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Testosterone and cortisol jointly mediate and modulate trust behavior in early adolescence

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ABSTRACT

During early adolescence, individuals undergo significant changes in neuroendocrine systems, neurodevelopment, and social sensitivity. Placing trust in the appropriate person becomes especially crucial for adolescents, given their increased peer interaction and heightened susceptibility to peer influence during this period. Adolescents take social distance into account when making trust decisions. However, the biological and cognitive mechanisms involved in trust decision-making towards peers of different social distances remain unclear. The present study investigated the interactions among hormonal (basal cortisol and basal testosterone), cognitive (impulsivity and theory of mind), and contextual (friends and strange peers) factors underlying trust decision-making in a sample of 142 adolescents (45 % females, M_{age} = 12.32 years, SD_{age} = 0.60). Using a balloon analog risk task, a cartoon story reasoning task, and a modified version of the trust game, we assessed adolescents' impulsivity, theory of mind, as well as trust investment and evaluation of return possibility towards their friends and strangers, separately. The results showed a unique hormonal-cognitive-contextual mechanism underlying trust investment, despite adolescents demonstrating a preference for trusting friends over strangers in both trust investment and trust evaluation. Cortisol predominantly influenced adolescents' general trust, directly and indirectly through impulsivity. Testosterone appeared to modulate the indirect effect of cortisol via impulsivity on general trust and impacted their strategic trust decisions through the theory of mind. These findings highlight the role of cortisol and testosterone in trust and its potential cognitive process and provide guidance for tailored interventions for promoting healthy social development.

1. Introduction

Adolescence signifies a pivotal transition between childhood dependence and adult independence when teenagers undergo intense physical growth, endocrine changes, cognitive development, and social maturation (Dahl et al., 2018; Wesarg-Menzel et al., 2023). This period, when adolescents are actively engaged in the more complex social world, equips them with key perspective-taking abilities and social skills necessary to thrive in society (Sweijen, te Brinke, et al., 2023a, 2023b). A primary goal throughout adolescence involves developing mature societal values and social relationships (Crone and Fuligni, 2020). Seeding trust emerges as a vital prerequisite for building impactful interpersonal connections (Schreuders et al., 2023). Extensive research has investigated the psychological (Ma et al., 2022; Sijtsma et al., 2023) and neural (Lemmers-Jansen et al., 2019; Sijtsma et al., 2023) mechanisms of trust in adolescents, as well as various influencing factors such as personality traits (Derks et al., 2014; Fett et al., 2014; van de Groep et al., 2020), and decision-making contexts (Sweijen, te Brinke, et al., 2023a, 2023b; Sweijen, van de Groep et al., 2020). However, limited attention to puberty hormones has left a gap in understanding how these factors interact with hormones and contribute collectively to adolescents' trust-related behaviors (Tereshchenko and Smolnikova, 2019). Our study aims to bridge this gap by simultaneously considering hormonal (basal cortisol and basal testosterone), cognitive (impulsivity and theory of mind, ToM), and contextual (friends and strangers) factors to elucidate the intricate dynamics of trust and to unravel the

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hormonal-cognitive-contextual mechanisms underlying trust behavior during this crucial developmental stage.

1.1. Reflective-impulsive model and adolescent contextual trust frameworks

Trust is defined as a willingness of individuals to take certain risks and entrust their resources to the other party in the context of social uncertainty (Reiter et al., 2023; Mayer et al., 1995). This willingness encapsulates an optimistic belief that the reciprocal actions of another will be beneficial but sometimes backfires (Schreuders et al., 2023). As such, trust is commonly considered as an investment incorporating risk and benefits. According to the reflective-impulsive model, trust is driven by both automatic, impulsive responses and deliberate, reflective thinking processes (Murray et al., 2011; Strack and Deutsch, 2004). Impulsive responses are characterized by quick, intuitive judgments based on immediate perceptions. In contrast, reflective processes involve more deliberate consideration of contextual information, weighing potential risks and benefits before making a decision. The interaction between these impulsive and reflective processes can vary depending on individual differences and trust scenarios (Hermes et al., 2018). For instance, individuals high in impulsivity tend to prioritize immediate gut reactions over thorough risk evaluations when gauging trust, leading to readily believing others (Ibáñez et al., 2016; Murray et al., 2011). In contrast, individuals with advanced ToM abilities can incorporate more nuanced social cues and mental state attributions into their trust judgments, thereby demonstrating a repertoire of adaptive strategies tailored to diverse situational demands (Fett et al., 2014; Prevost et al., 2015).

The developmental trajectories of impulsivity and ToM during adolescence diverge, along with structural and functional alterations in the social brain (Crone and Achterberg, 2022; Crone and Dahl, 2012; Kilford et al., 2016). Increased impulsivity during early adolescence (puberty) is likely attributable to heightened propensities for sensation-seeking and reward salience, resulting from a biologically driven remodeling of dopaminergic pathways in the social-emotional system (limbic regions including amygdala and insula) (Kragel et al., 2015; Steinberg, 2008). As the social-cognitive system (medial prefrontal cortex and temporoparietal junction) matures, enhancing the capacity of self-regulation enables the inhibition of impulsivity. Concurrently, the ToM undergoes gradual maturation (Andrews et al., 2021; Nelson et al., 2016; Van Overwalle, 2009). Variations in the maturation of adolescents' social-emotional and social-cognitive systems among adolescents contribute to discrepancies in their impulsive tendencies and ToM abilities, thereby showing divergent patterns in trust decision-making (Fett et al., 2014; van de Groep et al., 2020). In the present study, we investigated how impulsivity and ToM jointly influence adolescents' interpersonal trust. Traditionally, trust has been examined in relation to unknown others (Ma et al., 2022; Potts et al., 2019; Sabater-Grande et al., 2022). Notably, adolescents exhibit a unique social orientation, spending more time with friends and peers compared to children and adults, and showing particular sensitivity to peer relationships (Hostinar et al., 2015; Nelson et al., 2016). Recent studies demonstrated that adolescent trust was strongly dependent on the interaction partner. For example, Sweijen et al. (2023) found that adolescents (ages 11–20 years) trusted institutional community members less than friends but more than unknown peers. Güroglu et al. (2014) indicated that adolescents (ages 9–18 years) trusted more in friends than in unknown, neutral and disliked peers, with this tendency strengthening as age increased. Consequently, our study extends beyond examining how adolescents initially establish trust with their unknown peers to exploring the strategies and mechanisms applied in interactions with peers of different social distances (friends versus strangers). Specifically, we aim to explore the roles of impulsivity and ToM in both the average level of trust towards friends and strangers (general trust) and the difference in trust levels between friends and strangers (strategic trust). Based on the theoretical accounts and findings outlined above, one hypothesis is that adolescent general trust and strategic trust may be related to impulsivity and ToM, respectively (H1).

