
Hispanic	0.06	0.23	0.785	[−0.38, 0.50]
Age	−0.08	0.04	0.062	[−0.16, 0.00]
Sex(Female)	−0.20	0.18	0.262	[−0.56, 0.15]
T	0.06	0.10	0.544	[−0.13, 0.25]
C	−0.10	0.10	0.332	[−0.29, 0.10]
ΔT	0.09	0.11	0.409	[−0.13, 0.31]
ΔC	−0.11	0.10	0.288	[−0.31, 0.92]
Model 2 LR χ^2 (11) = 16.74, $p = 0.116$, $R^2 = 0.015$				
TxC	−0.25	0.09	**0.007**	[−0.43, −0.07]
ΔTxΔC	0.04	0.09	0.616	[−0.12, 0.21]
Model 3 LR χ^2 (13) = 10.56, $p = 0.648$, $R^2 = 0.009$				
TxSex	−0.14	0.21	0.492	[−0.54, 0.26]
CxSex	0.14	0.20	0.502	[−0.26, 0.53]
ΔTxSex	−0.16	0.25	0.526	[−0.64, 0.33]
ΔCxSex	0.21	0.22	0.337	[−0.22, 0.64]
Model 4 LR χ^2 (17) = 24.35, $p = 0.110$, $R^2 = 0.022$				
TxCxSex	0.01	0.22	0.965	[−0.43, 0.45]
ΔTxΔCxSex	0.68	0.31	**0.027**	[0.08, 1.29]

Note: T = Testosterone, C = Cortisol, Δ = change; R^2 based on pseudo R^2 reported for negative binomial model: p < .05 in bold.

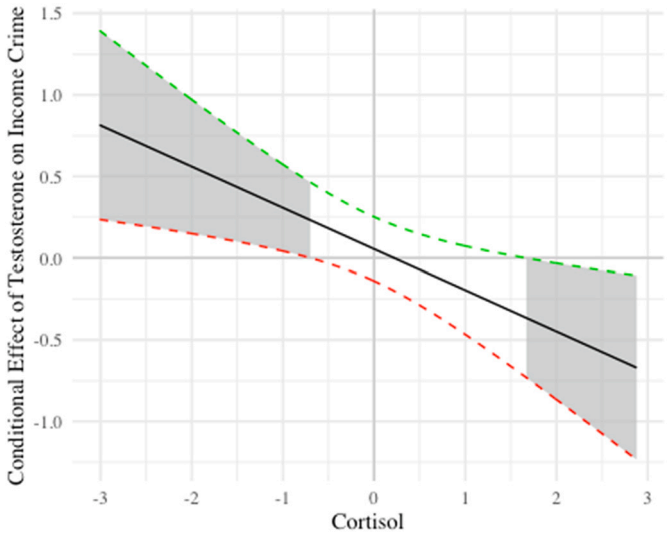

Fig. 1. Testosterone, cortisol and income generating crime
Notes: Hormone values standardized.

0.05) and the difference between Model 3 and Model 4 approached statistical significance (χ^2 difference = 5.78(2), $p < 0.1$).

3.4. Supplemental analyses

Tables with coefficients from the sensitivity analyses are included in the Supplementary Materials file. The positive association between testosterone and impulsive and violent crime in the full sample was again present with the sample restricted to the afternoon ($b = 0.31$, $SE = 0.12$, $p = 0.014$, *95 % CI* [0.06, 0.55]) but not with the sample restricted to the morning ($b = 0.02$, $SE = 0.13$, $p = 0.882$, *95 % CI* [−0.24, −0.28]). The association between cortisol and impulsive and violent crime emerged as statistically significant in the morning ($b = 0.38$, $SE = 0.14$, $p = 0.009$, *95 % CI* [0.09, 0.66]), but was attenuated in the afternoon ($b = 0.02$, $SE = 0.14$, $p = 0.915$, *95 % CI* [−0.26, 0.30]). The negative association between the interaction of testosterone with cortisol and income generating crime approached statistical significance in the morning ($b = -0.20$, $SE = 0.12$, $p = 0.089$, *95 % CI* [−0.43, 0.03]) but not in the afternoon ($b = -0.26$, $SE = 0.17$, $p = 0.129$, *95 % CI* [−0.60, 0.08]). A similar pattern was present for the three-way interaction (sex x change in testosterone x change in cortisol) which showed a trend towards significance in the morning ($b = 0.60$, $SE = 0.33$, $p = 0.071$, *95 % CI* [−0.05, 1.24]), but lacked statistical significance in the afternoon ($b = 0.74$, $SE = 0.64$, $p = 0.247$, *95 % CI* [−0.52, 2.00]).

