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Running title: Testosterone and sexual impulsivity

Exogeneous testosterone increases sexual impulsivity in heterosexual men

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Abstract

Testosterone has been hypothesized to promote sexual motivation and behavior. However, experimental evidence in healthy humans is sparse and rarely establishes causality. The present study investigated how testosterone affects delay of gratification for sexual rewards. We administered a single dose of testosterone to healthy young males in a double-blind, placebo-controlled, between-participant design (N = 140). Participants underwent a sexual delay discounting task, in which they made a choice between a variable larger-later option (i.e., waiting longer to view a sexual picture for a longer duration) and a smaller-sooner option (i.e., waiting for a fixed shorter period of time to view the same picture for a shorter duration). We found that testosterone administration increased preference for the smaller-sooner option and induced steeper discounting for the delayed option. These findings provide direct experimental evidence that rapid testosterone elevations increase impulsivity for sexual rewards and represent an important step towards a better understanding of the neuroendocrine basis of sexual motivation in humans.

Keywords: androgen; impulsivity; sexual reward; intertemporal choice; mating

1. Introduction

Testosterone is one of the major sex steroids, and the hypothalamus and pituitary are involved in the control of the secretion of testosterone. For men, it is primarily produced by the Leydig cells of the testes, while the ovaries, placenta and adrenal cortex produce it in women (Mooradian et al., 1987). Testosterone plays a primary role in sexual differentiation and function (Wallen, 1990). In many mammalian species, including humans, gonadal hormones regulate both the ability to copulate and sexual desire. Early studies on castrated men (Heim, 1981) and men undergoing a temporary pharmacological castration (Bagatell et al., 1994) demonstrated that suppression of testicular function led to decreased sexual activity and desire. Androgen therapy restored sexual motivation in these same men (Bagatell et al., 1994), further corroborating the causal role of testosterone in human patients.

Recent research in human neuroendocrinology has highlighted the role of testosterone in human decision-making and reward processing (Kurath and Mata, 2018). For example, risk-taking measured in an investment game was positively associated with salivary testosterone levels (Apicella et al., 2008). Testosterone fluctuation induced by winning or losing money in a chance-based competition predicted risk-taking tendencies (Apicella et al., 2014). Recent evidence suggests that testosterone and cortisol jointly regulate risk taking (Mehta et al., 2015). Moreover, both circulating levels of testosterone (Doi et al., 2015) and exogenous testosterone (Wu et al., 2020) were positively associated with decision impulsivity. Finally, endogenous testosterone levels correlated with sexual compulsivity scores (Nyby, 2008; Rodríguez-Nieto et al., 2021). These findings could be accommodated within the Challenge Hypothesis, according to which individual testosterone levels fluctuate in response to challenging cues in the environment, and these challenge-induced fluctuations in testosterone

could in turn modulate human social behavior, such as mating, aggression and risk taking (Archer, 2006; Wingfield et al., 1990).

It is well recognized that testosterone fluctuates in sexual contexts (Zilioli and Bird, 2017). For example, early research in this field showed that watching a sexually explicit movie led to plasma testosterone elevations in healthy young men (Pirke et al., 1974). More recent research showed that brief social interactions with a young woman effectively induced salivary testosterone increases in heterosexual men (Roney et al., 2007) and exposure to periovulatory odors had similar effects on men's testosterone level (Cerda-Molina et al., 2013). Moreover, visiting a sex club was associated with testosterone elevations, particularly among those men engaging in sexual activities (Escasa et al., 2011). These socially induced acute changes in testosterone levels represent a phylogenetically conserved phenomenon and may serve adaptive functions for sexual behavior as well as situationally affect it. For example, higher testosterone levels may lead to increased sexual impulsivity and risk taking.

In non-human animals, acute testosterone pulses affect behavior related to mating and, ultimately, reproductive fitness either directly (e.g., copulatory behavior) or indirectly (e.g., reward processing) (Nyby, 2008). Recent theoretical accounts propose similar relationships in humans (Goetz et al., 2019; Zilioli and Bird, 2017). There is increasing recognition that socially induced testosterone reactivity could modulate sexual desire and behavior in a variety of species. To date, very few studies have directly tested this hypothesis, and most of them relied on correlational data. One example study (Van Anders et al., 2009) measured testosterone and sexual desire before and after forty healthy premenopausal women watched an erotic video. Although testosterone levels did not increase in response to the sexual stimulus, post-video testosterone concentrations positively correlated with sexual desire. In

another study, men's testosterone and sexual desire increased in responses to women's olfactory cues (Cerda-Molina et al., 2013). Moreover, testosterone increases induced by men competing against each other was associated with subsequently elevated sexual motivation, assessed through courtship behaviors towards a female confederate (van der Meij et al., 2012). These studies have shown that the relationship between testosterone and sexual behavior is bidirectional. More compelling causal claims can be obtained in experimental designs in which sexual motivation is assessed after direct manipulation of testosterone concentration. So far, only few studies have directly tested the rapid effects of a single dose administration of testosterone on sexual motivation and behavior in healthy men.