1.2. Effects of cortisol and testosterone on trust behavior and decision making

A longstanding hypothesis holds that structural and functional brain reorganization and development observed during adolescence may be specifically related to the hormonal influences governing the onset of and progression through puberty (Blakemore et al., 2010; Chaku and Barry, 2023; Laube et al., 2020; Vijayakumar et al., 2018). Pubertal development involves two crucial endocrine events, adrenarche and gonadarche, which are triggered by activation of the hypothalamic-pituitary-adrenal (HPA) and hypothalamic-pituitary-gonadal (HPG) axes, respectively (L. M. Sisk and Gee, 2022; Trotman et al., 2013). Extensive studies indicated that adrenal (e.g., cortisol) and gonadal (e.g., testosterone) hormonal changes influenced adolescents' brain restructuring, especially in regions associated with sensation-seeking, motivation, and decision-making (Nguyen et al., 2017; Sinclair et al., 2014; C. L. Sisk and Zehr, 2005).

Cortisol, as the primary end-product of the HPA axis, is routinely used as a biomarker of general stress levels when examining the neuroendocrine stress response (Duan et al., 2013; Harris et al., 2017; Hellhammer et al., 2009). Prolonged exposure to stress and dysregulated cortisol secretion during adolescence can detrimentally impact cognitive function, particularly in areas related to executive function and decision-making (Pluck et al., 2021), leading to poor self-regulation (Poon et al., 2016), heightened risk-taking (Finy et al., 2014), increased aggressive and antisocial behaviors (Feilhauer et al., 2013). In terms of trust-related decision-making, although numerous studies have found the correlation between acute stress-reactive cortisol levels/changes and reduced trust (FeldmanHall et al., 2015; Heinrichs et al., 2018; Potts et al., 2019; Takahashi et al., 2005), research on the relationship between basal cortisol levels and trust has been limited and yielded inconsistent results (positive correlation: Javor et al., 2020; no significant correlation: Steinbeis et al., 2015). In addition to the different sources of cortisol samples (blood and saliva), other potential factors may contribute to explaining the incongruous findings. Firstly, cortisol exerts a direct effect on trust decisions, while concurrently, it may indirectly affect decision-making processes by influencing individual characteristics, such as impulsivity. On the one hand, chronic stress exposure can lead to blunted HPA axis activity and hyposecretion of cortisol (Fisher et al., 2011; Miller et al., 2007). Individuals with lower basal cortisol levels may adopt a conservative approach to social interactions, preferring to maintain their existing social relationships and exhibiting reluctance to trust others to cultivate new connections (Kornienko et al., 2016). On the other hand, cortisol is recognized for modulating the impulsive process of decision-making, increasing intuitive and motivated decisions (Margittai et al., 2016; Putman et al., 2010). Pfattheicher and Keller (2014) argued that the relationship between complex social decision-making (e.g., costly punishment) and basal cortisol could be expected based on the common underlying construct of impulsivity. Consistent with prior research on the negative relationship between impulsivity and basal cortisol (Feilhauer et al., 2013), they found that basal cortisol was indeed negatively correlated with costly punishment (Pfattheicher and Keller, 2014). This implies that individuals with lower basal cortisol levels, indicative of heightened impulsivity, may display a propensity to trust others easily due to over-reliance on intuition and insufficient deliberative risk evaluation. The direct effect of basal cortisol on trust, as opposed to its indirect effect through impulsivity, may lead to inconclusive findings in research on the cortisol-trust relationship. On these grounds, in the present study, we expect cortisol to exert its direct impact on adolescents' general trust through socially relevant hormonal mechanisms, as well as its indirect influence by shaping adolescents' impulsivity (H2). Additionally, testosterone, as the other significant hormone in adolescent development, may uniquely influence trust decisions, and based on the dual-hormone hypothesis (Mehta and Josephs, 2010), may also potentially suppress the effects of cortisol, masking the genuine relationship between cortisol and trust.

Testosterone, as a steroid hormone secreted by the HPG axis, predicts better adolescent inhibitory control (Shields et al., 2019), stronger social dominant motivation (Rowe et al., 2004; Schaal et al., 1996), and less social withdrawal (Hayashi et al., 2020) at higher concentrations. Regarding trust-related decision-making, research has consistently shown that testosterone decreased interpersonal trust, as evidenced not only in trust investments (Boksem et al., 2013) but also in facial trustworthiness ratings (Bos et al., 2010, 2012). Interestingly, Bos et al. (2010) conducted further analysis, revealing that this effect was determined by those who gave trust easily, and suggested that testosterone downregulated interpersonal trust by adaptively enhancing social vigilance and calming the impulse toward gullibility. Furthermore, while previous studies often linked higher testosterone levels to impulsivity (Kurath and Mata, 2018), evolutionary theories suggested that risk-taking behavior might have evolved as a strategic means to attain social status (Ellis et al., 2012; Salas-Rodríguez et al., 2021). Recent research found that pubertal testosterone was associated with the willingness to take greater financial risks in pursuit of social status (Cardoos et al., 2017). Individuals with higher testosterone levels even decreased their impulsivity, increased risk-aversion, and adopted safer and more conservative decision-making strategies upon recognizing the potential threat posed to their social dominance or reputation by their risk-taking behavior (van Anders et al., 2012; Votinov et al., 2022). Therefore, in the current study, we speculate that, on the one hand, testosterone moderates the impact of impulsivity on general trust to mitigate the possible losses from excessive credulity and its potential negative consequence on social dominance (H3); on the other hand, testosterone can selectively reduce adolescents' trust in unfamiliar peers over their trust in friends, strategically optimizing the risk-benefit trade-off across various trust contexts to better prepare them for competition over social status and interpersonal resources. Additionally, prior studies demonstrated that ToM was in relation to flexibility and diversity of adaptive strategies tailored to diverse trust situational demands (Fett et al., 2014; Prevost et al., 2015). Higher testosterone was associated with better and faster performance of ToM although only under the condition of lower basal cortisol and cortisol awakening response (Lausen et al., 2020; Wang et al., 2022). In light of these findings, we further hypothesize that the effect of testosterone on strategic trust may be mediated by ToM (H4).

1.3. The current project

Due to the functional crosstalk between the HPA and HPG axes (Joos et al., 2018; Mehta and Prasad, 2015), cortisol and testosterone have exhibited mutual inhibition with each other across multiple behavioral domains, such as aggression (Denson et al., 2013), impulsivity (Mehta et al., 2015), ToM (Lausen et al., 2020; Wang et al., 2022), and social decision-making (Mehta et al., 2017; Prasad et al., 2019). Specifically, the hormonal effects of cortisol or testosterone are significant only when the concentrations of the other hormone are low. This suggests that the interaction between cortisol and testosterone, along with their individual hormonal effects on trust and its influencing factors (e.g., impulsivity and ToM), may collectively contribute to the complexity of hormonal regulation in trust decision-making. Considering the intricate mechanism involved, the present study systematically explored (1) the roles of impulsivity and ToM in adolescents' initial trust in strangers, general trust towards friends and strangers, as well as in strategic trust differences between friends and strangers; how (2) cortisol and (3) testosterone respectively influenced trust decision-making and the effect of impulsivity and ToM on general and strategic trust; (4) how cortisol and testosterone interacted to influence trust decision-making and the effect of the impulsivity and ToM on general and strategic trust. Based on the aforementioned theoretical accounts and empirical findings, we propose the following hypotheses: (1) adolescents' general trust (average trust towards friends and strangers) is associated with impulsivity, whereas their strategic trust (trust difference between friends and strangers) is linked to ToM; (2) cortisol influences general trust both directly, through socially relevant hormonal mechanisms, and indirectly, by shaping impulsivity; (3) testosterone moderates the relationship between impulsivity and general trust, potentially mitigating the risks of excessive credulity and its negative consequences for social dominance; (4) testosterone influences strategic trust through ToM (Fig. 1B).

