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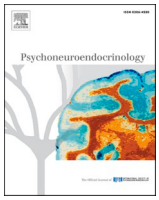

Cortisol and testosterone jointly affect adolescent fairness

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ABSTRACT

Fairness is crucial in social interactions, shaping relationships and fostering cooperation, especially during adolescence. The developmental period, characterized by significant hormonal changes such as fluctuations in cortisol and testosterone levels, is pivotal for physiological and behavioral maturation. Despite the importance of the hormones, studies investigating their interaction effects on fairness within adolescent populations remain limited. The current study explored adolescent fairness development and how cortisol (bedtime basal cortisol and cortisol awakening response, CAR) and testosterone interacted in strategic and pure fairness towards friends and strangers, using adapted versions of the Ultimatum Game (UG) and Dictator Game (DG), separately, in 381 typically developing adolescents (37 % female, M_{age} = 14.6 years, SD_{age} = 1.95). As adolescents matured, they increasingly favored friends over strangers in both strategic and pure fairness decision-making. Testosterone was positively associated with allocation differences in strategic fairness only at high bedtime basal cortisol levels. Additionally, testosterone was positively correlated with allocation differences in strategic fairness at low CAR levels but negatively at high CAR levels. This hormonal pattern was observed only in male adolescents. These findings underscore sex-specific patterns in dual-hormonal influences on adolescent fairness decisions and highlight the role of physiological hormones in the development of moral values in distinct ways for males and females.

1. Introduction

Fairness is fundamental to social interactions, influencing relationships, cooperation, and societal harmony (Brosnan and de Waal, 2014). During adolescence, individuals face increasingly complex social situations and need to develop mature societal values and social relationships (Crone and Fuligni, 2020), in which fairness and equity play pivotal roles (Güroğlu et al., 2009; Steinbeis et al., 2012). Adolescence is a critical developmental period marked by significant hormonal changes and maturation of neural circuits involved in social cognition and behavior (Andrews et al., 2021; Chaku and Barry, 2023; Laube et al., 2020; Nelson et al., 2016; Vijayakumar et al., 2018). The pubertal hormones, cortisol and testosterone, known for their effects on stress and social status/dominance respectively, have been proposed to influence various social behaviors, including fairness (Nguyen et al., 2017; Prasad et al., 2019; Sinclair et al., 2014; Sisk and Zehr, 2005). However, the specific mechanisms through which these two hormones interact to influence fairness-related behaviors during adolescence have not been thoroughly investigated.

The HPA and HPG axes are commonly perceived as mutually inhibitory systems, with the dual-hormone hypothesis suggesting that the behavioral effects of cortisol and testosterone are suppressed by the other hormone (Mehta and Josephs, 2010; Mehta and Prasad, 2015). Although the precise mechanisms for dual-hormone effects remain unclear, evidence across psychological, neurological, and molecular levels provides plausible mechanisms supporting this hypothesis. Psychologically, cortisol and testosterone operate within opposed motivational systems (Carver and White, 1994), with cortisol being associated with submission and social withdrawal (Bernard et al., 2015; van der Westhuizen and Solms, 2015), while testosterone is linked to approach

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behavior (Platje et al., 2015). Correspondingly, at the neural level, testosterone enhances reward-seeking behavior by activating the nucleus accumbens in rodents (de Souza Silva et al., 2009) and increasing neural activity in the human ventral striatum associated with reward anticipation (Hermans et al., 2010). In contrast, cortisol is related to decreased activity in reward-related networks (Kinner et al., 2016). At the molecular level, elevated cortisol levels suppress the HPG axis at multiple levels. This suppression includes inhibiting gonadotropin-releasing hormone neurons in the hypothalamus, reducing the release of luteinizing hormone and follicle-stimulating hormone from the pituitary gland, and decreasing gonadal hormone production (Dorn and Biro, 2011; Trotman et al., 2013). Conversely, androgens can suppress HPA axis function by acting on the androgen receptor or ERbeta (Handa and Weiser, 2014). Existing research on adult samples has substantiated the dual-hormone hypothesis across various domains, including status-related behaviors such as dominance, risk-taking, aggression, and psychopathy (Dekkers et al., 2019; Manigault et al., 2019; Mehta et al., 2015), as well as social cognition and decisions like emotion recognition (Lausen et al., 2020), fairness (Prasad et al., 2017, 2019), and empathy (Nitschke and Bartz, 2020; Zilioli et al., 2015).

Despite several strands of theoretical and empirical evidence supporting the dual-hormone hypothesis, some researchers argue that HPA and HPG do not necessarily operate in opposition, but can function together in specific contexts, moments and developmental stages (like adolescence) (Knight et al., 2022; Marceau et al., 2012; Shirtcliff et al., 2015). Shirtcliff et al. (2015) propose that the observed crosstalk function between these axes in adults may not fully apply to adolescents. Instead, adolescence appears to present a temporary and unique pattern of neuroendocrine coupling. This unique HPA-HPG hormone coupling pattern aligns with the coexistence of "storm and stress" and "sex/romance" characteristics during adolescence (McClintock and Herdt, 1996). Furthermore, the two axes are characterized by increased activity during prenatal and postnatal development, dormancy during childhood, and reactivation during adolescence. Both cortisol and testosterone typically rise across puberty (Ruttle et al., 2015). If an increase in one hormone automatically leads to a decrease in the other, even if this inhibition is minimal, then stress exposure will be associated with delayed/slowed puberty or reduced HPG function, but usually the opposite is the case (Ellis, 2004; Ellis and Del Giudice, 2019). Exposure to early life stressors typically heightens gonadal functioning and advances puberty (Ellis and Essex, 2007; Ellis and Garber, 2000). Similar to adulthood, where a mutually inhibitory relationship exists between the sex and stress axes, i.e., stress inhibits reproduction, due to the potential loss or death of offspring during stressful periods, the unique coupling pattern during adolescence is also adaptive (Dekkers et al., 2019; Hamilton et al., 2015). Ellis (2004) describes the inter-related Child Development Theories and highlights the role of environmental factors such as Extrinsic Morbidity-Mortality cues and Unpredictability/Instability in accelerating reproductive maturation, towards a fast Life History trajectory favoring early development. In stable and safe environments, childhood duration extends to facilitate learning, skill development, and growth, with minimal costs to delaying reproductive maturation. Conversely, uncertain or challenging environments shift trade-offs towards shorter, faster reproductive life spans, and the accelerated transition into adulthood is also better for individual survival (Belsky et al., 1991; Ellis et al., 2011; Ellis and Garber, 2000). Additionally, animal research indicates that simultaneous increases in testosterone and cortisol levels play functional roles, particularly in enhancing reproductive preparedness among males during the breeding season and when establishing social dominance (Lynch et al., 2002). Existing research on dual-hormone effects in adolescents has predominantly focused on the molecular level, with few studies addressing their impact on adolescent behaviors, especially social behaviors (Harden et al., 2016; Wang et al., 2022).

In the present study, we investigated the interaction of cortisol and testosterone on adolescent fairness (both strategic and pure fairness) using the Ultimatum Game (UG) and the Dictator Game (DG), respectively. In both games, one player decided how to split a fixed number of resources between themselves and another player. What set the two games apart was the second player's role. In the UG, the responder could reject the offer, meaning neither player received anything. In the DG, the recipient had no say and had to accept whatever was given. This key difference made it possible to tease apart different motivations behind fair behavior. The UG was typically used to assess "strategic fairness", as proposers had to consider the possibility of rejection and often offered more equitable splits to ensure acceptance (Yamagishi et al., 2016). The DG, on the other hand, served as a measure of "pure fairness", since proposers were not constrained by external consequences and could allocate resources solely based on internalized norms or personal preferences (Güroğlu et al., 2009). The UG introduced social and strategic pressures that shaped decision-making in ways not present in the DG. Because proposers in the UG risked receiving nothing if their offer was declined, they often adjusted their allocations to account for the responder's anticipated reaction. In this sense, the UG engaged a more interdependent form of decision-making, where individuals acted with regard to others' perspectives and potential responses. Conversely, the DG reflected a more independent mode of reasoning, as proposers made decisions in isolation from external input and solely according to their own values (Liu et al., 2024). Together, the UG and DG provided a comprehensive framework for studying the development of distributive fairness among adolescents. Previous developmental research using these paradigms highlighted age-related differences in fairness motivation. For instance, Güroğlu et al.(2009) found that in the DG, participants across age groups consistently chose self-serving offers, suggesting little developmental change in fairness when rejection was not possible. In contrast, in the UG, older adolescents made more equitable offers, indicating increased perspective-taking and social reasoning with age. While strategic and pure fairness paradigms illuminate underlying motivational processes, they do not operate in a social vacuum. Adolescents' fairness-related decisions are not only shaped by social cognitive development and strategic reasoning but are also profoundly influenced by social affiliations and identity-related factors. Emerging evidence suggests that as adolescents grow, their fairness behaviors become more selective, reflecting parochial tendencies whereby equitable treatment is more likely extended to socially close or in-group members than to distant others or out-group members (Angerer et al., 2017; Bindra et al., 2020; Fehr et al., 2013). Fehr et al. (2013) further found sex differences in fair behaviors, with girls aged 11 and 17 being significantly more egalitarian than boys, with this difference increasing with age. Sutter et al. (2019) summarized experimental economics behaviors of children and adolescents and also found that females are more inclined to make egalitarian decisions, while males tended to prioritize efficiency and parochialism. The male-warrior hypothesis helped explain this pattern, suggesting that boys were more likely to exhibit parochial behaviors due to the evolutionary history of male cooperation, which was shaped by violent intergroup conflicts that fostered a coalitional (us versus them) mindset (Lazić et al., 2021; McDonald et al., 2012; Vugt et al., 2007). Therefore, our study investigated the development of strategic and pure fairness during adolescence with both close peers (e.g., friends) and relatively distant peers (e.g., strangers), alongside exploring sex differences and potential dual-hormonal mechanisms involved.

Regarding hormonal measures, basal testosterone concentrations were used to index HPG-axis activity. For the HPA axis, we measured both basal cortisol concentrations and the cortisol awakening response (CAR), two well-established indicators of stress-related physiological activity (Tian et al., 2021; Wang et al., 2022; Zhu et al., 2019). Cortisol, the end product of the HPA axis and commonly referred to as the "stress hormone", played a central role in the body's response to stress and was widely used as a biomarker in psychoneuroendocrinological research. Its secretion followed a distinct diurnal rhythm, characterized by

relatively stable basal levels in the evening and low-level nocturnal activity during sleep, which together reflected tonic aspects of HPA axis functioning. Superimposed on the rhythm was the CAR, a sharp and transient increase in cortisol levels occurring approximately 30 min after morning awakening (Pruessner et al., 2003; Schmidt-Reinwald et al., 1999). The CAR was understood as a preparatory mobilization of neuroendocrine resources in anticipation of the demands of the upcoming day (Elder et al., 2014; Fries et al., 2009; Stalder et al., 2025). In the current study, we focused on two specific cortisol-based indices: bedtime basal cortisol, which reflected trait-like aspects of HPA axis regulation and chronic stress load, and CAR, which served as a psychophysiological indicator of HPA axis reactivity and flexibility. Elevated basal cortisol has been associated with chronic stress exposure, while blunted or exaggerated CAR responses have been implicated in the pathophysiology of various mood and anxiety disorders (Hardeveld et al., 2014; Rauch et al., 2020; Zhu et al., 2019). Furthermore, longitudinal research suggested that CAR levels remained relatively stable across adolescence, with consistent sex differences showing higher CAR levels in girls compared to boys (Kuhlman et al., 2019; Platje et al., 2013). In the present study, we examined the interactive effects of testosterone with basal cortisol and with CAR on adolescents' strategic and pure fairness.