The aim of the present study was to investigate the effects of testosterone on sensitivity to sexual rewards, particularly on sexual impulsivity, which was assessed via a sexual delay discounting task (SDDT). In a typical delay discounting task, participants are asked to choose between two rewarding options, a smaller reward available sooner and a larger reward available later (Bickel and Marsch, 2001). As delay increases, the value of the larger reward decreases. This decrease corresponds to discounting and is typically well captured by hyperbolic functions. More impulsive individuals have a stronger preference for smaller-sooner (vs. large-later) rewards and exhibit steeper discounting (Johnson et al., 2020; Kable and Glimcher, 2007). In the SDDT, participants were asked to choose between two options: (a) wait for a short amount of time (i.e., 1 s) to briefly (1 s) view a sexual picture; or (b) wait for longer (i.e. between 3 s and 15 s) to view the sexual picture for a longer duration (3 s; Girard et al., 2019). We hypothesized that testosterone administration would increase impulsivity for sexual rewards. Given that sexual compulsion and crime is more prevalent among men than women (Elliott et al., 2004; Finkelhor et al., 1990), we recruited only men in the present study.

2. Methods

2.1. Participants

One hundred and forty healthy heterosexual men (mean age = 20.79 years, *SD* = 1.89, age range = 18-26) were recruited through university advertisement. We screened participants through telephone interview, and those individuals who were taking psychotropic medications or having any psychiatric/neurological disorders were not included. We recruited men as the dosing and pharmacokinetics of single-dose topical testosterone administration with Androgel are only established for men (Eisenegger et al., 2013). Participants were instructed to abstain from alcohol, caffeine intake, and smoking for 24 h before the testing session. Participants' sexual orientation was measured with the Kinsey Scale (Kinsey et al., 2003), a self-reported sexual orientation scale (0 is exclusively heterosexual, 3 is equally heterosexual and homosexual, and 6 is exclusively homosexual) (*M* = 0.06, *SD* = 0.32, range = 0-2), and they were asked to abstain from any sexual activity for 24 hours before the experimental session. Participants' trait impulsivity level was measured using the Barratt Impulsivity Scale (BIS-11) (Patton et al., 1995). Each participant received a single dose of Androgel or placebo gel in a double-blind, placebo-controlled, between-participants design. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Shenzhen University Medical Research Ethics Committee. Written informed consent was obtained from all participants. Participants were compensated with 170 Chinese Yuan (~ $ 24) as a participation fee.

2.2. Testosterone administration

All sessions started at 13:00 and lasted approximately 4 hours. Participants in the testosterone group received a single dose of testosterone gel, containing 150 mg testosterone [Androgel®].

Participants in the placebo group received a colorless hydroalcoholic gel. In both treatment groups, the gel was applied to the participant's shoulders and upper arms by a male research assistant, who was blind to both the experimental condition (i.e., the testosterone gel and placebo were packed identically) and purpose of the study. Participants waited three hours before the start of the experimental tasks in accordance with previous pharmacokinetic data, which showed a peak 3 hours after administration and elevated serum levels still 7 hours after administration (Carré et al., 2016; Eisenegger et al., 2013; Wu et al., 2018, 2019). Participants also completed two additional tasks on social cognition that are not reported here. The order of the tasks was counterbalanced across participants. During the waiting period, participants were asked to stay in the testing rooms and were provided with newspapers and magazines that were not related to the study.