2. Methods

2.1. Participants

Participants consisted of 172 typically developing adolescents enrolled in the final (sixth) year of primary school in the Beijing urban area. 30 participants were excluded due to their missing data on testosterone or cortisol. Finally, data from 142 participants (45 % females, $M_{\text{age}} = 12.32$ years, $SD_{\text{age}} = 0.60$, range = 10–14 years) were analyzed in the current study. Both adolescents and their legal guardians signed informed consent forms before their participation. All protocols were approved by the institutional review board at Beijing Normal University. All participants received gifts in the form of stationery, pencils, and pens for their participation.

2.2. Experimental procedure

The current study was conducted over two consecutive days (Fig. 1). On the first day, participants were instructed on how to use the Salivette collection device (Sarstedt, Nümbrecht, Germany) to collect saliva samples (for cortisol level analysis), including verbal guidelines and written information in a package. Participants were instructed to collect five saliva samples as directed under parental supervision and to bring them to school the next day: one sample at 50 minutes before bedtime in the evening (S0); four more samples immediately upon waking up the next morning (S1), then at 15 minutes (S2), 30 minutes (S3), and 60 minutes (S4) after waking. They were asked to store these samples in the refrigerator or freezer in the interim. To avoid saliva contamination, participants were reminded to refrain from eating, drinking, or brushing teeth for at least 60 minutes before each collection. They were also asked to avoid consuming any caffeinated products (e.g., coffee, tea, and cocoa) and engaging in excessive exercise the day before their saliva was sampled. They were also required to keep track of sampling times to obtain reliable salivary data as outlined in previous studies. On the second day, participants completed the balloon analog risk task (BART), ToM and empathic accuracy task, and trust game (TG) in sequence at school. We collected the saliva samples either before the start of the BART task or after the completion of the TG task for testosterone level analysis. Saliva samples were then transported on dry ice to an external laboratory for analysis.

2.3. Salivary cortisol and testosterone assay and analysis

The salivary samples transported to the laboratory were immediately stored in a freezer at −80 ℃ until they were assayed for cortisol and testosterone. Samples were excluded from further analysis if participants reported any illness (such as periodontitis, fever, or endocrine diseases), were taking medication (particularly hormone medicines) within the past two weeks, or had a menstrual cycle that was close to the time of sampling (for female participants). The frozen samples were thawed and centrifuged at 3500 rpm for 5 minutes. Cortisol and testosterone concentrations were analyzed by use of electrochemiluminescence immunoassay (Cobas e 601, Roche Diagnostics, Nümbrecht, Germany), with a sensitivity of 0.500 nmol/L (lower limit) and a standard range in the assay of 0.5–1750 nmol/L. The intra- and

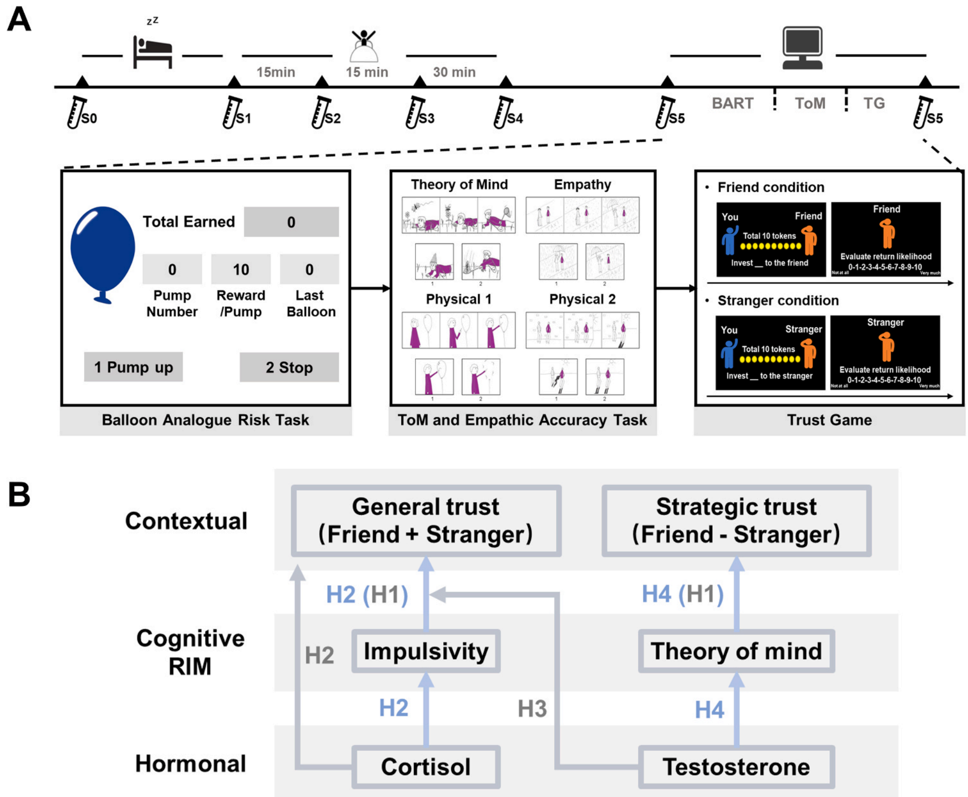

Fig. 1. Study Design and Conceptual Framework. (A) Study flow chart. The study was conducted over two consecutive days. Participants collected five saliva samples under parental supervision: one 50 minutes before bedtime (S0) on the first day, and four upon waking on the second day: immediately (S1), and then at 15 minutes (S2), 30 minutes (S3), and 60 minutes (S4) post-awakening. On the second day, participants completed the BART, ToM, and Empathic Accuracy Task, and the TG at school. An additional saliva sample for testosterone analysis (S5) was collected either before the BART or after the TG. (B) Conceptual diagram. The hypothesized hormonal-cognitive-contextual mechanism underlying adolescent trust decision-making illustrates the relationships among cortisol, testosterone, impulsivity, ToM, and trust behavior (general and strategic trust). H1: Impulsivity is associated with general trust, while ToM is associated with strategic trust. H2: Cortisol influences general trust both directly and indirectly through its effect on impulsivity. H3: Testosterone moderates the pathway linking cortisol, impulsivity, and general trust. H4: Testosterone influences strategic trust via its effect on ToM.

inter-assay coefficient variations were below 10 %. In addition to using pre-bedtime basal cortisol to quantify HPA-axis activity, we calculated other indices, such as AUCg and $AUCi_{night}$, and performed exploratory analyses (see SM: Supplementary analysis of other cortisol indices, Table S1, S2, S4, S11 for details).