In summary, our study systematically examined: (1) the effects of age-related changes and sex differences on adolescent fairness towards friends and strangers in the UG and DG; (2) how testosterone and cortisol (both basal cortisol and CAR) independently and interactively influenced adolescent fairness; and (3) whether sex moderated the interaction between cortisol and testosterone in relation to fairness. Building upon the previous findings outlined above, we anticipated that adolescents would show greater fairness towards friends compared to strangers, and that this parochial fairness would increase with age. We also expected to observe sex differences in parochial fairness decision-making and the underlying hormonal mechanisms. Furthermore, while previous dual-hormone hypothesis research has posited that cortisol attenuates the behavioral influence of testosterone, especially in socially dominant or aggressive contexts, we anticipated that this interaction may differ in adolescence. Specifically, drawing on emerging neuroendocrine evidence that adolescence is characterized by a transient pattern of HPA-HPG axis coupling (Harden et al., 2016; Shirtcliff et al., 2015), we hypothesized that this developmental phenomenon may modulate or even reverse the traditional dual-hormone hypothesis effect in social decision-making contexts such as fairness.

2. Methods

2.1. Participants

Our sample included 381 typically developing adolescents (age range = 10–17 years; $M = 14.6$, $SD = 1.95$), who had no history of neurological or psychiatric illness, no current use of any medication or drugs, and no major exams within a week. Participants who failed to complete both trials of the UG and DG tasks were excluded from the analysis. Given that each game involved only two trials (one with a friend and one with a stranger), participants who missed more than one trial were excluded. Specifically, one participant was excluded from the UG due to missing both trials, leaving a final sample of 380 participants (36.84 % female, 63.16 % male) with a mean age of 14.49 years (SD = 1.97, range: 11–17). In the DG, six participants were excluded due to missing both trials, resulting in a final sample of 375 participants (37.07 % female, 62.93 % male) with a mean age of 14.49 years (SD = 1.97, range: 11–17). The mean age of male participants was significantly higher than that of female participants (UG: t (378) = 3.35, $p < 0.001$, *Cohen's d* = 0.36; DG: t (373) = 3.24, $p < 0.001$, *Cohen's d* = 0.35). The experimental protocol was approved by the ethical committee at Beijing Normal University. Written informed consent was obtained from participants and their parents.

2.2. Salivary cortisol and testosterone collection and analysis

Participants and their parents were provided with comprehensive written instructions and precautions for saliva collection, along with Salivette collection devices (Sarstedt, Nümbrecht, Germany). Additionally, participants received verbal guidance and practical training on the proper procedure for collecting saliva samples while at school. They were instructed to obtain five saliva samples, with parental assistance if necessary: one sample before bedtime in the evening (S0), and the remaining four samples collected immediately upon awakening the following morning (S1), followed by subsequent samples at 15-minute (S2), 30-minute (S3), and 60-minute (S4) intervals thereafter. To ensure the reliability of salivary data, participants were instructed to adhere to specific sleep patterns, aiming to fall asleep before 11:30 p.m. and wake up after 5 a.m., averaging 7.5 h of sleep per day, in the week leading up to the experiment. They were also asked not to brush teeth, smoke, drink, eat or exercise excessively for at least 60 min before sampling. Upon collection, the samples were taken back to the school by the participants and then transported back to the laboratory with dry ice, where they were kept at −80°C until assay. Samples were excluded from further analysis if participants reported any form of illness (such as periodontitis, fever, or endocrine diseases), had taken medication, especially hormone medications, within the preceding two weeks, were in close proximity to their menstrual cycle (for female participants), or failed to adhere strictly to the designated sampling times.

The samples were thawed and centrifuged at 3500 rpm for 5 min. Salivary testosterone levels were assessed using an enzyme-linked immunoassay kit developed for saliva (Salimetrics, State College, PA), featuring a sensitivity of 0.500 nmol/L (lower limit). The assay's standard range spanned from 0.5 to 1750 nmol/L testosterone. Due to limited sample volume, we did not assess assay precision. Salivary cortisol concentrations were analyzed by use of electrochemiluminescence immunoassay (Cobas e 601, Roche Diagnostics, Nümbrecht, Germany), with the following parameters: sensitivity, 0.500 nmol/L (lower limit), and standard range in the assay, 0.5–1750 nmol/L. Intra- and inter-assay coefficient variations were 6.25 % and 8.33 %, respectively.

Testosterone levels were derived from the pre-bedtime sample (S0) to assess HPG-axis activity. Testosterone follows a circadian rhythm, peaking in the morning and declining throughout the day to its lowest point in the evening (Bremner et al., 1983; Kuzawa et al., 2016). The pre-bedtime sample reflects this evening nadir and has been shown to be a stable indicator of basal testosterone (Wang et al., 2022). Basal cortisol levels were also assessed from the pre-bedtime sample (S0). Cortisol follows a similar rhythm, with a rapid increase upon awakening (CAR) and a gradual decline to a stable low in the evening (Endler and Kocovski, 2001; Gunnar and Cheatham, 2003). Evening cortisol levels have been used as a reliable proxy for basal cortisol (Tarullo et al., 2020; Tian et al., 2021; Wang et al., 2022; Zhu et al., 2019). The calculation of the area under the curve (AUC) based on four points in the morning served as an indicator of the CAR, computed as follows:

$$\text{CAR} = \text{AUCi} = (\text{S1} + \text{S2}) \times 0.25/2 + (\text{S2} + \text{S3}) \times 0.25/2 + (\text{S3} + \text{S4}) \times 0.5/2 - \text{S1} \times (0.25 + 0.25 + 0.5)$$

The missing hormone data (no missing data for testosterone; 22 missing data for S0 and S1, 24 for S2 and S3, and 26 for S4) were interpolated using the mean value for each sampling point. Following mean imputation, we assessed the normality of hormonal indicators (testosterone, basal cortisol and CAR). Raw hormonal data were log-transformed to adjust for skew (Table S1). Prior to commencing formal data analysis, z-transformation was conducted on hormonal indicators based on sex-specific concentration differences (Table S2). Specifically, CAR and testosterone were z-transformed within sex groups to account for the observed disparities, whereas basal cortisol, unaffected by sex differences, underwent direct z-transformation across the

entire dataset.

2.3. Psychological tasks

2.3.1. Ultimatum game (UG)

This task was adapted from the classic Ultimatum Game (UG) (Güth et al., 1982), which could be used to measure strategy fairness (Fehr and Gintis, 2007). In the current version of the UG (Fig. 1A), participants played as the proposer and needed to divide 10 tokens between themselves and a responder, who could choose to accept or reject the offer. If the responder accepted the proposal, the tokens were divided according to the proposer's suggestion. However, if the responder rejected the proposal, neither player received any tokens. Each participant completed two rounds of the UG, once with a friend and once with a stranger, with the order randomized. Importantly, participants did not receive feedback on whether their offers were accepted or rejected. Compensation was performance-based, with the final reward value determined by the number of tokens participants retained across the games.

2.3.2. Dictator game (DG)

This task was derived from the classic Dictator Game (DG), where the dictator's decision served as a measure of pure fairness (Kahneman et al., 1986). In the adapted version of the DG (Fig. 1B), participants acted as the dictator and were tasked with dividing 10 tokens between themselves and another player (the receiver); however, different from the UG, the receiver had to accept the dictator's allocation. Participants completed two rounds of the DG, one with a friend and one with a stranger, with the order randomized. As in the UG, compensation was performance-based, determined by the number of tokens participants retained across the games.

2.4. Statistical analysis

In exploring the development of fairness decision-making in adolescents, we initially performed Spearman correlations between age and various fairness indicators. These indicators included the amounts allocated to the friend and stranger, as well as the allocation differences (friend minus stranger, used as the indicator of the effect of social distance on corresponding fairness) in the UG (strategic fairness) and DG (pure fairness). Furthermore, to understand the influence of social distance and sex on fairness, we conducted separate mixed two-way repeated-measures ANOVAs on strategic and pure fairness. Here, sex (female, male) served as a between-subject variable, while social distance (friend, stranger) acted as a within-subject variable.

We then conducted initial analyses on adolescents' cortisol diurnal patterns using repeated-measures ANOVAs, considering sampling time as a within-subject factor, sex as a between-subject factor, and age as a covariate. Additionally, we examined sex differences in testosterone concentrations using independent-sample t-tests. To investigate the separate impacts of the HPA axis and the HPG axis on adolescents' fair behaviors, we conducted a series of regression analyses. The dependent variables in these models included the amount allocated to the friend and stranger, as well as the allocation differences (friend minus stranger), in both the UG and DG. Initially, we entered HPA axis indices (basal cortisol and CAR) and testosterone as predictors in separate regression models, with biological sex (coded as male = 1; female = 0) and age as covariates. Subsequently, to explore the interaction between cortisol and testosterone on fairness decision-making, we separately regressed the indexes of the HPA axis, testosterone and their interaction term (mean-centered) on fairness indicators, with sex and age as covariates. We then conducted further exploratory analyses to examine whether sex moderated the relationship among fairness, testosterone and cortisol, incorporating two-way interactions of cortisol × sex and testosterone × sex, and the three-way interaction of cortisol × testosterone × sex to the multiple regression models. Simple slope analyses were performed following statistically significant interactions (±1 SD). While our primary goal was to explore how hormonal indices predict allocation to each target and the allocation difference (as an index of the effect of social distance on fairness), we also performed linear mixed-effects models (LMMs) using the *lme4* package (Douglas Bates et al., 2015) to account for the within-subject nature of the social distance manipulation (friend vs. stranger) and served as a robustness check for the main regression analyses. These models included social distance, basal cortisol (or CAR), testosterone, and their interactions as fixed effects, with sex and age as covariates and participant as a random intercept. We further expanded these models to include sex and its two-way and three-way interactions with cortisol (or CAR) and testosterone, again controlling for age. The LMMs were conducted separately for the UG and DG, and the results are presented in Supplementary Tables S11–S14, which correspond to the main regression results reported in Tables S6–S9. The findings from the LMMs were consistent with the main regression analyses, confirming the robustness of the hormonal effects on fairness.