2.3. ***Sexual delay discounting task (SDDT)***

Participants completed 60 trials of the SDDT adapted from Girard and colleagues (2019). Each trial started with the presentation of a fuzzy sexual picture for 0.5 s (Figure 1). Next, participants were presented with a thermometer representing one of five possible delay levels (12 trials per level), ranging from 3 to 15 s in increments of 3 s, together with two choice options, "to wait" and "not to wait". If they decided to wait, the thermometer was framed by a red rectangle, and participants had to wait for the delay indicated on the thermometer before seeing the clear version of the sexual picture for 3 s (larger-later reward, i.e., LL). If participants decided not to wait, the thermometer turned blue and was framed by a blue rectangle, and participants waited for 1 s before seeing the clear version of the sexual picture for 1 s (smaller-sooner reward, i.e., SS). Participants had to make a choice within 2.5 s. If they failed to do so, the trial was aborted, and the task proceeded to the next trial (number of missing trials per participant, $M = 0.68$, $SD = 2.42$, range = 0-16). The position (right or left)

of the two options (“To wait” or “Not wait") was counterbalanced across trials within each participant. To prevent the strategy of choosing the SS option more often in order to see more sexual pictures, the total duration of the reward delivery phase plus intertrial interval was fixed (Mean = 4.5 s, range: 3.5 s - 5.5 s) (Girard et al., 2019; Prevost et al., 2010). In addition, participants were explicitly instructed that choosing the SS option more often would not allow them to see more pictures or finish the study earlier.

----------insert Figure 1 about here----------

Sexual stimuli. Sixty pictures were selected from various website, depicting nude women only. These stimuli were validated in a previous study (Cui et al., 2021).

Ratings of the fuzzy cues. To assess individual’s motivation to view each picture, participants were asked to rate the 60 fuzzy cue pictures after the SDDT. They were asked to rate “To what extent would you like to see this picture in its clear form” from 1 to 9 with an increment of 0.1, with 1 indicating not at all, 5 indicating neutral and 9 indicating very much. These ratings were used in the following computational analysis to calculate the subjective value associated with each option (see below).

2.4. ***Computational modelling and statistical analysis***

Data of one participant was lost due to program dysfunction. Data of 19 participants who showed biased choices, i.e., selected the LL or SS option (mean proportions of choosing the same option = 94.3%, *SD* = 3.1%) for more than 90% of trials (54 out of 60 trials) were excluded from analysis (Johnson and Bickel, 2008; Peters and Büchel, 2010). The sample for the final analysis was 120 (mean age = 20.71 years, *SD* = 1.83, age range = 18-26). Of these,

55 received testosterone and 65 received placebo. To correct for skewness, response time data was log-transformed.

Linear mixed-effects models. To capture both between- and within-subject variability, linear mixed-effects models were used to assess the choice and response times with the lme4 package in R (Bates et al., 2012). For both models, the main effect of delay intervals and groups, the interaction between delay intervals and groups were modeled as fixed effects of interest. In addition to including subjects and pictures as random-effect variables, we also included delay intervals as random slopes, in line with maximal random effects structure (Barr et al., 2013). Choice was treated as a binary variable, coded 1 for selection of the LL option and 0 for selection of the SS option.

Hierarchical hyperbolic discounting model. Beyond the model-free analyses on choice behavior and reaction time, we employed a hyperbolic discounting model estimated by hierarchical Bayesian analysis (Gelman et al., 2013) to reveal participants' discounting rate *k* (i.e., a larger value of *k* means greater impulsivity), α (the ratio of reward magnitude of LL to SS) and β (i.e. the inverse temperature parameter). The hyperbolic model was implemented as follows:

$$SV = \frac{rating \cdot f(t)}{1 + k \cdot delay}$$

$$f(t) = \begin{cases} 1, & if\ t = 1s \\ \alpha, & if\ t = 3s \end{cases}$$

$$p_{LL} = \frac{1}{1 + e^{-\beta(SV_{LL} - SV_{ss})}}$$

SV denotes the subjective value of each option, calculated as the amount of reward divided by the individually weighted delay. We operationalized reward amount either by participants' rating of their motivation to clearly see a fuzzy cue or with an objective constant. Moreover,

we modulated these amounts by the duration of presentation of the clear pictures. The effect of presentation duration on subjective value is not necessarily linear and the same for every participant. Therefore, we captured presentation duration with a subjective term in $f(t)$. As we only had two levels of presentation duration, 1s for SS and 3s for LL, we used a simplified scalar parameter (α) to capture the relative difference between SS and LL options, with the SS option fixed at 1 and the LL option scaled relative to the SS option by α. If α is larger than one then the participant values the LL reward more than the SS reward. The cost of delay was quantified as the delay interval multiplied by the participant's degree of discounting by delay (i.e., a larger value of k corresponds to greater impulsivity). The softmax function served to fit the probability of choosing the LL option based on the subjective value differences between the LL and SS options, weighted by β (i.e., inverse temperature parameter, which captures the degree of stochasticity in choice behavior).