2.4. Psychological tasks

2.4.1. Trust game (TG)

The TG was implemented as an investment game to explore the participants' trust behavior in an uncertain situation (Berg et al., 1995; Su et al., 2020). The task involved investing in two rounds with friends and strangers in a random order. In each round, participants, playing as an "investor", were endowed with 10 tokens and were asked to invest any amount of these 10 tokens with a designated "trustee". The trustee received the tripled investment amount and subsequently could decide to repay half of this tripled investment back to the investor or keep the entire amount. The investor would profit if the trustee repaid half, but would lose if they kept everything. Therefore, the amount invested by the investor represented the investor's level of trust, while the amount repaid by the trustee signified the trustee's trustworthiness. After the participants determined how many tokens to invest in, they were required to rate the possibility of receiving a return on their investment from 0 (not at all likely) to 10 (very likely) (Fig. 1A Trust Game).

Participants' amounts invested in friends and strangers, as well as their ratings of return likelihood of friends and strangers, were recoded to calculate trust indicators: *initial trust*, the amount invested for the stranger (Fett et al., 2014); *general trust*, the mean amount invested in the friend and stranger; *strategic trust*, the amount invested in the friend minus the amount invested in the stranger; *initial expectation*, the rating of return likelihood of the stranger; *general expectation*, the mean rating of return likelihood of the friend and stranger; *strategic expectation*, the rating of return likelihood of the friend minus the rating of return likelihood of the stranger.

2.4.2. ToM and empathic accuracy task

Participants performed the task derived from Völlm et al. (2006) consisting of four conditions: ToM, Empathy, Physical 1 (control for ToM), and Physical 2 (control for Empathy). The ToM and Physical 1 stories featured one character, while the Empathy and Physical 2 stories featured two characters. In ToM and Empathy conditions, participants were asked to infer the character's intention and emotion, respectively. In the control conditions (Physical 1 and 2), they made inferences based on physical causality (Fig. 1A ToM and Empathy Accuracy Task).

The task comprised 40 comic strips depicting short stories. These were presented across 8 blocks, with each block containing 5 strips from one condition. The sequences of blocks and strips within blocks were counterbalanced across participants. Each block began with a 6 s introductory question indicating the required inference type (ToM condition: "What will the main character do next?"; Empathy condition: "What will make the main character feel better?"; Physical 1 and Physical 2 conditions: "What is most likely to happen next?"). After viewing each 6 s strip, two possible outcome cartoons were shown at the bottom of the screen for 4.5 s. Participants had to make a choice between the two outcomes as quickly as possible. Accuracy was recorded for all cartoons. A score of one was given for a correct answer, and a score of zero for an incorrect one. The accuracy in the ToM condition was used to evaluate the level of individual ToM.

2.4.3. Balloon analog risk task (BART)

We used the standardized BART computerized gambling task (Lejuez et al., 2002) to assess the participants' impulsive traits (Fig. 1A Balloon Analog Risk Task). Participants were instructed to pump up a simulated balloon on the screen by pressing keys, aiming to maximize the balloon size without causing it to explode in order to earn more rewards. As the balloon grew larger, the chance of explosion also increased. If the balloon exceeded its maximum inflation point, it would explode and reset the earnings for that round to zero. After each balloon explosion or money collection, a new balloon would appear until a total of 30 balloons had been completed. The mean of the standard Z-scores for the proportion of exploded balloons and the average number of unexploded balloons ("adjusted number of pumps") served as a representation of the participant's impulsivity.

2.5. Statistical analysis

Before carrying out the statistical analyses, the hormonal data were assessed for normality with the Shapiro-Wilk test and lg-transformed for those with asymmetric distributions. All hormone indicators were further converted to standardized Z-scores to eliminate range disparity. We conducted Spearman correlation analyses between basal cortisol and testosterone levels and the time of sample collection, excluding the effect of collection time on hormone levels ($ps > 0.05$). After data normalization and excluding the influence of sample acquisition time, gender differences across demographic and hormonal variables were examined using the independent sample *t*-test for continuous variables.

We initially investigated whether adolescents considered social distance in trust decisions through paired *t*-tests to compare the investments and ratings of return likelihood between interactions with friends and strangers. Subsequently, we exploratively performed Spearman correlation analyses between ToM, impulsivity, and trust indicators (Table S3 and S10). Following this, we conducted linear mixed models (LMM, "lme4") (Douglas Bates et al., 2015) on adolescents' initial trust, general trust, strategic trust, initial expectation, general expectation, and strategic expectation, respectively, with impulsivity and ToM as predictors. We used by-participant intercepts for all LMMs.

Next, to test for the possible relationships between cortisol, impulsivity, ToM, and adolescent interpersonal trust, we used basal cortisol, AUCg, and $AUCi_{night}$ as cortisol indexes to conduct Spearman correlation analyses with ToM, impulsivity, and trust indicators, respectively (Table S4 and S11). According to the results, we further applied model 4 of the PROCESS macro to investigate the mediating effect of impulsivity between basal cortisol and general trust, with age and gender as covariates.

In addition, we calculated correlations between testosterone and ToM, impulsivity, and trust indicators (Table S5 and S12). Based on the results, we further utilized Model 4 of the PROCESS macro to investigate the mediating effect of ToM on the relationship between testosterone and trust difference, with age and gender as covariates. Given the sex-specific nature of testosterone, we repeated the above analyses separately for female and male participants, with age as a covariate (Van Anders et al., 2015).

Finally, to explore how dual hormones influence adolescent trust behavior, we utilized several PROCESS models to examine potential moderated mediations. Specifically, we used Model 5, Model 7, Model 8, Model 14, Model 15, Model 58, and Model 59 to analyze the modulating effect of testosterone on cortisol-mediated pathways (Fig. S3) and the modulating effect of cortisol on testosterone-mediated pathways (Fig. S4), with age and gender as covariates.

All statistical analyses were conducted using SPSS (version 25, Chicago, IL, USA) and R (v.4.1.1). All tests were two-tailed and a value of $p < 0.05$ was used to determine statistical significance. Bonferroni adjustments were used to reduce the risk of Type I error when multiple statistical tests were conducted. However, as the Spearman correlation analyses were exploratory, no correction for multiple comparisons was applied. For the LMMs, based on Luke (2017), using restricted maximum likelihood (REML) estimation with the Satterthwaite approximation for *p*-value calculation was suggested to effectively control Type I error inflation, so no additional correction was applied. Bootstrap analyses were used to calculate bias-corrected 95 % confidence intervals for the indirect effects of each putative mediator and moderator (n = 5000 subsamples).

