LETTERS

Prejudice and truth about the effect of testosterone on human bargaining behaviour

C. Eisenegger[1], M. Naef[1,2], R. Snozzi[1], M. Heinrichs[3] & E. Fehr[1]

Both biosociological and psychological models, as well as animal research, suggest that testosterone has a key role in social interactions[1–7]. Evidence from animal studies in rodents shows that testosterone causes aggressive behaviour towards conspecifics[7]. Folk wisdom generalizes and adapts these findings to humans, suggesting that testosterone induces antisocial, egoistic, or even aggressive human behaviours. However, many researchers have questioned this folk hypothesis[1–6], arguing that testosterone is primarily involved in status-related behaviours in challenging social interactions, but causal evidence that discriminates between these views is sparse. Here we show that the sublingual administration of a single dose of testosterone in women causes a substantial increase in fair bargaining behaviour, thereby reducing bargaining conflicts and increasing the efficiency of social interactions. However, subjects who believed that they received testosterone—regardless of whether they actually received it or not—behaved much more unfairly than those who believed that they were treated with placebo. Thus, the folk hypothesis seems to generate a strong negative association between subjects' beliefs and the fairness of their offers, even though testosterone administration actually causes a substantial increase in the frequency of fair bargaining offers in our experiment.

Testosterone is a steroid hormone which the male testes and, to a lesser extent, the female ovaries secrete in mammals. Testosterone is present in the central nervous system throughout life and affects brain development and sexual behaviour. In rodents, testosterone administration leads to a substantial increase in aggressive behaviours[7], and folk wisdom holds that it causes antisocial, egoistic, or even aggressive behaviours in humans[8]. In fact, this 'wisdom' has even reached the courtrooms because steroid-induced rage has been used as legitimate legal defence in the United States[9]. There is indeed evidence indicating a link between testosterone and antisocial behaviour in humans[10,11]. In a sample of 692 adult male prisoners, for example, those who had a history of rape, murder and armed robbery had higher salivary testosterone levels than those who had only a history of theft and drug abuse[10]. According to disciplinary records, those inmates with relatively higher testosterone levels were reported to be more involved in overt confrontations in prison and more likely to violate prison rules compared to those with relatively lower levels. A similar pattern was observed in a study comprising 87 female prison inmates[11].

Although these facts are consistent with the folk hypothesis, they do not constitute convincing evidence for two reasons. First, the evidence is purely correlative and does not show that testosterone is causally involved in generating the observed behaviours. Second, an alternative hypothesis proposes that testosterone has an important role in status-related behaviours in human social interaction; it can also explain the norm-violating behaviours[1–5]. According to this hypothesis, testosterone induces status seeking, in particular in those social situations that constitute a potential challenge to a person's status. Thus, in settings such as prisons, where rigid social hierarchies impose subordinate positions on individuals, those who are predisposed to seek social status may question the hierarchy in antisocial and rebellious ways. The evidence mentioned above[10,11] is thus also consistent with the social status hypothesis.

Although the social status hypothesis constitutes a plausible alternative to the folk hypothesis, it unfortunately remains largely based on correlative evidence[1–5]. However, a clean separation of the two hypotheses is possible because testosterone-induced status seeking may take a prosocial dimension if the prosocial behaviour enables individuals to master a challenge in order to secure their social position and thus to attain access to resources. Among the interactive games developed to examine prosocial behaviour[12,13], the ultimatum bargaining game[14–20] can be used for this purpose. In this game real money is at stake and two parties, A and B, have to agree on the division of 10 money units (MUs). Party A, the proposer, can propose how the 10 MUs will be allocated between A and B. Party B, the responder, can only accept or reject A's proposal, but cannot make a counteroffer. Thus, A has the power to stipulate an ultimatum to B, which gave the game its name. If B accepts A's proposal, the proposed allocation will be implemented. Party B can also veto A's proposal, however; in this case, neither party earns anything.

Many studies[14–20] indicate that subjects perceive low offers in the ultimatum game to be unfair, whereas the equal split is the salient fairness norm in this situation. As a consequence, many subjects in the role of party B reject low offers, meaning that neither player earns anything. Thus, if A proposes an equal split there is no risk of rejection, whereas if A wants to appropriate more than 50% of the available money, the probability of rejection becomes positive. Typically, some individuals playing the role of party A propose an equal split because they are intrinsically motivated by fairness concerns, but a considerable share of party A players also make fair offers for purely strategic reasons; that is, to prevent a rejection[15,16].

From the viewpoint of the folk hypothesis, one question is whether the administration of testosterone increases the frequency of low offers. In the context of our experiment, low offers constitute an unambiguous violation of a prevailing normative standard and can thus be viewed as a form of antisocial behaviour. Low offers can be considered antisocial, not just owing to the fact that they violate a fairness norm, but also because they bear the increased risk of social conflict (that is, a rejection), meaning that both players may ultimately end up with zero earnings. Thus, the folk hypothesis unambiguously predicts that testosterone will induce proposers to make more unfair offers.

The status hypothesis proposes that subjects who receive testosterone will place a higher value on social status than subjects with placebo.

[1]Institute for Empirical Research in Economics, Laboratory for Social and Neural Systems Research, University of Zurich, 8006 Zurich, Switzerland. [2]Department of Economics, Royal Holloway, University of London, Egham TW20 0EX, UK. [3]Department of Psychology, Laboratory for Biological and Personality Psychology, University of Freiburg, 79104 Freiburg, Germany.