Supplementary Materials also include a series of regression models testing the interaction between baseline testosterone and change in cortisol (Supplementary Tables 5 and 6). These models were motivated by theory and evidence as outlined in Prasad et al. (2017) and Prasad et al., 2019. The interaction of baseline testosterone with change in cortisol was not related to either crime measure. Interactions between baseline testosterone, change in cortisol, and sex were also not associated with either crime measure. In models testing testosterone by change in cortisol interactions all significant associations between hormones and crime measures present in earlier analyses remained statistically significant.

4. Discussion

4.1. Summary of results

Results show direct positive associations between cortisol and testosterone for impulsive and violent crime but not income generating crime, and interactive associations between testosterone and cortisol for income generating crime but not impulsive and violent crime. Income generating crime was also associated with a three-way interaction between sex, change in cortisol and change in testosterone.

The positive association between testosterone and impulsive and violent crime found in the current study joins prior research showing increases in testosterone are associated with crime in general population samples and research showing testosterone was positively associated with aspects of criminality in incarcerated samples (Booth and Osgood, 1993; Dabbs et al., 1995; Dabbs et al., 1987; Dabbs et al., 1991; Dabbs and Morris, 1990; Ehrenkranz et al., 1974; Kreuz and Rose, 1972). While tentative, the current results and those of prior studies also provide some evidence that the association between testosterone and crime is specific to impulsive and violent criminal behavior (Dabbs et al., 1995; Ehrenkranz et al., 1974; Kreuz and Rose, 1972). In the results presented herein, direct associations between cortisol and crime were also specific to impulsive and violent criminal behavior. The positive association between cortisol and impulsive and violent criminal behavior found in the current study was somewhat surprising as the majority of prior work relating cortisol to criminal and antisocial behavior points to a negative relationship (i.e., Brewer-Smyth et al., 2004; Cima et al., 2008; Fairchild et al., 2018; van Goozen et al., 2007). However, there is also substantive, and with the current results, growing evidence that increased cortisol can be associated with elevated risk for criminal and antisocial behavior (McBurnett et al., 2005; van Bokhoven et al., 2005). The bifurcated pattern of increased risk for criminal behavior at both low and high cortisol may be explained in the context of cortisol as an indicator of stress system activity. Here low cortisol/decreased stress system activity may be associated with hypo-arousal and increased antisocial behavior through stimulation seeking and/or decreased affect and a lack of concern for distress in others (Lykken, 1995; Patrick et al., 1993). In contrast, increased cortisol/stress system activity may be associated with criminal behavior through increased negative affect including depression and anger (Jonsdottir et al., 2012; Kemeny and Shestyuk, 2008).

In addition to direct associations between testosterone, cortisol and crime, the current work also found the interaction of testosterone with

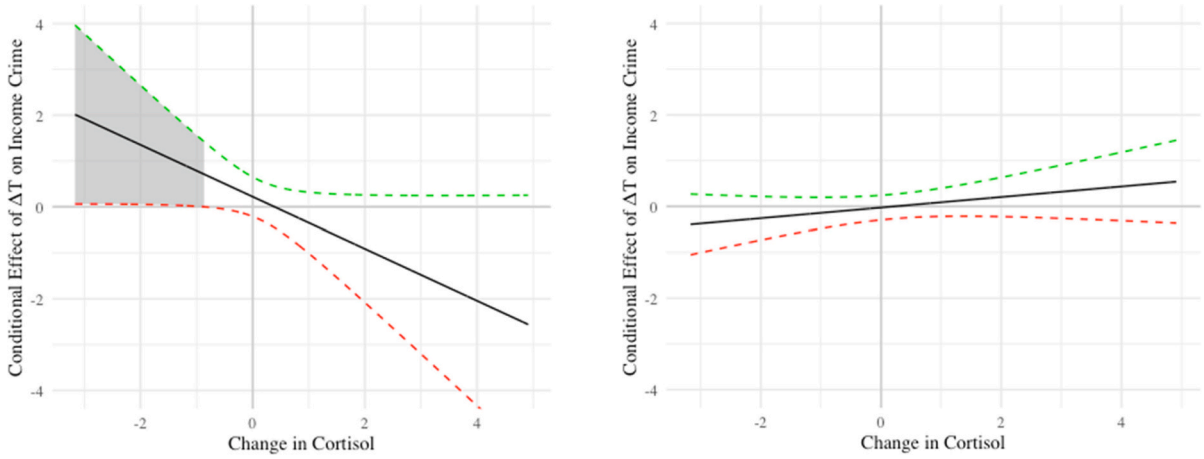

Fig. 2. Sex differences in the association between income generating crime and the interaction of change in testosterone with change in cortisol
Panel A – Men Panel B – Women
Notes: Hormone values standardized; ΔT = change in Testosterone.