3. Results

3.1. Participant demographics and endocrinal measures

All adolescents went to bed before midnight and woke up after 4:30 am the next morning, sleeping an average of 8.27 hours (Fig. S1A). The HPA axis in adolescents exhibited prominent diurnal dynamics (Fig. S1B). Cortisol levels increased significantly from pre-bedtime (S0, 3.42 ± 0.19 nmol/L) to immediately upon awakening (S1, 12.87 ± 0.44 nmol/L), peaked 15–30 minutes later (S2, 16.51 ± 0.58 nmol/L; S3, 16.49 ± 0.65 nmol/L), then rapidly declined 60 minutes after awakening (S4, 12.26 ± 0.60 nmol/L). Additional independent *t*-tests were used to examine gender differences in major cortisol indicators and testosterone concentration. No significant differences were found between boys and girls in basal cortisol levels (boys: 3.37 ± 2.12 nmol/L, girls: 3.47 ± 2.58 nmol/L, $t(140) = -0.26$, $p = 0.80$, *Cohen's d* = -0.04; Table S2) and basal testosterone (boys: 3.82 ± 1.17 nmol/L, girls: 3.73 ± 1.18 nmol/L, $t(140) = 0.43$, $p = 0.67$, *Cohen's d* = 0.07; Table S2).

3.2. Adolescents' interpersonal trust in different social contexts

Adolescents trusted friends more than strangers, as evidenced by both greater token investments ($M_{friend} = 3.38$, $M_{stranger} = 2.94$, $t(139) = 2.69$, $p_{bonf} < 0.01$, *Cohen's d* = 0.23; Fig. 2A) and higher expected likelihoods of return ($M_{friend} = 5.76$, $M_{stranger} = 4.64$, $t(139) = 4.60$, $p_{bonf} < 0.001$, *Cohen's d* = 0.39; Fig. 2B).

Initial trust and initial expectation There were significant correlations between adolescents' initial trust and impulsivity ($rho = 0.23$, $p < 0.01$; Fig. 3A) and ToM ($rho = -0.17$, $p = 0.05$; Fig. 3D). Regression analyses indicated that initial trust was positively related to impulsivity ($B =$

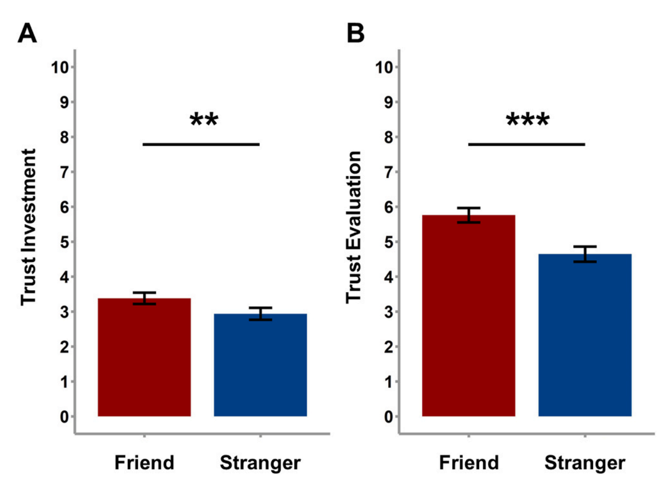

Fig. 2. Trust investment and trust evaluation towards the friend and stranger. Adolescents trusted friends more than strangers, as evidenced by both greater token investment (A) and higher expected likelihood of return (B). Error bars represent the standard error of the mean (s.e.m.). $**p < 0.01$; $***p < 0.001$.

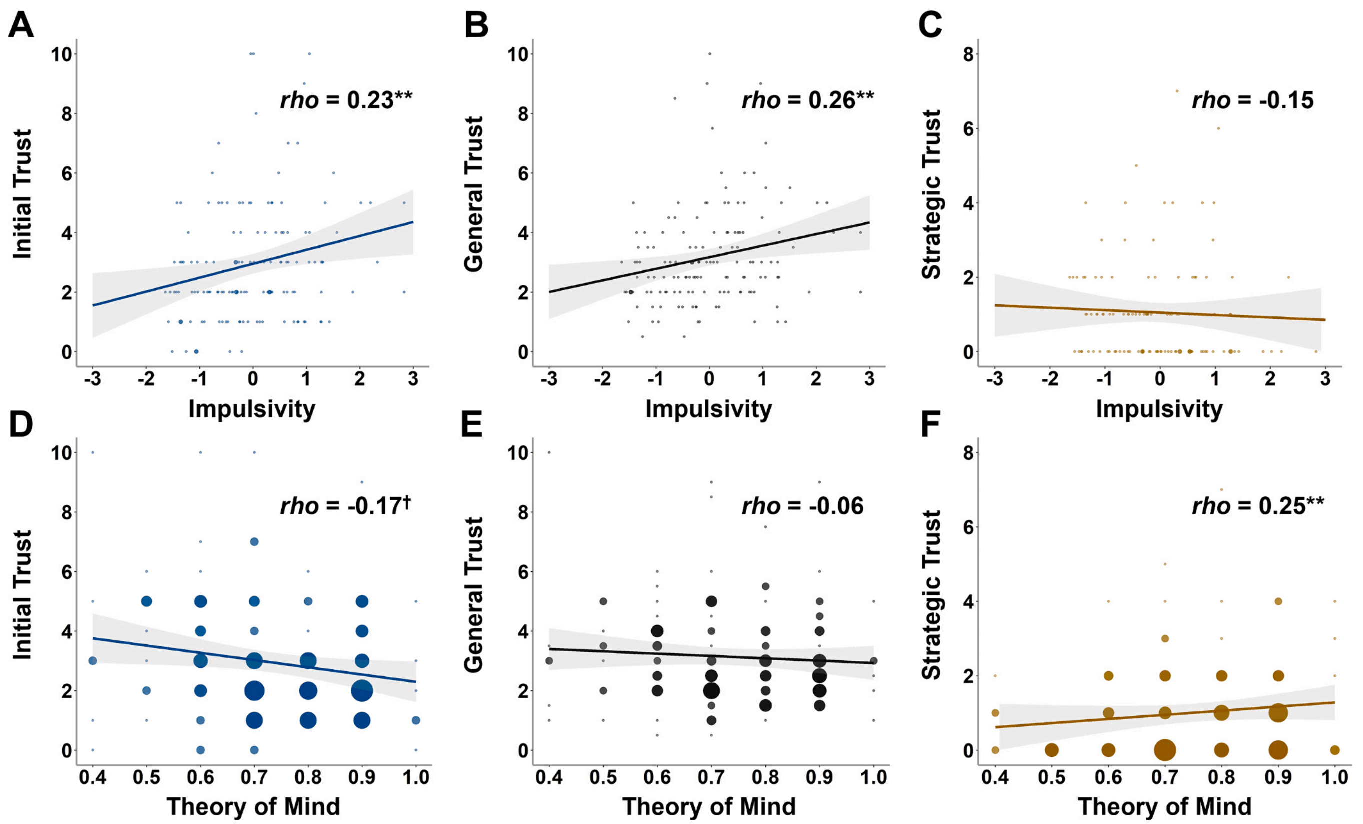

Fig. 3. Correlations between impulsivity, ToM, and trust investment indicators. Spearman correlations were used to analyze the relationships between variables. Data points are represented as bubbles, with size indicating the number of overlapping observations. The gray shaded area shows the 95 % confidence interval around the linear regression line. $^{\dagger}p < 0.1$, $**p < 0.01$.