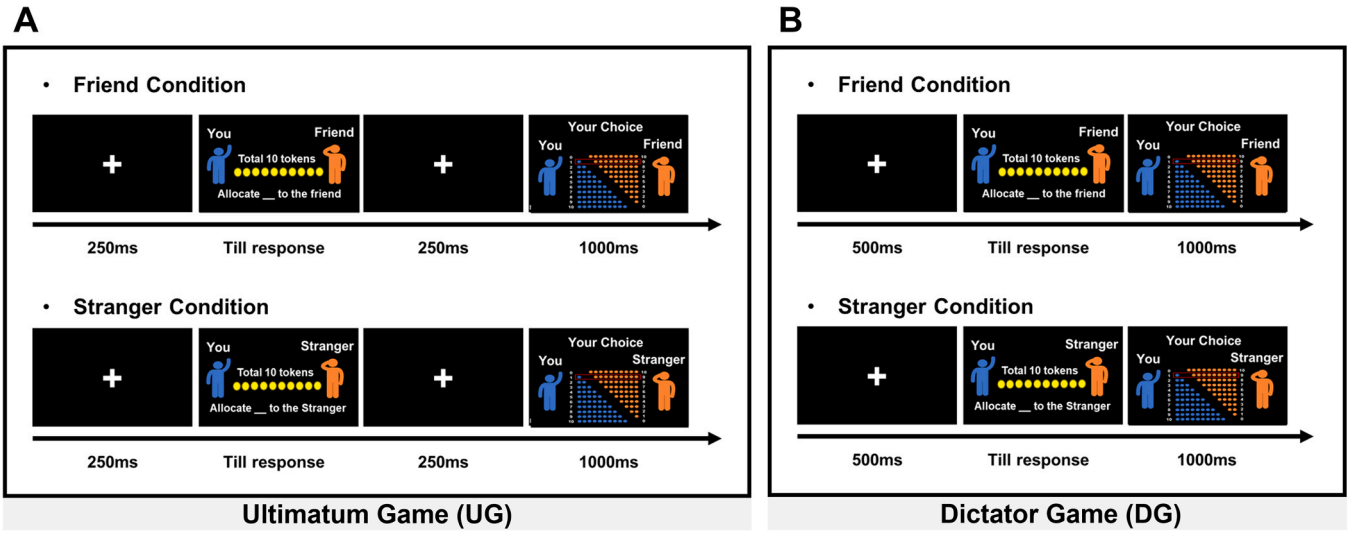

Fig. 1. Example trials of the ultimatum game (UG) and dictator game (DG). The sequence of events and timing in a trial when participants acted as proposers in the UG (A), playing either with a friend (top row) or a stranger (an unknown peer, bottom row), and as dictators in the DG (B), also playing either with a friend (top row) or a stranger (an unknown peer, bottom row). (derived from Su et al., 2020).

All statistical analyses were conducted using the SPSS (version 25, Chicago, IL, USA) and R (v.4.1.1). Greenhouse-Geisser correction was applied when the assumption of sphericity was violated in repeated-measures ANOVAs. Bonferroni correction was used for post-hoc pairwise comparisons following ANOVAs. To account for multiple comparisons in correlational and regression analyses, false discovery rate (FDR) correction was applied using the Benjamini-Hochberg procedure. FDR-adjusted p-values (p_{FDR}) are reported where applicable.

3. Results

3.1. Effects of social distance on adolescents' fairness

As adolescents matured, they paid more attention to social distance information when making strategic (*rho* = 0.3, $p < 0.001$, $p_{FDR} < 0.01$) and pure fair decisions (*rho* = 0.1, $p = 0.05$, statistical marginal significance, $p_{FDR} = 0.15$). The amounts allocated to friends and strangers were not significantly correlated with age in either strategic or pure fairness ($ps > 0.07$).

To further explore the influence of social distance and sex on adolescents' fairness, we conducted separate mixed two-way repeated-measures ANOVAs on strategic and pure fairness, with sex (female, male) as a between-subject variable, social distance (friend, stranger) as a within-subject variable (Fig. 2). Regarding strategic fairness, the analysis revealed a significant main effect of social distance, (F (1, 378) = 35.5, $p < 0.001$, *partial* $\eta^2 = 0.09$, $\omega^2 = 0.02$), indicating that the amount allocated to friends was significantly greater than that allocated to strangers. However, neither the main effect of sex nor the interaction between sex and social distance was significant ($ps > 0.22$). In terms of pure fairness, the results demonstrated a significant main effect of social distance (F (1, 373) = 98.1, $p < 0.001$, *partial* $\eta^2 = 0.21$, $\omega^2 = 0.07$), with the amount allocated to friends significantly exceeding that allocated to strangers. Similar to strategic fairness, neither the main effect of sex nor the interaction was significant ($ps > 0.17$).

Overall, as adolescents matured, they paid more attention to social distance information when making strategic and pure fairness decisions, while sex had no significant impact on fairness behavior. Notably, although both games revealed significant main effects of social distance, the effect size was substantially larger in the DG than in the UG. This suggests that social distance may exert a stronger influence on pure fairness than on strategic fairness, possibly reflecting less normative or strategic modulation in the former context.

3.2. Preliminary analyses of adolescents' cortisol and testosterone

Cortisol levels as a function of sampling time points (i.e., S0, S1, S2, S3, and S4) are shown in Fig. 3A. Repeated-measures analyses of variance with sampling time as a within-subject factor, sex as a between-subject factor, and age as a covariate for cortisol data demonstrated a significant main effect of time (F (2.75, 1035.73) = 14.28, $p < 0.001$, *partial* $\eta^2 = 0.04$, $\omega^2 = 0.02$), a significant main effect of sex (F (1, 377) = 18.69, $p < 0.001$, *partial* $\eta^2 = 0.05$, $\omega^2 = 0.02$) and a significant interaction effect of time × sex (F (2.75, 1035.73) = 6.39, $p < 0.001$, *partial* $\eta^2 = 0.02$, $\omega^2 = 0.01$). Participants exhibited a notable increase in cortisol responses from pre-bedtime (S0, basal cortisol) to immediate awakening in the morning (S1). Subsequently, cortisol levels continued to increase (S2) and peaked approximately 30 min later (S3), followed by a rapid decline 60 min after awakening (S4), observed consistently across both sexes. Further post-hoc analyses revealed that the pre-bedtime cortisol level was significantly lower than cortisol levels at all other four points the following morning for both sexes ($ps < 0.001$ for all other four points, Bonferroni corrected). Independent-sample t-tests were also conducted to examine potential sex differences in testosterone, CAR and cortisol levels at five sampling time points. These analyses revealed no significant differences between the sexes in their cortisol levels at pre-bedtime (S0, basal cortisol) and immediate awakening (S1, Table S2), $ps > 0.30$. However, male adolescents compared with female ones showed lower cortisol awaken responses and morning cortisol increases (CAR, S2, S3, and S4; Table S1 and S2; t_{CAR} (378) = -2.27, $p < 0.05$, *Cohen's d* = -0.24; t_{S2} (378) = -3.2, $p < 0.01$, *Cohen's d* = -0.34; t_{S3} (378) = -3.04, $p < 0.01$, *Cohen's d* = -0.32; t_{S4} (378) = -2.47, $p < 0.05$, *Cohen's d* = -0.26). The findings revealed prominent diurnal dynamics of the HPA-axis system in adolescents, featuring lower basal cortisol levels before sleep and elevated CAR in the morning, observed consistently across both sexes. Notably, CAR elevation was more evident in female adolescents than in males. Additionally, males demonstrated significantly higher testosterone concentrations compared to females (Fig. 3B; t (378) = 2.45, $p < 0.05$, *Cohen's d* = 0.26).

Overall, cortisol levels exhibited significant diurnal variations in adolescents, with a notable increase from pre-bedtime to immediate awakening, and while both sexes showed similar patterns, female adolescents had higher CAR, while males had significantly higher testosterone levels.

3.3. Separate effects of cortisol and testosterone on adolescents' fairness

We initially conducted several regressions to explore the separate influences of cortisol and testosterone on adolescents' strategic fairness and pure fairness, with sex and age as covariates. The results showed that basal cortisol was positively related to the amounts allocated to the friends in UG ($B = 0.12$, F (1, 376) = 5.29, $p < 0.05$, *partial* $\eta^2 = 0.02$,

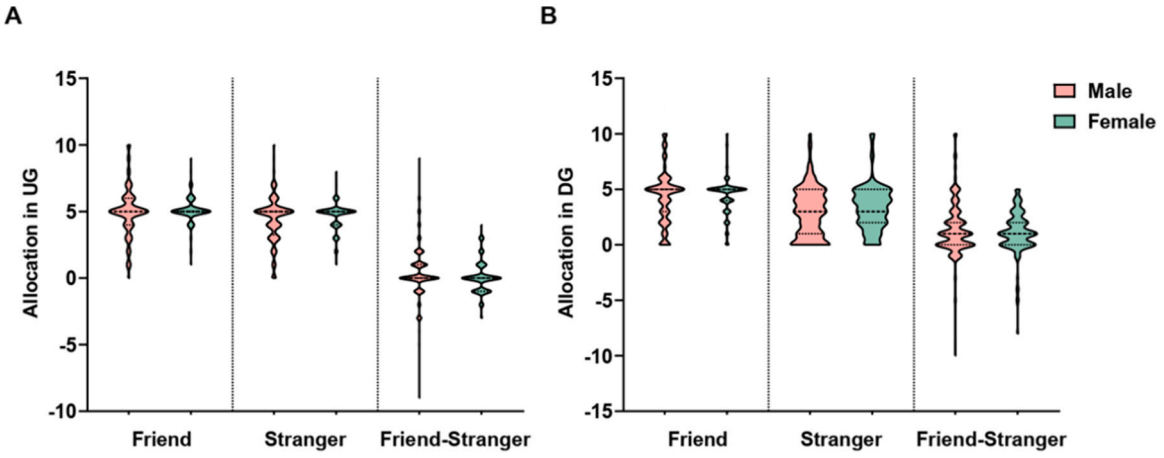

Fig. 2. Allocations to friends and strangers by different sexes in the Ultimatum Game (UG, A) and Dictator Game (DG, B). Adolescents exhibited evident parochial fairness in both the UG and DG. Error bars indicate the standard error of the mean (s.e.m.).