cortisol had a negative association with income-generating crime. This interaction was attributable to increases in income-generating crime with testosterone when cortisol was low. This pattern of association is consistent with the dual hormone hypothesis that holds that the positive effects of testosterone on status relevant behaviors is particularly strong at lower levels of cortisol (Mehta and Josephs, 2010; Mehta and Prasad, 2015). In the context of criminal behavior, income-generating crime may be seen as status striving whereas impulsive and violent crime may erode status and thus is not associated with the interaction between testosterone and cortisol. The current results are somewhat parallel to those in the only prior study to test the association between crime and the interaction of testosterone with cortisol. In a sample of incarcerated males, Dabbs et al. (1991) found that violent offenders who were below the median in cortisol had higher testosterone relative to those who were above the median in cortisol. The tendency of violent offenders who were low in cortisol to also have high testosterone may reflect differences in hormones associated with income-generating crime as offenders with convictions for robbery accounted for 52 % of the violent crime group. Thus, the violent crime designation largely captures an offense that is economically motivated.

There was a single interaction between sex and hormone measures in the analyses presented here. In this interaction, change in testosterone was positively associated with income-generating crime among males (when change in cortisol was low), but not females. This offers some indication that the joint effects of testosterone and cortisol have a stronger association with criminal behavior among males. A lack of significant interactions between sex and the direct effects of testosterone on criminal behavior stands somewhat in contrast to recent meta-analytical evidence showing associations between testosterone and aggression are stronger among males than females (Geniole et al., 2019). It is possible that these differences do not extend to criminal behavior or are eroded by the simultaneous consideration of cortisol and both baseline and change measures.

Sensitivity analyses indicated the direct associations between testosterone and cortisol and impulsive and violent crime varied with the time of day that saliva samples for hormone assays were gathered. Caution should be exercised when interpreting these differences. The current study was not designed as a formal test of the influence of time of day for sample collection on associations between hormones and crime. Nonetheless differences appear to be substantive and warrant some discussion. Stronger associations between cortisol and impulsive and violent criminal behavior found in the morning parallel the results of a meta-analysis showing aggressive and externalizing behaviors were associated with cortisol in the morning but not afternoon (Alink et al., 2012). In the current work, variation across the time of day in associations between hormones and the criminal behavior measure may suggest cortisol levels in the morning and/or high testosterone levels in the afternoon have a unique relevance for the explanation of risk for criminal behavior throughout the day. It is possible that high cortisol levels in the morning suppress variation in testosterone that is meaningful for the prediction of criminal behavior. The increases in cortisol occur after awakening and endure throughout the morning are ubiquitous and large in magnitude (Clow et al., 2010; Faiman and Winter, 1971; Rose et al., 1972; Zhang et al., 2017). A negative association between cortisol and testosterone is indicated by work showing that increases in cortisol with exercise and exogenous cortisol administration both lead to decreases in testosterone (Cumming et al., 1983; Brownlee et al., 2005). Variation in testosterone relevant to criminal behavior may then emerge in the afternoon as cortisol levels drop. Thus, differences in associations across the time of day at which samples may not be indicative of time specific associations between hormones and criminal behavior types, but rather evidence of change in the predictive efficacy of hormone measures across the time of day due to the interplay between testosterone and cortisol. Nonetheless, it is possible that our results are influenced by self-selection. Our study was not directly designed to investigate differences in associations between hormones and crime across time of day and participants were allowed to select when they attended the lab. Thus, it is possible that the tendency to select a particular time of day is confounded in some way with both hormone levels and the crime measure. In any case, the current results demonstrate the need for research directly designed to parse the role of time of day in associations between hormones and antisocial behavior in general and crime in specific.