0.26, $t = 2.98$, $p < 0.01$) and negatively related to ToM ($B = -0.18$, $t = -2.18$, $p = 0.03$). However, the ToM × impulsivity interaction was not statistically significant ($B = -0.12$, $t = -1.26$, $p = 0.21$). Impulsivity and ToM jointly shaped adolescents' initial trust behavior, with impulsivity promoting more adventurous trust tendencies and ToM fostering more cautious, rational decision-making. The lack of a significant interaction suggested that these two traits influenced trust independently rather than interactively during early adolescence. The ongoing development of both social cognition and impulse control during early adolescence may explain the lack of a significant interaction. Regarding initial expectation, only a marginally significant correlation was found with impulsivity ($rho = 0.15$, $p = 0.08$; Fig. 4A), but not with ToM ($rho = -0.02$, $p = 0.86$; Fig. 4D). Regression analyses revealed that initial expectation was positively correlated with impulsivity ($B = 0.16$, $t = 1.71$, $p = 0.09$, statistical marginal significance), but not with ToM ($B = -0.02$, $t = -0.27$, $p = 0.79$) or ToM × impulsivity interaction ($B = -0.02$, $t = -0.25$, $p = 0.81$).

General trust and general expectation Adolescents' general trust was mainly related to impulsivity ($rho = 0.26$, $p < 0.01$; Fig. 3B) rather than ToM ($rho = -0.06$, $p = 0.5$; Fig. 3E). Regression analyses indicated that general trust was positively related to impulsivity ($B = 0.24$, $t = 2.73$, $p < 0.01$), but not to ToM ($B = -0.06$, $t = -0.76$, $p = 0.45$) or the ToM × impulsivity interaction ($B = -0.07$, $t = -0.84$, $p = 0.40$). Regarding general expectation, a similar correlation was found with impulsivity ($rho = 0.20$, $p < 0.05$; Fig. 4B) rather than ToM ($rho = 0.06$, $p = 0.53$; Fig. 4E). Regression analyses revealed that general expectation was positively correlated with impulsivity ($B = 0.15$, $t = 1.67$, $p = 0.1$, statistical marginal significance), but not with ToM ($B = 0.04$, $t = 0.41$, $p = 0.68$) or the ToM × impulsivity interaction ($B = 0.07$, $t = 0.72$, $p = 0.48$). Adolescents with higher impulsivity showed increased general trust, extending to both friends and strangers. Concurrently, they tended to have more optimistic expectations regarding the likelihood of return, particularly in evaluations involving strangers, though this relationship was marginally significant.

Strategic trust and strategic expectation Adolescents' strategic trust was mainly associated with ToM ($rho = 0.25$, $p < 0.01$; Fig. 3C) rather than impulsivity ($rho = -0.15$, $p = 0.07$; Fig. 3F). Regression analyses indicated that strategic trust was positively related to ToM ($B = 0.25$, $t = 3.15$, $p < 0.01$) but not to impulsivity ($B = -0.14$, $t = -1.58$, $p = 0.12$) or the ToM × impulsivity interaction ($B = 0.11$, $t = 1.25$, $p = 0.22$). However, we found no significant relationships between adolescent strategic expectation and impulsivity (Spearman correlation: $rho = -0.02$, $p = 0.85$; LMM: $B = -0.08$, $t = -0.83$, $p = 0.41$; Fig. 4C), ToM (Spearman correlation: $rho = 0.13$, $p = 0.12$; LMM: $B = 0.09$, $t = 1.08$, $p = 0.28$; Fig. 4F) or the ToM × impulsivity interaction ($B = 0.15$, $t = 1.56$, $p = 0.12$). Adolescents with high ToM exhibited heightened strategic trust, but not strategic expectation.

3.3. *Effects of cortisol on adolescents' interpersonal trust*

To explore the role of cortisol in adolescents' trust-related decision-making, we conducted correlation analyses among cortisol indices (basal cortisol, AUCg and $AUCi_{night}$), cognitive factors (ToM and impulsivity) and trust indicators (initial trust, general trust and strategic trust; initial expectation, general expectation and strategic expectation) (Table S4). We found that adolescent cortisol indices were mainly related to impulsivity and general trust. Basal cortisol was negatively correlated with impulsivity ($rho = -0.2$, $p < 0.05$) and positively correlated with general trust ($rho = 0.16$, $p = 0.056$, marginal significance). AUCg was negatively correlated with impulsivity ($rho = -0.17$,