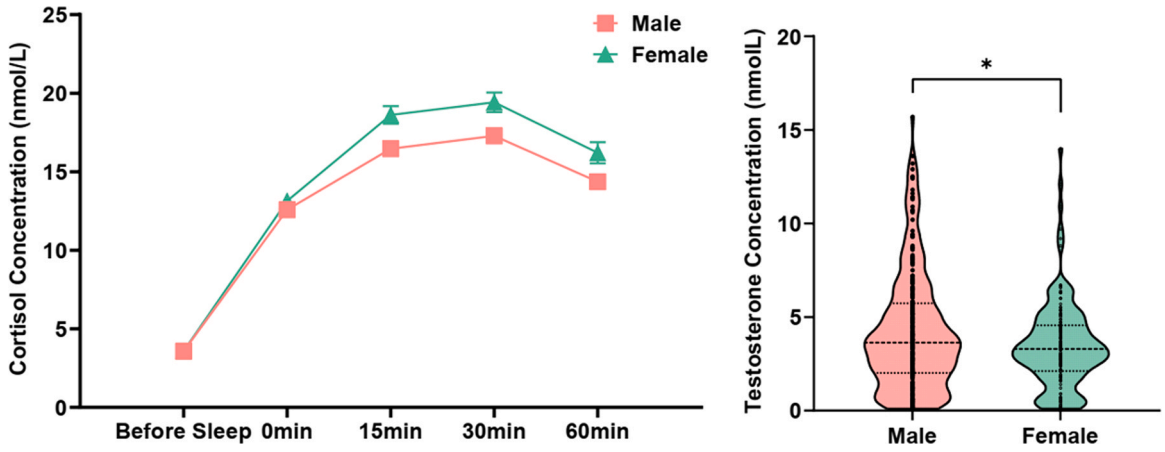

Fig. 3. Salivary cortisol and testosterone levels. (A) Average cortisol levels as a function of sampling time points for participants of different sexes. The x-axis represents five saliva sampling time points: pre-bedtime during the night; immediately after awakening (0 min); and 15 min, 30 min, and 60 min post-awakening. the y-axis represents salivary cortisol concentration (nmol/L). Females exhibited a higher cortisol awakening response (CAR) compared to males, whereas no significant difference in basal cortisol levels was observed between sexes. (B) Testosterone concentration differences between Male and Female adolescents. Male adolescents had significantly higher testosterone concentrations than female adolescents. Error bars indicate the standard error of the mean (s.e.m.). $^*p < 0.05$.

$p_{FDR} = 0.4$). Testosterone was negatively correlated to the amount allocated to friends in DG ($B = -0.1$, $F\,(1, 341) = 3.43$, $p = 0.07$, *partial* $\eta^2 = 0.01$, marginal significance, $p_{FDR} = 0.39$). Other effects were not significant ($ps > 0.15$; Tables S3 for basal cortisol, Tables S4 for CAR, Tables S5 for testosterone).

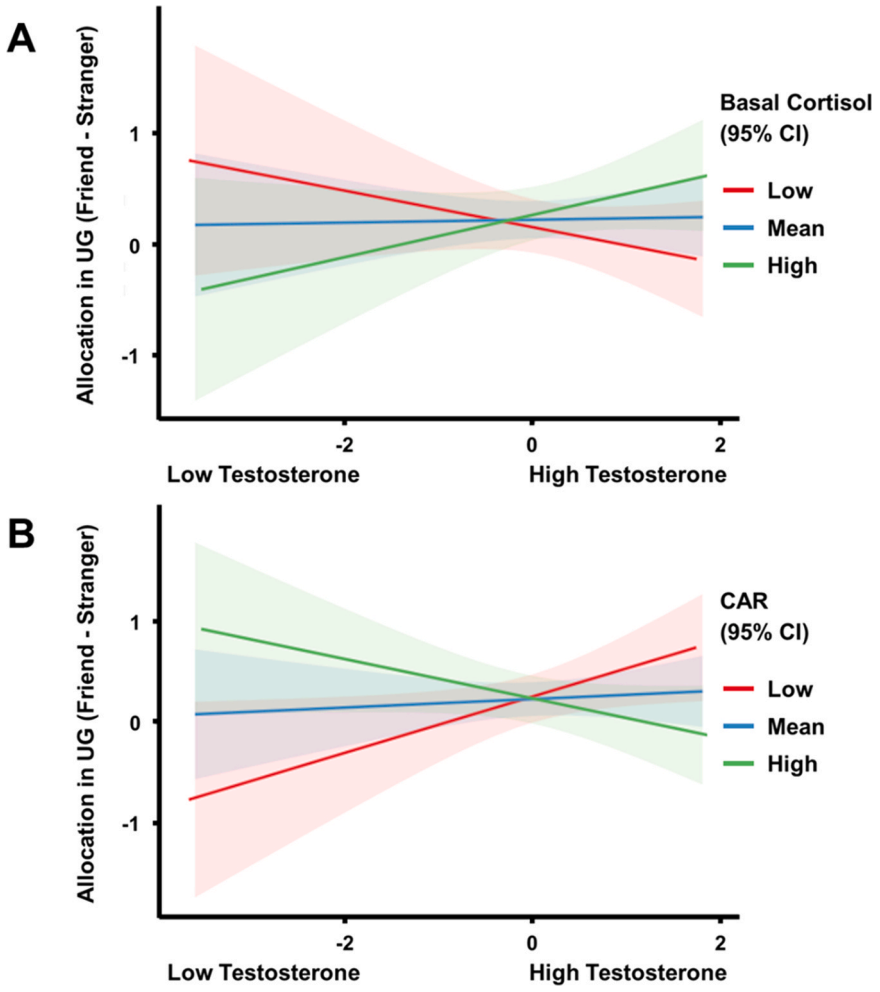

Fig. 4. Testosterone × basal cortisol and testosterone × CAR interactions in the differential allocation between friends and strangers in the UG. Testosterone was positively associated with differential allocation in UG only at high basal cortisol levels (A), and was positively correlated with differential allocation at low CAR and negatively correlated at high CAR (B). Note: Plotted lines represent conditional values at low (−1 SD), mean, and high (+1 SD) levels of basal cortisol and CAR.

3.4. Effects of interaction between basal cortisol and testosterone on adolescents' fairness

In terms of strategic fairness, we conducted several multiple regressions to examine whether testosterone and basal cortisol jointly influence adolescents' fair behavior in UG, using the amounts allocated to the friends, strangers, and their differences as dependent variables, respectively, with sex and age as covariates (Tables S6).

Regarding the differences in amounts allocated between friends and strangers in UG, the results showed a significant interaction between basal cortisol and testosterone ($B = 0.15$, F (1, 374) $= 5.1$, $p < 0.05$, *partial* $\eta^2 = 0.01$, $p_{FDR} = 0.15$) (Fig. 4A). Subsequent simple slope analysis of testosterone revealed that at high levels (+1 SD) of basal cortisol, adolescents' testosterone was positively correlated to allocation differences ($B = 0.15$, F (1, 374) $= 3.98$, $p < 0.05$, *partial* $\eta^2 = 0.01$). However, this correlation was not significant at low (-1 SD) and average (mean) levels of basal cortisol ($B = -0.11$, F (1, 374) $= 1.91$, $p = 0.17$, *partial* $\eta^2 = 0.005$; and $B = 0.02$, F (1, 374) $= 0.16$, $p = 0.69$, *partial* $\eta^2 = 0.00$, respectively). To explore whether sex moderated the relationship of fairness with testosterone and cortisol, we incorporated two-way interactions (cortisol × sex, testosterone × sex) and a three-way interaction (cortisol × testosterone × sex) into the regression (Tables S7). Apart from the basal cortisol × testosterone interaction ($B = 0.15$, F (1, 371) $= 5.27$, $p < 0.05$, *partial* $\eta^2 = 0.01$, $p_{FDR} = 0.15$), no sex-related interactions were significant ($ps > 0.44$).

Regarding the strategic fairness towards friends, apart from the marginally significant main effect of basal cortisol ($B = 0.09$, F (1, 374) $= 3.13$, $p = 0.08$, *partial* $\eta^2 = 0.01$, $p_{FDR} = 0.47$) and the interaction between basal cortisol and testosterone ($B = 0.1$, F (1, 374) $= 3.04$, $p = 0.08$, *partial* $\eta^2 = 0.01$, $p_{FDR} = 0.25$), all other effects were not significant ($ps > 0.19$). Subsequent simple slope analysis of testosterone revealed that at high levels (+1 SD) of basal cortisol, a marginally significant positive association between adolescents' testosterone and the amounts allocated to friends ($B = 0.14$, F (1, 374) $= 3.26$, $p = 0.07$, *partial* $\eta^2 = 0.01$). However, this correlation was not significant at low (-1 SD) and average (mean) levels of basal cortisol ($B = -0.07$, F (1, 374) $= 0.66$, $p = 0.42$, *partial* $\eta^2 = 0.002$; and $B = 0.04$, F (1, 374) $= 0.48$, $p = 0.49$, *partial* $\eta^2 = 0.001$, respectively). We then incorporated two-way interactions (cortisol × sex, testosterone × sex) and a three-way interaction (cortisol × testosterone × sex) into the regression and found no significant sex-related interactions ($ps > 0.35$).

Regarding the strategic fairness towards strangers, no effects were statistically significant ($ps > 0.32$). In summary, we found that in adolescents with high basal cortisol levels, testosterone was positively associated with the amount allocated to friends and the difference in allocations between friends and strangers. This suggests that among adolescents with high testosterone levels, individuals with high basal cortisol levels are more likely to distinguish between in-group and out-group fairness in strategic allocation, predominantly by demonstrating greater strategic fairness towards their friends.

In terms of pure fairness, we conducted several multiple regressions to examine whether testosterone and basal cortisol jointly influence adolescents' fair behavior in DG, using the amounts allocated to the friends, strangers, and their differences as dependent variables, respectively, with sex and age as covariates. None of the interaction effects reached statistical significance ($ps > 0.15$). We further incorporated two-way interactions (cortisol × sex, testosterone × sex) and a three-way interaction (cortisol × testosterone × sex) into the regressions and found no significant interactions ($ps > 0.12$) (Tables S6 and S7).

Overall, in terms of strategic fairness, adolescents with high testosterone levels and high basal cortisol were more likely to allocate more resources to friends than to strangers, with no significant effects found for pure fairness, nor any sex-related interactions.

3.5. Effects of interaction between CAR and testosterone on adolescents' fairness

In terms of strategic fairness, we conducted several multiple regressions to examine whether testosterone and CAR jointly influence adolescents' fair behavior in UG, using the amounts allocated to friends, strangers, and their differences as dependent variables, respectively, with sex and age as covariates (Tables S8).

Regarding the differences in amounts allocated between friends and strangers in UG, the results showed a significant interaction between CAR and testosterone ($B = -0.17$, F (1, 374) $= 10.29$, $p < 0.01$, *partial* $\eta^2 = 0.03$, $p_{FDR} < 0.01$) (Fig. 4B). Subsequent simple slope analysis of testosterone revealed that adolescents' testosterone was positively correlated to allocation differences at low levels (-1 SD) of CAR ($B = 0.21$, F (1, 374) $= 7.74$, $p < 0.01$, *partial* $\eta^2 = 0.02$), while was negative related to allocation differences at high levels (+1 SD) of CAR ($B = -0.13$, F (1, 374) $= 3.28$, $p = 0.07$, *partial* $\eta^2 = 0.01$, marginal significance). This association was not significant at average (mean) levels of CAR ($B = 0.04$, F (1, 374) $= 0.72$, $p = 0.4$, *partial* $\eta^2 = 0.002$).