We fitted the following four models (Table 1). Model 1 and model 2 included three parameters (i.e., k, α, and β), while model 3 and model 4 included two parameters (i.e., k and β; the value of α was fixed at three). Unlike model 1 and model 3, the subjective value calculation in model 2 and model 4 did not take into account the participant-specific ratings of pictures (i.e., the ratings of the fuzzy cue in all trials was set to one). Model comparison was implemented using the Leave-One-Out Information Criterion (LOOIC). The model with the smallest LOOIC is the winning model.

----------insert Table 1 about here----------

Posterior inference of the parameters was implemented through Markov chain Monte Carlo (MCMC) sampling methods using the rstan packages in R (Carpenter et al., 2017). The

group-level parameters (*K, A* and *B*) acted as priors for the corresponding subject-level parameters (k, α and β), such that $k \sim N(A, \sigma_k)$, $\alpha \sim N(B, \sigma_\alpha)$, and $\beta \sim N(K, \sigma_\beta)$. Three series of dummy variables were used to capture the group difference, including three hyperparameters (*dum_A*, *dum_B*, and *dum_K*) and individual parameters of the testosterone group, i.e., $dum\_k \sim N(dum\_K, dum\_\sigma_k)$, $dum\_\ \alpha \sim N(dum\_A, dum\_\sigma_\alpha)$, and $dum\_\ \beta \sim N(dum\_\ B, dum\_\sigma_\beta)$. The priors for these parameters are specified by normal distributions of $N(0,1)$; the priors for their σs were defined by a half-Cauchy distribution with scales of three (Gelman, 2006).

Four chains of 4,000 iterations were run for the sampling section, which followed 4,000 warmup iterations, and 16,000 samples for each parameter were obtained after a one-fold thinning for subsequent analyses. The Gelman–Rubin test served to test the convergence of the MCMC chains (Gelman et al., 2013). We found all variables in the model had $\hat{R} < 1.01$, indicating successful convergence of all four chains to our target posterior distributions. We report 95% highest density intervals (HDI) for all hyperparameters, i.e. the intervals which credibly covered most of the parameter distribution for these parameters (Kruschke, 2014). Specifically, a meaningful difference between the placebo and the testosterone groups was observed if the 95% HDI interval deviated from zero for the dummy group variables. In contrast to a null hypothesis test, HDI overlapping zero in dummy group variables did not mean that the two groups are identical on these parameters (Ahn et al., 2011; Kruschke, 2014).

To ensure predictive accuracy of the winning model, we simulated choices using the individual parameter estimates and calculated the proportion of LL choices for each delay

level in each group. We conducted correlational analyses between the simulated data and the real data separately for different delays and groups.

2.5. Open practice statement

All the data and analysis scripts are available on the Open Science Framework (OSF) page: https://osf.io/zecky/

3. Results

We first investigated whether the two groups differed in baseline trait impulsivity as measured by the BIS-11 and found no difference between participants assigned to the testosterone (M = 14.62, SD = 2.35) and placebo (M = 14.78, SD = 2.93) group, t (118) = 0.34, p = .735. The two groups did not differ on their ratings of fuzzy cues, t (118) = 0.34, p = .734; Testosterone: M = 5.36, SD = 1.22; Placebo: M = 5.44, SD = 1.20, suggesting comparable motivational significance of the fuzzy cues for the two groups.

3.1. *Choice*

For the choice model, we observed a significant main effect of delay duration (b = -0.22, SE = 0.03, Z = -8.27, p < .001), indicating that more SS options were selected with increasing delays (Figure 2A). We also found a significant main effect of group (b = -0.84, SE = 0.40, Z = -2.08, p = 0.037) such that participants in the testosterone group exhibited an overall preference for SS options compared to those in the placebo group. There was a marginally significant interaction between group and delay interval (b = 0.07, SE = 0.04, Z = 1.94, p = 0.053). Further analysis revealed that participants in the testosterone group chose the SS option more frequently than participants in the placebo group for a delay of 6 s (b = –0.55, SE = 0.25, Z = –2.19, p = 0.028) and there was a trend effect for a delay of 3 s (b = –0.49, SE =

0.29, $Z = -1.68$, $p = 0.094$). No group difference was found at the other delay levels (9 s: $b = -0.21$, $SE = 0.20$, $Z = -1.05$, $p = 0.293$; 12 s: $b = -0.01$, $SE = 0.19$, $Z = -0.08$, $p = 0.939$; 15 s: $b = 0.33$, $SE = 0.25$, $Z = 1.34$, $p = 0.181$). Together, these findings are compatible with the hypothesis that testosterone increases sexual impulsivity.