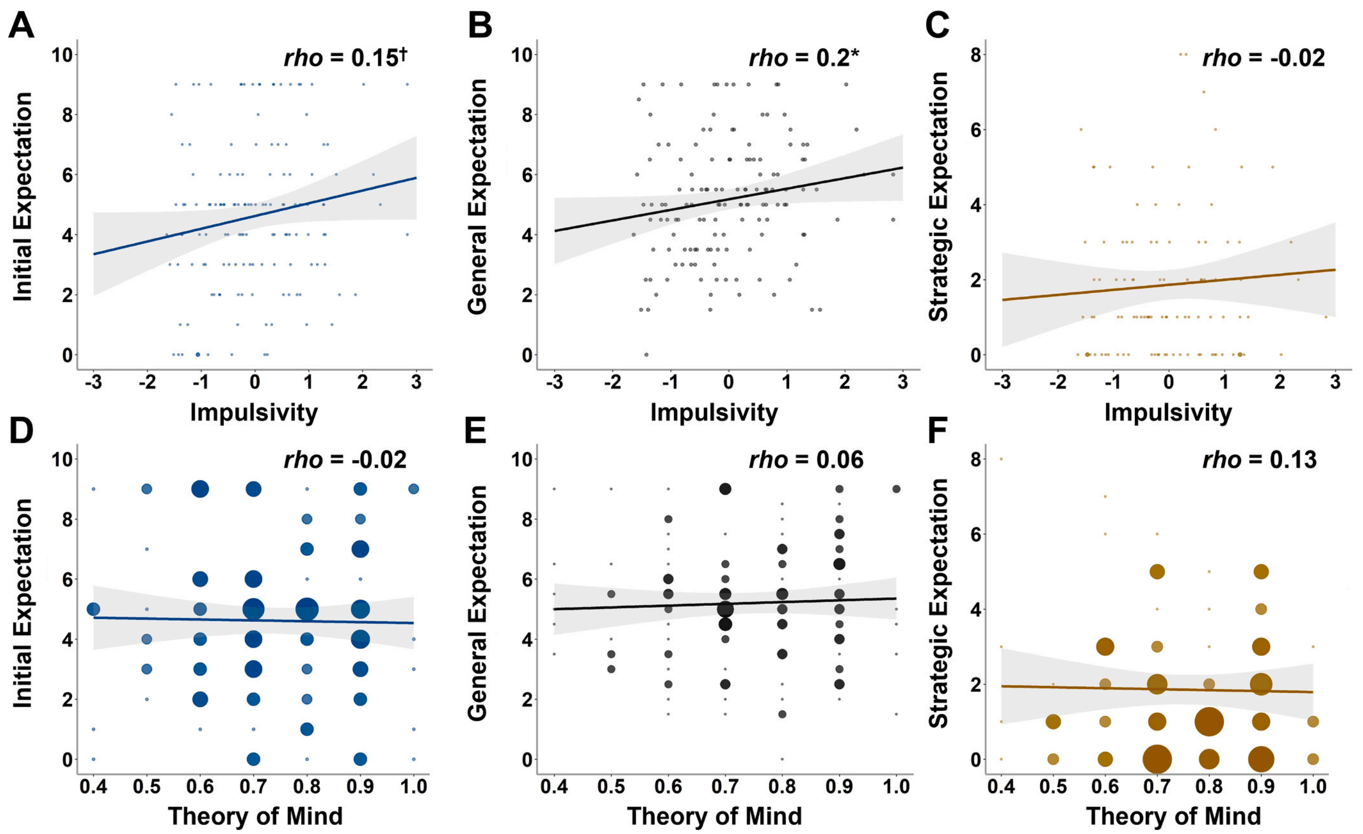

Fig. 4. Correlations between impulsivity, ToM, and trust evaluation indicators. Spearman correlations were used to analyze the relationships between variables. Data points are represented as bubbles, with size indicating the number of overlapping observations. The gray shaded area shows the 95 % confidence interval around the linear regression line. $^{\dagger}p < 0.1$, $^{**}p < 0.01$.

$p < 0.05$). AUCi$_{night}$ was negatively correlated with general trust ($rho = -0.17$, $p < 0.05$). Given these relationships, we further examined whether impulsivity mediated the relationship between basal cortisol and general trust. The findings revealed a significant direct effect of basal cortisol on general trust ($B = 0.22$, $p < 0.01$, *95 % CI* = [0.06, 0.39]), as well as an indirect effect via impulsivity ($B = -0.06$, $p < 0.05$,

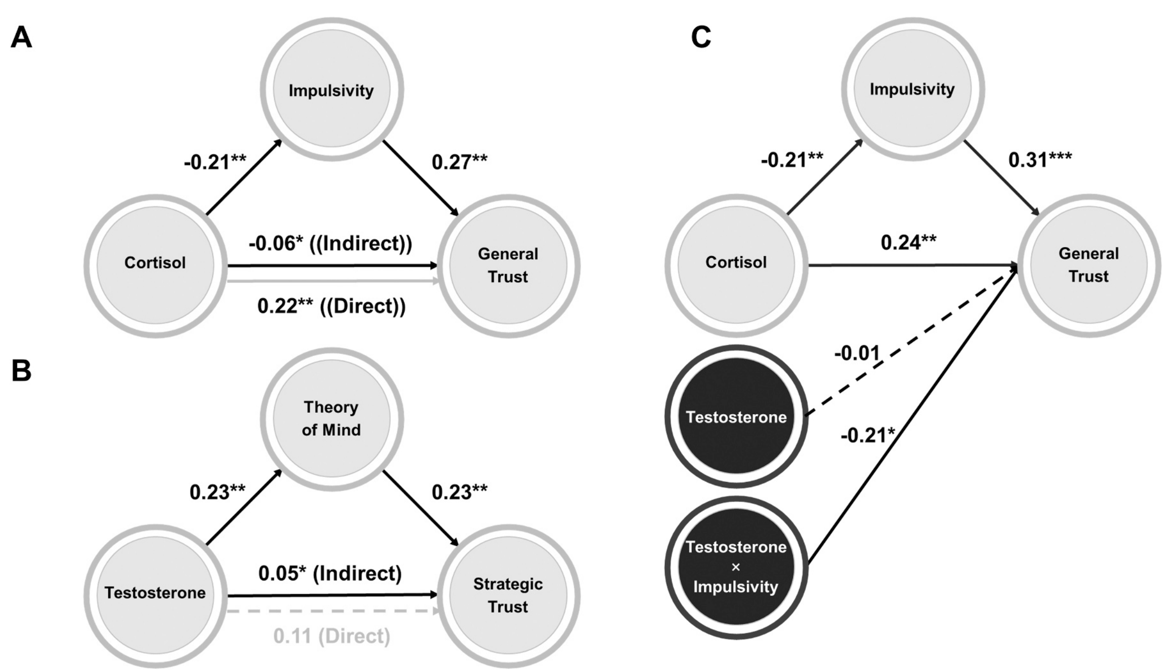

Fig. 5. Testosterone and cortisol jointly mediate and modulate trust behavior. (A) The effect of basal cortisol on general trust was partially mediated by impulsivity. (B) The effect of basal testosterone on strategic trust was fully mediated by ToM. (C) Testosterone moderated the mediating effect of cortisol on the association between impulsivity and general trust. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

95 % CI = [-0.12, −0.01]). Overall, these results suggested that the relationship between basal cortisol and general trust was partially mediated by impulsivity (Fig. 5A).

3.4. Effects of testosterone on adolescents' interpersonal trust

To investigate the role of testosterone in adolescents' trust-related decision-making, we conducted correlation analyses among testosterone, ToM, impulsivity, and trust indicators (Table S5). Adolescents' testosterone levels were positively associated with ToM ($rho = 0.21$, $p < 0.05$; boys: $rho = 0.22$, $p = 0.06$; girls: $rho = 0.2$, $p = 0.12$) and strategic trust ($rho = 0.15$, $p = 0.08$, marginal significance; Boys: $rho = 0.26$, $p < 0.05$; Girls: $rho = 0.01$, $p = 0.93$). Based on these results, we examined the mediating role of ToM between testosterone and strategic trust. The relationship between testosterone and strategic trust was fully mediated by ToM ($B = 0.05$, $p = 0.03$, *95 % CI* = [0.01, 0.12]). We further repeated the mediation analysis separately for male and female participants, and found a significant mediation effect only among male participants. The results showed both a significant direct effect of basal testosterone on strategic trust ($B = 0.28$, $p = 0.02$, *95 % CI* = [0.04, 0.52]), and an indirect effect through ToM ($B = 0.08$, $p = 0.04$, *95 % CI* = [0.06, 0.18]). Adolescents with higher basal testosterone levels demonstrated enhanced ToM abilities that guided their strategic trust (Fig. 5B). This effect was primarily driven by the male sample.

3.5. Effects of dual-hormones on adolescents' interpersonal trust

To investigate the influence of dual hormones on adolescent trust-related decision-making, we employed several PROCESS models to test potential moderated mediation effects. We first explored the moderating effect of testosterone on the cortisol-impulsivity-general trust mediation model. The cross-product term between testosterone and impulsivity on general trust was statistically significant ($B = -0.21$, $p < 0.05$, *95 % CI* = [-0.40, −0.01]). Using conventional procedures, we plotted the conditional effects at high (+1 *SD*) and low (-1 *SD*) levels of testosterone. The indirect effect of cortisol on general trust through impulsivity was observed when testosterone levels were moderate and low ($B = -0.11$, *95 % CI* = [-0.23, −0.02]), but not when participant's testosterone concentration was high ($B = -0.02$, *95 % CI* = [-0.07, 0.02]) (Table S6 and S7; Fig. 5C). We tested alternative model pathways but found no significant effects. We also investigated whether cortisol modulated the mediating effect of testosterone on strategic trust through ToM. However, we did not find any statistically significant effects for cortisol modulations.