To explore whether sex moderated the relationship of fairness with testosterone and cortisol, we incorporated two-way interactions (cortisol × sex, testosterone × sex) and a three-way interaction (cortisol × testosterone × sex) into the regression (Tables S9). The cortisol × testosterone × sex interaction was marginally significant ($B = 0.2$, F (1, 374) $= 3.51$, $p = 0.06$, *partial* $\eta^2 = 0.01$, $p_{FDR} = 0.19$). Subsequently, separate simple slope analyses of CAR for both sexes showed that among male adolescents, testosterone was positively correlated with the allocation differences at low levels (-1 SD) of CAR ($B = 0.31$, F (1, 371) $= 11.17$, $p < 0.001$, *partial* $\eta^2 = 0.03$), while it was negatively related to the allocation differences at high levels (+1 SD) of CAR ($B = -0.18$, F (1, 371) $= 3.91$, $p < 0.05$, *partial* $\eta^2 = 0.01$) (Fig. 5A). No significant interaction between CAR and testosterone was observed in female adolescents ($ps > 0.61$; Fig. 5B).

Regarding the strategic fairness towards friends, the interaction between CAR and testosterone was significant ($B = -0.13$, F (1, 374) $= 5.69$, $p < 0.05$, *partial* $\eta^2 = 0.02$, $p_{FDR} = 0.05$). Subsequent simple slope analysis of testosterone revealed a positive association between adolescents' testosterone and the amounts allocated to friends ($B = 0.14$, F (1, 374) $= 3.21$, $p = 0.07$, *partial* $\eta^2 = 0.01$, marginal significance) at low levels (-1 SD) of CAR. However, this correlation was not significant at average (mean) and high (+1 SD) levels of CAR ($B = 0.004$, F (1, 374) $= 0.01$, $p = 0.94$, *partial* $\eta^2 = 0.000$; and $B =$ -0.13, F (1, 374) $= 2.7$, $p = 0.1$, *partial* $\eta^2 = 0.01$, respectively). We then incorporated sex-related interactions into the regression and found a significant triple interaction ($B = 0.27$, F (1, 371) $= 5.89$, $p < 0.05$, *partial* $\eta^2 = 0.02$, $p_{FDR} = 0.1$). Subsequently, separate simple slope analyses of CAR for both sexes showed that among male adolescents, testosterone was positively correlated with the allocations to friends at low levels (-1 SD) of CAR ($B = 0.3$, F (1, 371) $= 9.65$, $p < 0.01$, *partial* $\eta^2 = 0.03$), while it was negatively related to the allocation differences at high levels (+1 SD) of CAR ($B = -0.17$, F (1, 371) $= 3.37$, $p = 0.07$, *partial* $\eta^2 = 0.01$, marginal significance). No significant interaction between CAR and testosterone was observed in female adolescents ($ps > 0.63$).

Regarding the strategic fairness towards strangers, neither model was statistically significant ($ps > 0.24$). In summary, we found that among male adolescents with low CAR, the associations between testosterone and the amount allocated to friends and the difference in allocations between friends and strangers were positive, while among those with high CAR, these associations were negative.

In terms of pure fairness, we conducted several multiple regressions to examine whether testosterone and CAR jointly influence adolescents' fair behavior in DG, using the amounts allocated to the friends, strangers, and their differences as dependent variables, respectively, with sex and age as covariates. None of the interaction effects reached statistical significance ($ps > 0.16$). We further incorporated two-way interactions (cortisol × sex, testosterone × sex) and a three-way

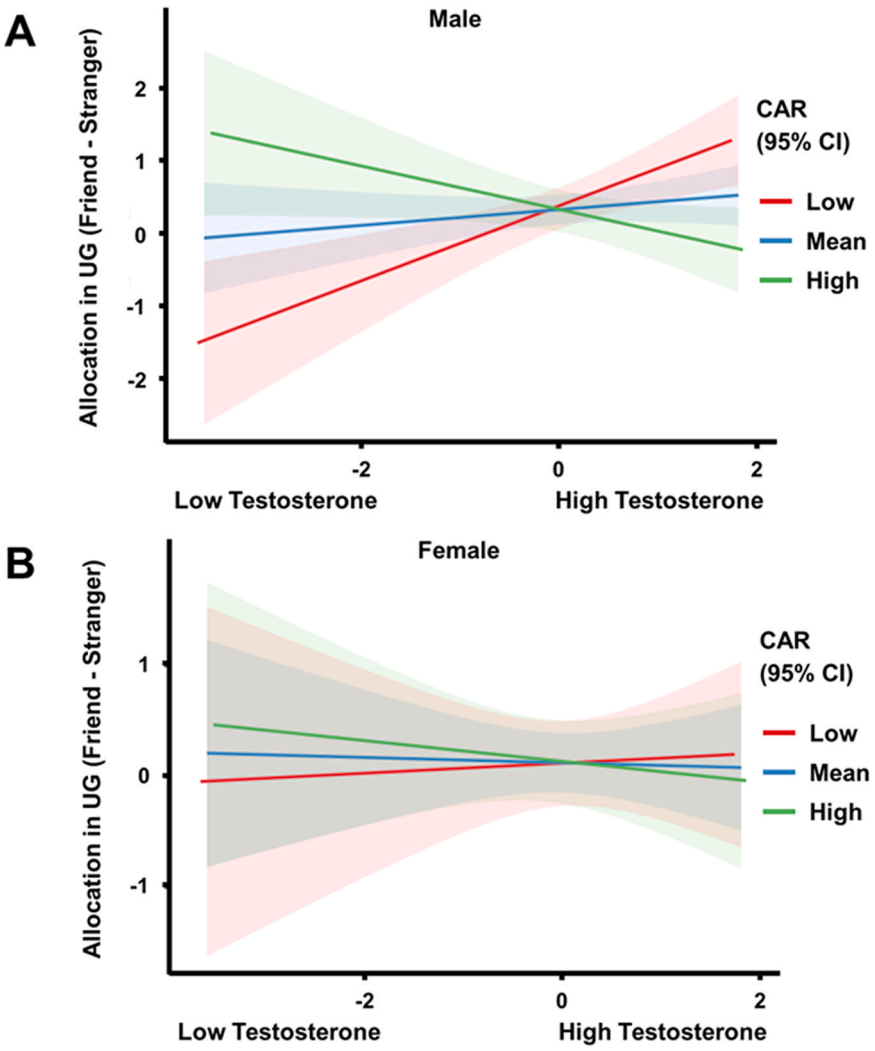

Fig. 5. Interaction between testosterone and cortisol awakening response (CAR) on differential allocation between friends and strangers in the UG, moderated by sex. Testosterone was positively correlated with differential allocation in UG at low CAR and negatively correlated at high CAR in male adolescents (A), with no such correlations in female adolescents (B). Note: Plotted lines represent conditional values at low (−1 SD), mean, and high (+1 SD) levels of CAR.

interaction (cortisol × testosterone × sex) into the regressions and found no significant interactions (*ps* > 0.15) (Tables S8 and S9).

Overall, in terms of strategic fairness, the interaction between CAR and testosterone influenced adolescents' behavior, with male adolescents showing a positive correlation between testosterone and both differential allocations and allocations to friends at low CAR levels, and a negative correlation at high CAR levels, while no significant effects were found for pure fairness or in female adolescents.

4. Discussion

Adolescence is a critical period for developing moral and ethical values (Dahl et al., 2018). Fairness plays a central role in shaping their sense of justice and notions of right and wrong (Rutland and Killen, 2017). The current study examined how cortisol (basal cortisol and CAR) and testosterone influenced adolescents' strategic and pure fairness towards friends and strangers, and revealed sex differences and potential dual-hormone mechanisms in fairness decision-making. As adolescents matured, they demonstrated increased parochial fairness by allocating more tokens to friends than strangers in both strategic and pure fairness decisions. No sex differences were found in strategic and pure fairness. Testosterone was positively associated with differential strategic fairness at high basal cortisol levels. Moreover, testosterone was positively correlated at low CAR levels, while negatively correlated at high CAR levels. This hormonal pattern was observed in male adolescents, but not in females. The findings emphasize sex-specific dual--hormonal influences on adolescent fairness decisions, demonstrating distinct physiological pathways through which hormones contribute to the development of moral values in males and females.

Consistent with previous research, our study found that adolescents increasingly considered social distance in their fairness decisions as they aged (Fehr et al., 2013; Güroğlu et al., 2009). There was a notable age-related increase in their preference for allocating more tokens to friends than to strangers in both the UG and DG. They place greater emphasis on social relationships when making decisions about resource allocation and showed a growing awareness of the potential for reciprocity and social cohesion within their peer groups (Leider et al., 2011). Higher sharing behavior towards friends may serve as a strategy to enhance social status and acceptance among peers (Hawley, 1999). However, contrary to expectations, no significant sex differences were observed in either strategic or pure fairness.

Notably, we observed that high testosterone levels were positively correlated with allocation differences between friends and strangers at high basal cortisol levels, whereas this correlation was not significant at lower basal cortisol levels. This dual-hormone interaction also influenced allocations specifically towards friends rather than strangers. Our

findings contradicted the dual-hormone hypothesis where cortisol and testosterone mutually inhibited each other's behavioral effects (Mehta and Josephs, 2010). According to the dual-hormone hypothesis, high testosterone levels should be positively linked to the allocation differences and allocation to friends at low basal cortisol levels but not at high basal cortisol levels, and vice versa. One candidate explanation for the inconsistency was the unique developmental stage of adolescence, where both the HPA and HPG axes experienced reactivation and unprecedented maturation, including co-intense increases in hormones of the adrenal and gonadal origin (Ellis and Del Giudice, 2019; Ruttle et al., 2015; Shirtcliff et al., 2015). The interaction between HPA and HPG axis activity may influence behavioral decision-making, potentially affecting the relationship between basal cortisol and testosterone on strategic fairness. However, we did not find a corresponding dual-hormone pattern for pure fairness in adolescents. Moreover, research in adults also demonstrated the positive coupled interaction wherein the influence of testosterone on behavior was strengthened at high cortisol concentrations (Denson et al., 2013). We further conjectured that the behavioral expression of dual-hormone interactions is not merely a direct reflection of their neuroendocrine patterns. Instead, it is likely influenced by environmental factors with an adaptive purpose, leading to different interaction patterns in varying contexts. Recently, Knight et al. (2022) extended the prior theoretical framework and further proposed a context-dependent dual-hormone hypothesis that individuals exhibited distinct dual-hormonal patterns depending on different motivations. For low-cortisol individuals, increased testosterone enhanced status-seeking motivation, leading them to prefer competing against high-status opponents; by contrast, for high-cortisol individuals, increased testosterone triggers status-loss avoidance motivation, making them prefer competing against low-status opponents to mitigate the risk of losing to higher-status ones. In the context of the UG, characterized by critical social negotiations and potential total loss upon rejection, where adolescents with high basal cortisol and testosterone are more likely motivated by status-loss avoidance (Overgaauw et al., 2012). This inclination encouraged them to allocate more resources to friends rather than strangers, as favoring friends serves as a strategy to maintain and protect their social status within their immediate social group. By ensuring a preferential allocation to friends, these adolescents reinforced intra-group cohesion, thereby mitigating the potential for conflicts or challenges to their social status within their social network. In contrast, the DG involved unilateral decisions where adolescents allocated resources without considering reciprocity or social implications (Güroğlu et al., 2009). Therefore, the motivational framework related to status-seeking or status-loss avoidance, as observed in the UG, may not be as relevant or impactful in the DG.