The implications of the current work for our understanding of the role of hormones in the explanation of criminal behavior is conditioned by aspects of the study's methodology. There is some question as to the efficacy of enzyme-linked immunoassays of saliva samples to determine hormone levels. Enzyme linked immunoassays may overestimate testosterone levels (Taieb et al., 2003) and the correlation between salivary testosterone levels and serum testosterone is stronger among men than women (Shirtcliff et al., 2002). The potential influence of the method used to determine hormone concentrations on associations between hormones and criminal behavior is also indirectly indicated by evidence of cross-method variation (enzyme-linked immunoassays

versus liquid chromatography tandem mass spectrometry) in the association between testosterone, cortisol, and psychopathic traits (Prasad et al., 2019b; Roy et al., 2019; Welker et al., 2016). Despite this, studies using enzyme-lined immunoassays to estimate hormone levels provide meaningful evidence regarding the association between hormones and criminal behavior, particularly when work considering the joint influence of testosterone and cortisol on criminal behavior is rare (Granger et al., 2004). Enzyme-lined immunoassays are also particularly useful for the development of large samples such as the one used here.

The lack of association between hormone change scores and criminal behavior in the current work may be attributable to the choice of stressor used to induce hormones changes. Stressors that are outside the control of the participant and include direct threat of negative social evaluation are associated with larger changes in cortisol (Dickerson and Kemeny, 2004). In the stressor used here, the threat of negative social evaluation was indirect when subjects were told that the recording of their speech would be evaluated later, and the task, while embarrassing, was largely within the subject's control. Thus, a stressor with direct negative social evaluation where the task was outside of the subject's control may have induced larger changes in cortisol, potentially strengthening the association between change in cortisol and crime measures. Similarly, stressors including provocations that are likely to illicit and aggressive response may result in changes in testosterone that have a stronger relationship with impulsive and violent criminal behaviors. Prior work has shown considerable variation in change across conditions potentially impacting testosterone levels. In general, athletic competition tends to induce increases in testosterone, but non-athletic competition and other conditions in laboratory studies induce varying changes including decreases in testosterone (Casto and Edwards, 2016). It is also possible that the short rest period built into the laboratory protocol resulted in baseline hormone measures that were influenced by the laboratory experience itself or by stimuli occurring shortly before arrival at the lab. A longer rest period may result in baseline hormone measures with less error and change scores more directly reflecting change uniquely attributable to social stress.

The pattern of associations between hormone measures and criminal behavior found in the current work may also be influenced by the use of self-report measures of crime. Work testing the association between testosterone and aggressive behavior indicates associations with self-report measures are weaker than those with laboratory measures (Geniole et al., 2019). The implications of this difference are somewhat tangential to studies concerned with the association between hormones and crime as basic laboratory measures of serious criminal behavior are clearly out of the question. However, laboratory measures that parallel criminal behavior and measures that are more proximal to the collection of hormone measures themselves may serve to more accurately specify the association between hormones and crime. In addition, the data used in the current study are cross-sectional rather than longitudinal and therefore associations between hormones and criminal behavior measures are not necessarily causal. In addition, cross-sectional data do not allow the specification of the directionality of effects and some of the associations in the current study may be due to the influence of criminal activity on hormone levels. Finally, participants were not asked about oral contraceptive use. Oral contraceptives reduce testosterone and may be related to cortisol response to stress (Nielsen et al., 2013; Zimmerman et al., 2014). Should oral contraceptive use also be related to the criminal behavior measures used in the current analyses, a lack of control for oral contraceptive use may explain associations present in the current work.

5. Conclusion

The current study provides additional evidence that hormones play a role in the etiology of criminal behavior. Collectively, work in this area points to a positive direct association between testosterone and criminal behavior and also suggests that both high cortisol and low cortisol may increase risk for criminal behavior. A more circumscribed body of research indicates that testosterone and cortisol may interact to influence criminal behavior with the positive association between testosterone and crime stronger when cortisol is low. Future efforts to understand the role of hormones in the explanation of criminal behavior may benefit from a consideration of associations between hormones and other biological substrates associated with criminal behavior and associations between hormones and traits related to antisocial and criminal behavior. Such a consideration may further inform the theoretical framework that suggests criminal propensity mediates the association between hormones and crime by specifying the traits that are associated with both variation in hormones, and increased risk for criminal behavior.

Funding

This study was supported by an Enhancement Grant for Professional Development from the Office of Research and Sponsored Programs at Sam Houston State University. Additional support was provided by an internal grant from the College of Criminal Justice at Sam Houston State University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yhbeh.2022.105260.

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