4. Discussion

Trust, often called the "lubricant of society", is crucial for developing mature relationships and societal values during adolescence. The current study explored how basal cortisol and basal testosterone, impulsivity, and ToM mutually influence general trust and strategic trust towards friends and strangers, and revealed the hormonal-cognitive-contextual mechanisms underlying trust decision-making in early adolescents (Fig. S5). When making trust decisions, adolescents considered social distance and showed a tendency to trust friends over strangers in trust investment and evaluation. High impulsivity increased general trust levels (including investment and evaluation), while high ToM increased strategic trust (only in investment) by selectively decreasing their trust in strangers. The biological and cognitive processes involved in trust investment interacted in a specific manner. Cortisol predominantly influenced general trust, directly and indirectly through impulsivity. Testosterone modulated the indirect effect of cortisol via impulsivity on trust and impacted strategic trust through ToM.

Adolescence marks a critical window of social reorientation, where peer influence and trust violations can significantly impact mental health and social development (Nelson et al., 2016; Schreuders et al., 2023). It is therefore imperative for adolescents to learn whom to trust and adjust their behaviors accordingly. We found that adolescents could utilize social cues, such as social distance, to make strategic trust decisions, trusting friends more than strangers. Our findings highlight the distinct roles of impulsivity and ToM in trust investment and evaluation. Impulsivity led to higher general trust and more optimistic evaluations of returns, especially towards strangers, whereas ToM helped adolescents strategically assess risks and optimize trust with both friends and strangers. Specifically, ToM is linked to a selective decrease in trust towards strangers, reducing trust investment but not evaluation. This suggests that adolescents with advanced ToM may recognize greater uncertainty in strangers, leading to more cautious investment decisions, though they do not necessarily expect lower returns from them.

We found that basal cortisol was negatively related to impulsivity and positively related to general trust investment, with a complex relationship. On the one hand, low basal cortisol has been associated with underarousal and reduced sensitivity to stress, which may diminish fear of consequences and increase impulsivity (fearlessness theory) (Raine, 1993, 1996). Cortisol also modulates decision-making, promoting more intuitive, motivated choices (Margittai et al., 2016). Therefore, adolescents with lower cortisol levels exhibit greater impulsivity and are more inclined to trust others, likely driven by a reliance on intuitive judgments rather than deliberate risk evaluation. On the other hand, adolescents with lower basal cortisol levels display diminished general trust. HPA activation can be associated with the development of social connections as a means of acquiring essential resources from social groups to overcome stressful conditions ("tend-and-befriend" pattern) (Taylor, 2006; Taylor et al., 2000). Therefore, adolescents with lower basal cortisol may have trouble developing new relationships due to a lack of basic trust in others. In summary, adolescents with lower basal cortisol levels exhibit contradictory tendencies—both social withdrawal and reluctance to trust, as well as impulsive desires to trust others. Neither pattern supports the development of healthy relationships. Reluctance to trust can lead to isolation, while impulsive trust increases vulnerability to exploitation. However, our findings suggest that testosterone may act as a buffer, helping to navigate these challenges.

We found that adolescent basal testosterone was related to ToM and strategic trust , with the relationship between testosterone and trust fully mediated by ToM. Higher testosterone levels were associated with better ToM, which guided selective trust in more trustworthy individuals, like friends over strangers. The adaptive behavior can help adolescents navigate social environments, fostering integration, resource allocation, and stronger social bonds. We also found that testosterone modulated the cortisol-impulsivity-general trust relationship. When testosterone levels were moderate and low, cortisol influenced trust through impulsivity; however, this effect was absent at high testosterone levels. HPA and HPG axes are commonly considered as mutually inhibitory systems (Joos et al., 2018; Mehta and Prasad, 2015). Elevated cortisol levels can suppress the HPG axis at multiple levels, including the inhibition of gonadotropin-releasing hormone neurons in the hypothalamus, the release of luteinizing hormone and follicle-stimulating hormone from the pituitary gland, and gonadal hormone production (Dorn and Biro, 2011; Trotman et al., 2013). Conversely, androgens inhibited the HPA function through actions at the androgen receptor or ERbeta (Handa and Weiser, 2014). The dual-hormone hypothesis proposes that the HPA axis and HPG axis are connected by extensive functional cross-talk, with testosterone and cortisol potentially inhibiting the behavioral effects of each other, supported by numerous studies across multiple behavioral domains such as dominance, risk-taking, emotion recognition, as well as social cognition and decisions (Denson et al., 2013; Lausen et al., 2020; Mehta et al., 2015, 2017; Nitschke and Bartz, 2020; Prasad et al., 2019; Wang et al., 2022; Zilioli et al., 2015). Furthermore, testosterone is well-known to be associated with the pursuit and maintenance of status and dominance within social hierarchies (Eisenegger et al., 2011; Liao et al., 2023).

Hence, testosterone serves as both a physiological and psychological moderator of the influence of cortisol, mediates through impulsivity, on general trust. This moderation allows for prudent trust decisions, reducing vulnerability to exploitation while maintaining social connections necessary for cooperation and support. In summary, testosterone's adaptive mechanism facilitates adolescents' ability to optimize social functioning and enhance overall fitness within their own social hierarchies.

Some limitations in our study should be mentioned. First, our focus on trust excluded other important aspects of social decision-making, such as fairness and cooperation, which future studies should address for a more comprehensive understanding. Second, the cross-sectional design limited the study to a single point in time, preventing an examination of how trust behaviors evolve with adolescents' changing life circumstances. As adolescents age, increasing academic pressure and pubertal hormonal fluctuations may influence both trust behaviors and hormonal regulation (e.g., cortisol and testosterone). Future studies should use longitudinal designs to explore how academic stress, pubertal development, and hormonal changes interact to shape trust behaviors over time. Third, the study's focus on social distance by only differentiating between friends and strangers overlooked the complexity of social relationships. Future research should include a broader range of social relationships, such as family, acquaintances, and teachers, to better understand how different dynamics influence trust formation and maintenance. Fourth, neurobiological models of socioemotional development emphasized the interaction between affective and regulatory brain systems. Integrating neuroimaging could shed light on the brain regions involved in trust-related decision-making, deepening our understanding of the cognitive mechanisms behind trust behaviors. Finally, the relatively small sample size restricted our ability to conduct more complex analyses, such as Structural Equation Modeling (SEM). The sample size was insufficient to support a unified SEM framework incorporating all relevant variables, which would have allowed for a more nuanced exploration of the complex interrelationships among cortisol, testosterone, impulsivity, theory of mind, and various trust indicators. Future research with larger samples would be essential to advance our understanding of these relationships through more robust and comprehensive models.

5. Conclusions

The current study delves into the hormonal-cognitive-contextual mechanisms underlying adolescent trust behaviors. Cortisol predominantly influences general trust, directly and indirectly through impulsivity. Testosterone moderates this indirect effect and impacts strategic trust via ToM. These findings deepen our comprehension of trust decision-making during adolescence, guiding tailored interventions for promoting healthy social development.

CRediT authorship contribution statement

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

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.2025.107483.

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