We found the sex-specific dual-hormone mechanisms underlying strategic fairness. Initially, there were sex differences in the activity of HPA and HPG axes, with males having higher testosterone levels and females showing more evident CAR, which aligned with the prior findings (Barry et al., 2011; González-Sales et al., 2016; Handelsman et al., 2018; Oskis et al., 2009; Wright and Bukowski, 2021). Moreover, we also found the sex-specific interaction of CAR and testosterone on adolescent strategic fairness. Testosterone was positively associated with differential strategic fairness at low CAR, but negatively correlated at high CAR. The same pattern was also observed in male adolescents' allocation towards friends in UG. Interestingly, there were different patterns between basal cortisol and CAR in their interactions with testosterone on strategic fairness in adolescents. The differences could be attributed to the unique physiological roles of CAR, which represented the body's mobilization of energy to meet the anticipated demands of the forthcoming day (Elder et al., 2014; Fries et al., 2009). Recently, CAR was regarded as a biological mechanism that connected social relationships (or their absence) with health outcomes (Armstrong-Carter and Telzer, 2021; Baliyan et al., 2021). Elevated CAR may enhance an individual's readiness and ability to engage with social environments daily (Baliyan et al., 2021; Sladek and Doane, 2015; Wang et al., 2022). Among adolescents with both high CAR and high testosterone, we observed lower differentiation in strategic fairness between friends and strangers. This pattern suggested that the combination of a heightened state of readiness (reflected by high CAR) and increased status-seeking motivation (driven by high testosterone) enhanced adolescents' willingness to allocate more fairly towards strangers, potentially as a strategy to establish new social connections and expand their social networks. This behavior appeared to be more aligned with a status-seeking orientation. In contrast, adolescents with both low CAR and high testosterone showed the greatest differentiation in strategic fairness, favoring friends over strangers. This suggested a more conservative, in-group-focused approach, possibly motivated by a desire to avoid status loss. These individuals likely preferred to reinforce existing social bonds rather than invest effort in developing new ones, reflecting a protective strategy to maintain social standing within their current peer group.

Although the interaction patterns between basal cortisol and testosterone and those between CAR and testosterone on strategic fairness differed in direction, they may share a common underlying mechanism. Specifically, individuals with high basal cortisol and low CAR—typically associated with chronic stress—in combination with high testosterone, may be more strongly influenced by status-loss avoidance motivation during fairness-related decision-making. This tendency likely drives them to allocate more resources to friends rather than strangers, thereby reinforcing their status and securing their position within their immediate social group.

Despite novel contributions, there were several limitations to the present study. First, the observed associations between hormonal levels and fairness-related decisions were correlational in nature, and no causal inferences could be made. It was possible that unmeasured third variables, such as pubertal development or environmental context, may have underlain both hormonal profiles and behavioral outcomes. Although we controlled for chronological age, individual differences in pubertal timing could have introduced additional variability in hormone levels. Future research would benefit from incorporating direct measures of pubertal status, such as self-reported menstruation onset, Tanner staging, or physician-assessed indicators. Second, we did not include measures of early life stress or socioeconomic status, both of which may have moderated the interplay between hormones and decision-making processes. Given the theoretical emphasis on environmental influences, future studies should consider including indices such as the Risky Family Scale or objective socioeconomic indicators to test moderation models involving environmental harshness or unpredictability. Third, methodological limitations related to hormone assessment warranted consideration. Cortisol and testosterone were analyzed using assay methodologies, which may have introduced unwanted methodological variance, particularly when examining hormonal interactions. Additionally, saliva samples were collected using Salivettes, which have been shown in some studies to inflate hormone levels, particularly testosterone concentrations (Giltay et al., 2012; Prasad et al., 2017; Shirtcliff et al., 2001). This issue may have also differentially impacted measurement validity across sexes, with testosterone levels being more validly measured in males than in females (Keevil et al., 2014; Schultheiss and Mehta, 2019). These measurement constraints may have partially accounted for the stronger effects observed in males, in particular the similar patterns being observed in females. Future work should consider using more sensitive and standardized methods, and may also benefit from including female sex hormones (e.g., estradiol, oxytocin) to further explore sex-specific hormonal dynamics. In addition, hormone data missingness was addressed via mean imputation due to the relatively low proportion of missing values. While this approach offered simplicity and minimized distortion of group-level estimates, it may underestimate variability and introduce bias, especially when interactions were modeled. Finally, while we examined CAR and bedtime levels, we did not analyze the diurnal slope, which could have provided additional insights into HPA axis functioning. Future

studies should aim to collect afternoon samples to enable a more comprehensive assessment of diurnal cortisol patterns.

5. Conclusions

As adolescents mature, they increasingly consider social distance in both strategic and pure fairness decisions, favoring friends over strangers. High testosterone levels are positively associated with allocation differences in strategic fairness at high basal cortisol levels, but not at low levels. Furthermore, in male adolescents only, testosterone levels are positively correlated with allocation differences in strategic fairness at low CAR, but negatively correlated at high CAR. These findings reveal hormonal influences on fairness during adolescence and offer insights for promoting fair and ethical behavior in youth.

CRediT authorship contribution statement

Rui Su: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Huagen Wang:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Xiang Ma:** Writing – original draft, Data curation. **Nan Sun:** Visualization, Data curation. **Chao Liu:** Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

We declare that there are no conflicts of interest or competing interests that could influence the work presented in this manuscript. The research and preparation of this article were conducted independently, without any financial or personal relationships that could be perceived as influencing the objectivity of the findings.

Furthermore, all authors have reviewed and approved the final version of this manuscript and confirm that it represents original work not previously published or currently under consideration elsewhere.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2025.107520.

References

Andrews, J.L., Ahmed, S.P., Blakemore, S.J., 2021. Navigating the social environment in adolescence: the role of social brain development. Biol. Psychiatry 89 (2), 109–118. https://doi.org/10.1016/j.biopsych.2020.09.012.

Angerer, S., Dutcher, E.G., Glätzle-Rützler, D., Lergetporer, P., Sutter, M., 2017. Gender differences in discrimination emerge early in life: evidence from primary school children in a bilingual city. Econ. Lett. 152, 15–18. https://doi.org/10.1016/j.econlet.2016.12.031.

Armstrong-Carter, E., Telzer, E.H., 2021. Daily provision of instrumental and emotional support to friends is associated with diurnal cortisol during adolescence. Dev. Psychobiol. 63 (5), 1266–1278. https://doi.org/10.1002/dev.22101.

Baliyan, S., Cimadevilla, J.M., de Vidania, S., Pulopulos, M.M., Sandi, C., Venero, C., 2021. Differential susceptibility to the impact of the COVID-19 pandemic on working memory, empathy, and perceived stress: the role of cortisol and resilience. Brain Sci. 11 (3), 1–21. https://doi.org/10.3390/brainsci11030348.

Barry, J.A., Hardiman, P.J., Siddiqui, M.R., Thomas, M., 2011. Meta-analysis of sex difference in testosterone levels in umbilical cord blood. In: Journal of Obstetrics and Gynaecology, 31. Taylor & Francis, pp. 697–702. https://doi.org/10.3109/01443615.2011.614971.

Belsky, J., Steinberg, L., Draper, P., 1991. Childhood experience, interpersonal development, and reproductive strategy: an evolutionary theory of socialization. Child Dev. 62 (4), 647–670. https://doi.org/10.1111/j.1467-8624.1991.tb01558.x.

Bernard, K., Zwerling, J., Dozier, M., 2015. Effects of early adversity on young children's diurnal cortisol rhythms and externalizing behavior. Dev. Psychobiol. 57 (8). https://doi.org/10.1002/dev.21324.

Bindra, P.C., Glätzle-Rützler, D., Lergetporer, P., 2020. Discrimination at young age: experimental evidence from preschool children. J. Econ. Behav. Organ. 175 (7396), 55–70. https://doi.org/10.1016/j.jebo.2019.12.026.

Bremner, W.J., Vitiello, M.V., Prinz, P.N., 1983. Loss of circadian rhythmicity in blood testosterone levels with aging in normal men. J. Clin. Endocrinol. Metab. 56 (6), 1278–1281. https://doi.org/10.1210/jcem-56-6-1278.

Brosnan, S.F., de Waal, F.B., 2014. Evolution of responses to (un)fairness. Science 346 (6207), 1251776. https://doi.org/10.1126/science.1251776.

Carver, C.S., White, T.L., 1994. Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: the BIS/BAS scales. J. Personal. Soc. Psychol. 67 (2), 319–333. https://doi.org/10.1037/0022-3514.67.2.319.

Chaku, N., Barry, K., 2023. Exploring profiles of hormone exposure: associations with cognition in a population-based cohort of early adolescents. Infant Child Dev. February, 1–28. https://doi.org/10.1002/icd.2415.

Crone, E.A., Fuligni, A.J., 2020. Self and others in adolescence. Annu. Rev. Psychol. 71, 447–469. https://doi.org/10.1146/annurev-psych-010419-050937.

Dahl, R.E., Allen, N.B., Wilbrecht, L., Suleiman, A.B., 2018. Importance of investing in adolescence from a developmental science perspective. Nature 554 (7693), 441–450. https://doi.org/10.1038/nature25770.

Dekkers, T.J., van Rentergem, J.A.A., Meijer, B., Popma, A., Wagemaker, E., Huizenga, H.M., 2019. A meta-analytical evaluation of the dual-hormone hypothesis: does cortisol moderate the relationship between testosterone and status, dominance, risk taking, aggression, and psychopathy? Neurosci. Biobehav. Rev. 96 (September 2017), 250–271. https://doi.org/10.1016/j.neubiorev.2018.12.004.

Denson, T.F., Mehta, P.H., Ho Tan, D., 2013. Endogenous testosterone and cortisol jointly influence reactive aggression in women. Psychoneuroendocrinology 38 (3), 416–424. https://doi.org/10.1016/j.psyneuen.2012.07.003.

van der Westhuizen, D., Solms, M., 2015. Social dominance and the affective neuroscience personality scales. Conscious. Cogn. 33, 90–111. https://doi.org/10.1016/j.concog.2014.12.005.

Dorn, L.D., Biro, F.M., 2011. Puberty and its measurement: a decade in review. J. Res. Adolesc. 21 (1), 180–195. https://doi.org/10.1111/j.1532-7795.2010.00722.x.

Douglas Bates, M.M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67 (1), 1–48.

Elder, G.J., Wetherell, M.A., Barclay, N.L., Ellis, J.G., 2014. The cortisol awakening response - applications and implications for sleep Medicine. Sleep. Med. Rev. 18 (3), 215–224. https://doi.org/10.1016/j.smrv.2013.05.001.