----------insert Figure 2 about here----------

3.2. Response times

The response time model revealed a significant main effect of delay duration ($b = 0.003$, $SE = 0.001$, $Z = 2.74$, $p = 0.007$), suggesting that participants spent more time for decisions with increasing delay (Figure 2B). Neither the main effect of group ($b = -0.049$, $SE = 0.029$, $Z = -1.66$, $p = 0.099$) nor the interaction between group and delay interval ($b = -0.0005$, $SE = 0.002$, $Z = 0.32$, $p = 0.747$) was significant.

3.3. Modelling results

We extracted the three parameters from the model fit for each group. Specifically, k represented discounting rate, with larger values indicating greater impulsivity; α represented the ratio of reward magnitude of LL to SS, with values larger than one indicating that the participant valued the LL reward more than the SS reward. Finally, β was the inverse temperature parameter, with larger values corresponding to smaller stochasticity (i.e., larger dependence on the subjective value difference) in choice behavior.

For both groups, the winning model was the three-parameter model (i.e., k, α, and β parameters; Table 1) without taking the ratings of the fuzzy cue as subjective value inputs in each trial (i.e., the value of ratings was set at one). Overall, we found an elevated discounting

rate (*k*; illustration of model fit: Figure 2C) in the testosterone group (median = 0.61) relative to the placebo group (median = 0.24), with zero not included in the 90% HDIs (McElreath, 2016) for group comparisons on *k*: 90% HDI [0.03, 0.70]. There was no significant group difference in α: 90% HDI [–0.60, 0.74] (Testosterone: median = 2.07; Placebo: median = 2.02) and β: 90% HDI [–1.98, 0.32] (Testosterone: median = 3.17; Placebo: median = 4.03) (Figure 2D). Taken together, our modeling data suggested that the participants in the testosterone group exhibited increased sexual delay discounting compared to those in the control group.

Finally, we performed posterior predictive checks. There was a close relationship between simulated proportions of LL choices and actual choices in all delay intervals for both groups (averaged correlational coefficients across delay intervals of the testosterone group: 0.854, range: 0.729 ~ 0.961; placebo group: 0.862, range: 0.809~ 0.942).

4. Discussion

By combining testosterone administration with a sexual delay discounting task (SDDT), we showed that healthy young heterosexual males in the testosterone group were less likely to wait longer to view sexual pictures for a longer duration than participants in the placebo group. Computational modelling corroborated this finding by showing that men who received testosterone had a larger discounting rate than men who received placebo. Taken together, these findings suggest that the administration of a single testosterone dose increases impulsivity for sexual rewards. These results are consistent with a recent report highlighting the role of testosterone in sexual compulsivity and behavior (Rodríguez-Nieto et al., 2021).

Acute testosterone elevations in response to sexual stimuli are phylogenetically conserved, which might indicate that they have evolved to modulate physiological and behavioral mechanisms that maximize reproductive fitness. Studies using pharmacological procedures that mimicked these hormonal responses (e.g., testosterone injections) showed that testosterone elevations were associated with behaviors that either directly (e.g., copulatory behavior) or indirectly (e.g., reward processing) promoted sexual behavior (Gleason et al., 2009; Nyby, 2008). Recent theoretical accounts hypothesize similar relationships in humans (Gray et al., 2019; Zilioli and Bird, 2017); however, to date, very few experimental data exist that support this hypothesis. Our study fills this gap in the literature by showing that the administration of a single dose of testosterone increased preference for immediate sexual rewards as compared to long-term ones in a sample of young heterosexual men. Note that our design did not include non-sexual reward as control stimuli, thus future studies are needed to test if the effects observed here are domain-general or specific to sexual rewards.

Our findings could be interpreted in light of the literature on testosterone and impulsivity. Testosterone has been associated with impulsivity as assessed with monetary delay discounting tasks (Kurath and Mata, 2018). For example, correlational studies showed that salivary testosterone levels were positively associated with delay discounting rate in women (Doi et al., 2015) and with a greater response bias towards the SS option among boys at puberty (Laube et al., 2020). The advent of single dose testosterone administration studies in humans clarified the directionality of the relationship between testosterone and impulsivity by showing that exogenous testosterone increased impulsive behavior for monetary reward (Wu et al., 2020). The present study extends past research by showing that exogenous testosterone is associated with increased impulsivity also in a sexual delay discounting task. By showing that testosterone is associated with a preference for sooner rewards, our results

also speak to the literature on testosterone and risk-taking behavior (Kurath and Mata, 2018; Mehta et al., 2015; Rodríguez-Nieto et al., 2021).