Ellis, B.J., 2004. Timing of pubertal maturation in girls: an integrated life history approach. Psychol. Bull. 130 (6), 920–958. https://doi.org/10.1037/0033-2909.130.6.920.

Ellis, B.J., Del Giudice, M., 2019. Developmental adaptation to stress: an evolutionary perspective. Annu. Rev. Psychol. 70, 111–139. https://doi.org/10.1146/annurev-psych-122216-011732.

Ellis, B.J., Essex, M.J., 2007. Family environments, adrenarche, and sexual maturation: a longitudinal test of a life history model. Child Dev. 78 (6), 1799–1817. https://doi.org/10.1111/j.1467-8624.2007.01092.x.

Ellis, B.J., Garber, J., 2000. Psychosocial antecedents of variation in girls' pubertal timing: maternal depression, stepfather presence, and marital and family stress. Child Dev. 71 (2), 485–501. https://doi.org/10.1111/1467-8624.00159.

Ellis, B.J., Shirtcliff, E. a, Boyce, W.T., Deardorff, J., Essex, M.J., 2011. Quality of early family relationships and the timing and tempo of puberty: effects depend on biological sensitivity to context. Dev. Psychopathol. 23 (1), 85–99. https://doi.org/10.1017/S0954579410000660.

Endler, N.S., Kocovski, N.L., 2001. State and trait anxiety revisited. J. Anxiety Disord. 15 (3), 231–245. https://doi.org/10.1016/S0887-6185(01)00060-3.

Fehr, E., Gintis, H., 2007. Human motivation and social cooperation: experimental and analytical foundations. Annu. Rev. Sociol. 33, 43–64. https://doi.org/10.1146/annurev.soc.33.040406.131812.

Fehr, E., Glätzle-Rützler, D., Sutter, M., 2013. The development of egalitarianism, altruism, spite and parochialism in childhood and adolescence. Eur. Econ. Rev. 64, 369–383. https://doi.org/10.1016/j.euroecorev.2013.09.006.

Fries, E., Dettenborn, L., Kirschbaum, C., 2009. The cortisol awakening response (CAR): facts and future directions. Int. J. Psychophysiol. 72 (1), 67–73. https://doi.org/10.1016/j.ijpsycho.2008.03.014.

Giltay, E.J., Enter, D., Zitman, F.G., Penninx, B.W.J.H., van Pelt, J., Spinhoven, P., Roelofs, K., 2012. Salivary testosterone: associations with depression, anxiety disorders, and antidepressant use in a large cohort study. J. Psychosom. Res. 72 (3), 205–213. https://doi.org/10.1016/j.jpsychores.2011.11.014.

González-Sales, M., Barrière, O., Tremblay, P.O., Nekka, F., Desrochers, J., Tanguay, M., 2016. Modeling testosterone circadian rhythm in hypogonadal males: effect of age and circannual variations. AAPS J. 18 (1), 217–227. https://doi.org/10.1208/s12248-015-9841-6.

Gunnar, M.R., Cheatham, C.L., 2003. Brain and behavior interface: stress and the developing brain. Infant Ment. Health J. 24 (3), 195–211. https://doi.org/10.1002/imhj.10052.

Güroğlu, B., van den Bos, W., Crone, E.A., 2009. Fairness considerations: increasing understanding of intentionality during adolescence. J. Exp. Child Psychol. 104 (4), 398–409. https://doi.org/10.1016/J.JECP.2009.07.002.

Güth, W., Schmittberger, R., Schwarze, B., 1982. An experimental analysis of ultimatum bargaining. J. Econ. Behav. Organ. 3 (4), 367–388.
Hamilton, L.D., Carré, J.M., Mehta, P.H., Olmstead, N., Whitaker, J.D., 2015. Social neuroendocrinology of status: a review and future directions. Adapt. Hum. Behav. Physiol. 1 (2), 202–230. https://doi.org/10.1007/s40750-015-0025-5.
Handa, R.J., Weiser, M.J., 2014. Gonadal steroid hormones and the hypothalamo–pituitary–adrenal axis. Front. Neuroendocrinol. 35 (2), 197–220. https://doi.org/10.1016/j.yfrne.2013.11.001.
Handelsman, D.J., Hirschberg, A.L., Bermon, S., 2018. Circulating testosterone as the hormonal basis of sex differences in athletic performance. In: Endocrine Reviews, 39. Oxford Academic, pp. 803–829. https://doi.org/10.1210/er.2018-00020.
Harden, K.P., Wrzus, C., Luong, G., Grotzinger, A., Bajbouj, M., Rauers, A., Wagner, G.G., Riediger, M., 2016. Diurnal coupling between testosterone and cortisol from adolescence to older adulthood. Psychoneuroendocrinology 73, 79–90. https://doi.org/10.1016/j.psyneuen.2016.07.216.
Hardeveld, F., Spijker, J., Vreeburg, S.A., De Graaf, R., Hendriks, S.M., Licht, C.M.M., Nolen, W.A., Penninx, B.W.J.H., Beekman, A.T.F., 2014. Increased cortisol awakening response was associated with time to recurrence of major depressive disorder. Psychoneuroendocrinology 50, 62–71. https://doi.org/10.1016/j.psyneuen.2014.07.027.
Hawley, P.H., 1999. The Ontogen1. hawley, P. H. the ontogenesis of social dominance: a Strategy-Based evolutionary perspective. Dev. rev. 19, 97–132 (1999).esis of social dominance: a Strategy-Based evolutionary perspective. Dev. Rev. 19 (1), 97–132. ⟨http://linkinghub.elsevier.com/retrieve/pii/S0273229798904701⟩.
Hermans, E.J., Bos, P.A., Ossewaarde, L., Ramsey, N.F., Fernández, G., van Honk, J., 2010. Effects of exogenous testosterone on the ventral striatal BOLD response during reward anticipation in healthy women. NeuroImage 52 (1), 277–283. https://doi.org/10.1016/j.neuroimage.2010.04.019.
Kahneman, D., Knetsch, J.L., Thaler, R., 1986. Fairness as a constraint on profit seeking: entitlements in the market. Am. Econ. Rev. 76 (4), 728–741.
Keevil, B.G., MacDonald, P., Macdowall, W., Lee, D.M., Wu, F.C.W., 2014. Salivary testosterone measurement by liquid chromatography tandem mass spectrometry in adult males and females. Ann. Clin. Biochem. 51 (3), 368–378. https://doi.org/10.1177/0004563213506412.
Kinner, V.L., Wolf, O.T., Merz, C.J., 2016. Cortisol alters reward processing in the human brain. Horm. Behav. 84, 75–83. https://doi.org/10.1016/j.yhbeh.2016.05.005.
Knight, E.L., Morales, P.J., Christian, C.B., Prasad, S., Harbaugh, W.T., Mehta, P.H., Mayr, U., 2022. The causal effect of testosterone on Men's competitive behavior is moderated by basal cortisol and cues to an Opponent's status: evidence for a Context-Dependent Dual-Hormone hypothesis. J. Personal. Soc. Psychol. 123 (4), 693–716. https://doi.org/10.1037/pspa0000305.
Kuhlman, K.R., Robles, T.F., Dickenson, L., Reynolds, B., Repetti, R.L., 2019. Stability of diurnal cortisol measures across days, weeks, and years during middle childhood and early adolescence: exploring the role of age, pubertal development, and sex. Psychoneuroendocrinology 100, 67–74. https://doi.org/10.1016/j.psyneuen.2018.09.033.
Kuzawa, C.W., Georgiev, A.V., McDade, T.W., Bechayda, S.A., Gettler, L.T., 2016. Is there a testosterone awakening response in humans? Adapt. Hum. Behav. Physiol. 2 (2), 166–183. https://doi.org/10.1007/s40750-015-0038-0.
Laube, C., van den Bos, W., Fandakova, Y., 2020. The relationship between pubertal hormones and brain plasticity: implications for cognitive training in adolescence. Dev. Cogn. Neurosci. 42 (December 2019), 100753. https://doi.org/10.1016/j.dcn.2020.100753.
Lausen, A., Broering, C., Penke, L., Schacht, A., 2020. Hormonal and modality specific effects on males' emotion recognition ability. Psychoneuroendocrinology 119, 104719. https://doi.org/10.1016/j.psyneuen.2020.104719.
Lazić, A., Purić, D., Krstić, K., 2021. Does parochial cooperation exist in childhood and adolescence? A meta-analysis. Int. J. Psychol. 56 (6). https://doi.org/10.1002/ijop.12791.
Leider, S., Mobius, M.M., Rosenblat, T., Do, Q.-A., 2011. How much is a friend worth? Directed altruism and enforced reciprocity in social networks. SSRN Electron. J. 07. https://doi.org/10.2139/ssrn.1021700.
Liu, S., Hu, X., Ge, W., Mai, X., 2024. Distributive fairness during the transition to adolescence: the role of peer comparison and social value orientation. PsyCh. J. August 2024, 118–130. https://doi.org/10.1002/pchj.800.
Lynch, J.W., Ziegler, T.E., Strier, K.B., 2002. Individual and seasonal variation in fecal testosterone and cortisol levels of wild Male tufted capuchin monkeys, cebus apella nigritus. Horm. Behav. 41 (3), 275–287. https://doi.org/10.1006/HBEH.2002.1772.
Manigault, A.W., Zoccola, P.M., Hamilton, K., Wymbs, B.T., 2019. Testosterone to cortisol ratio and aggression toward one's partner: evidence for moderation by provocation. Psychoneuroendocrinology 103 (October 2018), 130–136. https://doi.org/10.1016/j.psyneuen.2019.01.018.
Marceau, K., Dorn, L.D., Susman, E.J., 2012. Stress and puberty-related hormone reactivity, negative emotionality, and parent-adolescent relationships. Psychoneuroendocrinology 37 (8), 1286–1298. https://doi.org/10.1016/j.psyneuen.2012.01.001.
McClintock, M.K., Herdt, G., 1996. Rethinking puberty. Curr. Dir. Psychol. Sci. 5 (6), 178–183. https://doi.org/10.1111/1467-8721.ep11512422.
McDonald, M.M., Navarrete, C.D., van Vugt, M., 2012. Evolution and the psychology of intergroup conflict: the Male warrior hypothesis. Philos. Trans. R. Soc. B Biol. Sci. 367 (1589), 670–679. https://doi.org/10.1098/rstb.2011.0301.
Mehta, P.H., Josephs, R.A., 2010. Testosterone and cortisol jointly regulate dominance: evidence for a dual-hormone hypothesis. Horm. Behav. 58 (5), 898–906. https://doi.org/10.1016/j.yhbeh.2010.08.020.
Mehta, P.H., Prasad, S., 2015. The dual-hormone hypothesis: a brief review and future research agenda. Curr. Opin. Behav. Sci. 3, 163–168. https://doi.org/10.1016/j.cobeha.2015.04.008.
Mehta, P.H., Welker, K.M., Zilioli, S., Carré, J.M., 2015. Testosterone and cortisol jointly modulate risk-taking. Psychoneuroendocrinology 56, 88–99. https://doi.org/10.1016/j.psyneuen.2015.02.023.
Nelson, E.E., Jarcho, J.M., Guyer, A.E., 2016. Social re-orientation and brain development: an expanded and updated view. Dev. Cogn. Neurosci. 17, 118–127. https://doi.org/10.1016/j.dcn.2015.12.008.
Nguyen, T.-V., Lew, J., Albaugh, M.D., Botteron, K.N., Hudziak, J.J., Fonov, V.S., Collins, D.L., Ducharme, S., McCracken, J.T., 2017. Sex-specific associations of testosterone with prefrontal-hippocampal development and executive function. Psychoneuroendocrinology 76, 206–217.
Nitschke, J.P., Bartz, J.A., 2020. Lower digit ratio and higher endogenous testosterone are associated with lower empathic accuracy. Horm. Behav. 119 (X). https://doi.org/10.1016/j.yhbeh.2019.104648.
Oskis, A., Loveday, C., Hucklebridge, F., Thorn, L., Clow, A., 2009. Diurnal patterns of salivary cortisol across the adolescent period in healthy females. Psychoneuroendocrinology 34 (3), 307–316. https://doi.org/10.1016/j.psyneuen.2008.09.009.
Overgaauw, S., Güroğlu, B., Crone, E.A., 2012. Fairness considerations when I know more than you do: developmental comparisons. Front. Psychol. 3 (OCT), 1–8. https://doi.org/10.3389/fpsyg.2012.00424.
Platje, E., Vermeiren, R.R.J.M., Branje, S.J.T., Doreleijers, T.A.H., Meeus, W.H.J., Koot, H.M., Frijns, T., van Lier, P.A.C., Jansen, L.M.C., 2013. Long-term stability of the cortisol awakening response over adolescence. Psychoneuroendocrinology 38 (2), 271–280. https://doi.org/10.1016/j.psyneuen.2012.06.007.
Platje, E., Popma, A., Vermeiren, R.R.J.M., Doreleijers, T.A.H., Meeus, W.H.J., van Lier, P.A.C., Koot, H.M., Branje, S.J.T., Jansen, L.M.C., 2015. Testosterone and cortisol in relation to aggression in a non-clinical sample of boys and girls. Aggress. Behav. 41 (5), 478–487. https://doi.org/10.1002/ab.21585.
Prasad, S., Narayanan, J., Lim, V.K.G., Koh, G.C.H., Koh, D.S.Q., Mehta, P.H., 2017. Preliminary evidence that acute stress moderates basal testosterone's association with retaliatory behavior. Horm. Behav. 92, 128–140. https://doi.org/10.1016/j.yhbeh.2016.10.020.
Prasad, S., Knight, E.L., Mehta, P.H., 2019. Basal testosterone's relationship with dictator game decision-making depends on cortisol reactivity to acute stress: a dual-hormone perspective on dominant behavior during resource allocation. Psychoneuroendocrinology 101 (ember 2018), 150–159. https://doi.org/10.1016/j.psyneuen.2018.11.012.
Pruessner, J.C., Kirschbaum, C., Meinlschmid, G., Hellhammer, D.H., 2003. Two formulas for computation of the area under the curve represent measures of total hormone concentration versus time-dependent change. Psychoneuroendocrinology 28 (7), 916–931. https://doi.org/10.1016/S0306-4530(02)00108-7.
Rauch, S.A.M., King, A., Kim, H.M., Powell, C., Rajaram, N., Venners, M., Simon, N.M., Hamner, M., Liberzon, I., Arbor, A., States, U., Arbor, A., States, U., Arbor, A., States, U., Division, T., Park, M., States, U., States, U., Square, O.B., 2020. Cortisol awakening response in PTSD treatment: predictor or mechanism of change. Psychoneuroendocrinology. https://doi.org/10.1016/j.psyneuen.2020.104714. Cortisol.
Rutland, A., Killen, M., 2017. Fair resource allocation among children and adolescents: the role of group and developmental processes. Child Dev. Perspect. 11 (1), 56–62. https://doi.org/10.1111/cdep.12211.
Ruttle, P.L., Shirtcliff, E.A., Armstrong, J.M., Klein, M.H., Essex, M.J., 2015. Neuroendocrine coupling across adolescence and the longitudinal influence of early life stress. Dev. Psychobiol. 57 (6), 688–704. https://doi.org/10.1002/dev.21138.
Schmidt-Reinwald, A., Pruessner, J.C., Hellhammer, D.H., Federenko, I., Rohleder, N., Schürmeyer, T.H., Kirschbaum, C., 1999. The cortisol response to awakening in relation to different challenge tests and a 12-hour cortisol rhythm. Life Sci. 64 (18), 1653–1660. https://doi.org/10.1016/S0024-3205(99)00103-4.
Schultheiss, O.C., Mehta, P.H., 2019. Routledge International Handbook of Social Neuroendocrinology. Routledge Abingdon.
Shirtcliff, E.A., Granger, D.A., Schwartz, E., Curran, M.J., 2001. Use of salivary biomarkers in biobehavioral research: cotton-based sample collection methods can interfere with salivary immunoassay results. Psychoneuroendocrinology 26 (2), 165–173. https://doi.org/10.1016/S0306-4530(00)00042-1.
Shirtcliff, E.A., Dismukes, A.R., Marceau, K., Ruttle, P.L., Simmons, J.G., Han, G., 2015. A dual-axis approach to understanding neuroendocrine development. Dev. Psychobiol. 57 (6), 643–653. https://doi.org/10.1002/dev.21337.
Sinclair, D., Purves-Tyson, T.D., Allen, K.M., Weickert, C.S., 2014. Impacts of stress and sex hormones on dopamine neurotransmission in the adolescent brain. Psychopharmacology 231 (8), 1581–1599. https://doi.org/10.1007/s00213-013-3415-z.
Sisk, C.L., Zehr, J.L., 2005. Pubertal hormones organize the adolescent brain and behavior. Front. Neuroendocrinol. 26 (3–4), 163–174. https://doi.org/10.1016/j.yfrne.2005.10.003.
Sladek, M.R., Doane, L.D., 2015. Daily diary reports of social connection, objective sleep, and the cortisol awakening response during Adolescents' first year of college. J. Youth Adolesc. 44 (2), 298–316. https://doi.org/10.1007/s10964-014-0244-2.
de Souza Silva, M.A., Mattern, C., Topic, B., Buddenberg, T.E., Huston, J.P., 2009. Dopaminergic and serotonergic activity in neostriatum and nucleus accumbens enhanced by intranasal administration of testosterone. Eur. Neuropsychopharmacol. 19 (1), 53–63. https://doi.org/10.1016/j.euroneuro.2008.08.003.
Stalder, T., Oster, H., Abelson, J.L., Huthsteiner, K., Klucken, T., Clow, A., 2025. The cortisol awakening response: regulation and functional significance. Endocr. Rev. 46 (1), 43–59.

Steinbeis, N., Bernhardt, B.C., Singer, T., 2012. Impulse control and underlying functions of the left DLPFC mediate age-related and age-independent individual differences in strategic social behavior. Neuron 73 (5), 1040–1051. https://doi.org/10.1016/J.NEURON.2011.12.027.

Su, R., Guo, L., Tang, H., Ye, P., Zhang, S., Xiao, Y., Liu, W., Liu, C., 2020. Comprehensive sexuality education weakens the effect of in-group bias on trust and fairness. Sex. Educ. 20 (1), 33–45. https://doi.org/10.1080/14681811.2019.1610373.

Sutter, M., Zoller, C., Glätzle-Rützler, D., 2019. Economic behavior of children and adolescents – a first survey of experimental economics results. Eur. Econ. Rev. 111, 98–121. https://doi.org/10.1016/j.euroecorev.2018.09.004.

Tarullo, A.R., Tuladhar, C.T., Kao, K., Drury, E.B., Meyer, J., 2020. Cortisol and socioeconomic status in early childhood: a multidimensional assessment. Dev. Psychopathol. 32 (5), 1876–1887. https://doi.org/10.1017/S0954579420001315.

Tian, T., Young, C.B., Zhu, Y., Xu, J., He, Y., Chen, M., Hao, L., Jiang, M., Qiu, J., Chen, X., Qin, S., 2021. Socioeconomic disparities affect Children's Amygdala-Prefrontal circuitry via stress hormone response. Biol. Psychiatry 90 (3), 173–181. https://doi.org/10.1016/j.biopsych.2021.02.002.

Trotman, H.D., Holtzman, C.W., Ryan, A.T., Shapiro, D.I., MacDonald, A.N., Goulding, S. M., Brasfield, J.L., Walker, E.F., 2013. The development of psychotic disorders in adolescence: a potential role for hormones. Horm. Behav. 64 (2), 411–419. https://doi.org/10.1016/j.yhbeh.2013.02.018.

Vijayakumar, N., Op de Macks, Z., Shirtcliff, E.A., Pfeifer, J.H., 2018. Puberty and the human brain: insights into adolescent development. Neurosci. Biobehav. Rev. 92 (June), 417–436. https://doi.org/10.1016/j.neubiorev.2018.06.004.

Vugt, M.Van, Cremer, D. de, Janssen, D.P., 2007. Gender differences in cooperation and competition: the Male-warrior hypothesis. Psychol. Sci. 18 (1), 19–23.

Wang, H., Zhang, S., Wu, S., Qin, S., Liu, C., 2022. Cortisol awakening response and testosterone jointly affect adolescents' theory of mind. Horm. Behav. 146 (August), 105258. https://doi.org/10.1016/j.yhbeh.2022.105258.

Wright, L., Bukowski, W.M., 2021. Gender is key: Girls' and Boys' cortisol differs as a factor of socioeconomic status and social experiences during early adolescence. J. Youth Adolesc. 50 (6), 1281–1291. https://doi.org/10.1007/s10964-020-01382-z.

Yamagishi, T., Takagishi, H., De Souza Rodrigues Fermin, A., Kanai, R., Li, Y., Matsumoto, Y., 2016. Cortical thickness of the dorsolateral prefrontal cortex predicts strategic choices in economic games. Proc. Natl. Acad. Sci. USA 113 (20), 5582–5587. https://doi.org/10.1073/pnas.1523940113.

Zhu, Y., Chen, X., Zhao, H., Chen, M., Tian, Y., Liu, C., Han, Z.R., Lin, X., Qiu, J., Xue, G., Shu, H., Qin, S., 2019. Socioeconomic status disparities affect children's anxiety and stress-sensitive cortisol awakening response through parental anxiety. Psychoneuroendocrinology 103 (19), 96–103. https://doi.org/10.1016/j.psyneuen.2019.01.008.

Zilioli, S., Ponzi, D., Henry, A., Maestripieri, D., 2015. Testosterone, cortisol and empathy: evidence for the Dual-Hormone hypothesis. Adapt. Hum. Behav. Physiol. 1 (4), 421–433. https://doi.org/10.1007/s40750-014-0017-x.