Previous research showed that viewing attractive women or sexual cues (e.g. women in lingerie) led to steeper discounting of monetary rewards (Van den Bergh et al., 2008; Wilson and Daly, 2004). It is well established that the motivational valorization of monetary and sexual rewards involves a common brain reward circuitry (Sescousse et al., 2013); thus, an increase in appetitive motivation induced by sexual cues could instigate generalized impatience as operationalized with delay discounting. Animal models showed that androgen receptors are located on dopamine neurons projecting to the ventral striatum (Creutz and Kritzer, 2004). In humans, testosterone may affect the mesolimbic dopaminergic pathway as suggested by the finding that testosterone administration increased activation of the ventral striatum during reward anticipation (Hermans et al., 2010). Future research could fruitfully investigate the neural mechanisms by which testosterone increases impulsivity for sexual rewards.

Some limitations warrant further discussion. First, we only tested male participants. Although we do not expect testosterone to exert substantially different behavioral effects on men and women (this is particularly true among species in which sex differences are less pronounced), future studies are needed to test if the findings found here could generalize to female samples. Second, we used sexual pictures, which strictly speaking are secondary rewards. Previous research showed that primary rewards (e.g.., food) is discounted more steeply than secondary rewards (e.g., money) (Estle et al., 2007). Whether testosterone has distinctive effects upon discounting primary vs. secondary rewards presented in the same task awaits empirical testing. Fourth, the winning model did not include the rating of images, which may

suggest more limited effects of testosterone on sexual rewards in our study. Future studies are needed to investigate the interactive effect between testosterone and sexually arousing stimuli on sexual reward impulsivity. Fifth, previous research has suggested that individual differences such as relationship status, initial endogenous testosterone levels and trait impulsivity could moderate the association between testosterone and social decision-making (Kurath and Mata, 2018). We encourage future research to include these individual and contextual factors. Sixth, individual BMI may well impact on the effects of the testosterone administration protocol. Future research could tailor testosterone doses to individual BMI.

In sum, our study showed that pharmacologically-induced increases in testosterone cause increases in impulsivity for sexual rewards in a sexual delay discounting task. These findings are among the first to experimentally show that acute manipulation of testosterone levels modulates sensitivity for sexual rewards in humans and represent an important step towards a more comprehensive understanding of the neuroendocrine basis of sexual motivation and behavior.

Conflict of interest statement

The authors declare that they had no conflict of interest with respect to their authorship or the publication of the article.

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Author Contributions

YW, JO and YL designed the study. YW and JO collected the data. JO and XW analyzed the data. YW wrote the first version of the paper. SZ and PNT provided critical revisions. All authors approved the final version for submission.

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Figure captions

Figure 1. Schematic illustration of the sexual delay discounting task. In each trial, participants were asked to choose between two options: (a) waiting longer (3-15 s; here 9s) to view the sexual picture in its clear form for a longer duration (3 s), or (b) waiting for 1 s to briefly (1s) view the sexual picture. Here we used the silhouette the represent the erotic picture used in the experiment.

Figure 2. Behavioural results. (A) Proportion of choosing the later option as function of delay duration. (B) Response times as a function of delay. (C) The subjective value of LL options for each delay interval fitted by the hyperbolic model. (D) Hierarchical Bayesian Modelling revealed that the testosterone group exhibited increased discounting rate (k), while the two groups did not differ on α (i.e. the ratio of reward magnitude of LL to SS) and β (i.e. the inverse temperature parameter). The estimated posterior mean of the three parameters for each subject is plotted. The boxplots of the two groups for each parameter are also shown. Error bars represent standard errors of means for (A), (B) and (C). * $p < .05$, † $p < .10$.

Table 1. Model comparison

Model	Estimated parameters	Rating as input	LOOIC for Placebo	LOOIC for Testosterone
1	*k,* α, β	Yes	4452.2	3776.8
2	*k,* α, β	No	4398.4	3714.4
3	*k,* β	Yes	4545.9	3926.4
4	*k,* β	No	4503.2	3921.4

Note. *k*: discounting rate; α: ratio of reward magnitude of LL vs. SS; β: inverse temperature; Rating as input: whether or not to include the rating of the fuzzy cue to calculate the subjective value of options in each trial; LOOIC: Leave-One-Out Information Criterion. The value of α was fixed at three in the model 3 and the model 4.