Previous evidence suggests that this impact of testosterone on status concerns is most likely to occur in situations in which subjects' social status can be challenged and they can avoid this threat with appropriate behaviours[1,3,4,6]. This is exactly the situation of a proposer in the ultimatum game, who faces the threat of rejection if she makes an unfairly low offer. By making a fair offer, the proposer can prevent being turned down (that is, a social affront) with near certainty, whereas the rejection probability is substantial in the case of an unfair offer. Thus, if testosterone induces a higher concern for social status in the sense that subjects want to prevent their proposal from being turned down, we should observe fairer offers among proposers who received testosterone. Note that according to the social status hypothesis, testosterone does not make subjects more altruistic or more prosocial per se; higher bargaining offers, however, are instrumental in preventing a rejection and gaining access to resources.

A total of 60 women participated in the role of a proposer in our experiment in a double-blind, placebo-controlled study design (Fig. 1). A single dose of 0.5 mg of testosterone or placebo was applied sublingually 4 h before subjects played the ultimatum game. We only recruited women because the parameters (quantity and time course) for inducing neurophysiological effects after a single sublingual administration of 0.5 mg of testosterone are known in women[21], whereas these parameters are unknown in men. In addition, previous evidence indicates a correlation between endogenous testosterone levels and status-related behaviours not only in men[1,3,4] but also in women[3,4,11,22–24]. To check whether subjects noticed which substance they had been given, we also asked them whether they believed that they received placebo or testosterone. Their beliefs were not significantly related to the actual substance they received (Mann–Whitney U-test, $P = 0.191$, $n = 60$), indicating that they were unaware of what they actually received. Every proposer played three independent ultimatum games with three different responders, and all interactions between proposers and responders took place via a computer network such that full anonymity between the participants was ensured. In each game, the proposer could offer the responder 0, 2, 3 or 5 MUs (out of 10 MUs).

Ethical concerns require researchers to inform subjects that they will either receive a placebo or testosterone, and the prior notions about testosterone may confound a possible impact of testosterone on behaviour. In particular, belief in the folk hypothesis may affect subjects' behaviour because testosterone is probably one of the most widely discussed hormones in the press and, therefore, it is possible that existing opinions on testosterone might affect behaviour[8]. A survey we conducted several months after the experiment confirmed that our subjects strongly believed in the folk hypothesis (see Supplementary Information). For this reason, we controlled for subjects' beliefs about whether they had received testosterone or placebo in our statistical analysis (see also Supplementary Information).

The folk hypothesis predicts that proposers who received testosterone will make lower offers. In contrast to this prediction, subjects who received testosterone actually made significantly higher offers (analysis of variance (ANOVA), main effect of testosterone, $F = 4.92$, $P = 0.031$; Cohens $f^2 = 0.24$, $n = 60$), with placebo subjects offering on average 3.40 MUs, whereas subjects with testosterone offered 3.90 MUs (Figs 2a and 3). Notably, we also find strong support for a 'belief effect'. Subjects who merely believed that they received testosterone made much lower offers than those who believed that they received placebo (Figs 2b and 3; ANOVA, main effect of believed testosterone, $F = 8.22$, $P = 0.006$; Cohens $f^2 = 0.34$, $n = 60$). The belief effect reduces offers by 0.92 MU whereas the pure testosterone effect increases offers by 0.64 MUs. This difference is not significant, however ($F = 0.50$, $P = 0.485$, $n = 60$). We also do not observe an interaction effect between testosterone and believed testosterone (ANOVA, interaction between testosterone and believed testosterone, $F = 0.90$, $P = 0.346$, $n = 60$). We also controlled for subjects' endogenous baseline testosterone levels before testosterone administration, and for a possible indirect effect of testosterone via its effect on cortisol levels, anxiety, anger, calmness, wakefulness and mood (see Methods and Supplementary Information), but none of these factors plays a role.

Taken together, the positive impact of testosterone on the fairness of bargaining offers casts strong doubt on the folk hypothesis and is consistent with the social status hypothesis. An alternative explanation for higher proposer offers is, however, that testosterone administration might have a positive influence on altruistic motivation. The social preference literature[13] defines altruism as putting a positive value on other people's payoff. Thus, if testosterone increased the valuation of others' payoffs, we should observe higher offers in the ultimatum game—which we do. However, an increase in altruistic motivations also predicts lower rejection rates by the responders because a rejection reduces the proposer's payoffs. Our responder data clearly refute this prediction. The main effect of testosterone on rejection rates in an ANOVA is clearly insignificant regardless of whether we control for baseline testosterone or not ($F = 0.73$, $P = 0.399$ without control for baseline testosterone; $F = 1.25$, $P = 0.271$ with control for baseline; $n = 55$). Moreover, as with the proposers, the baseline testosterone level has no main effect on rejection rates ($F = 0.53$, $P = 0.664$, $n = 55$) and the interaction between exogenously administered testosterone and endogenous baseline testosterone is also insignificant ($F = 1.77$, $P = 0.172$, $n = 55$). Thus, the absence of a testosterone effect on rejection rates rules out any effect of testosterone on altruistic motives. The absence of a testosterone effect on altruistic motives and on rejection behaviour

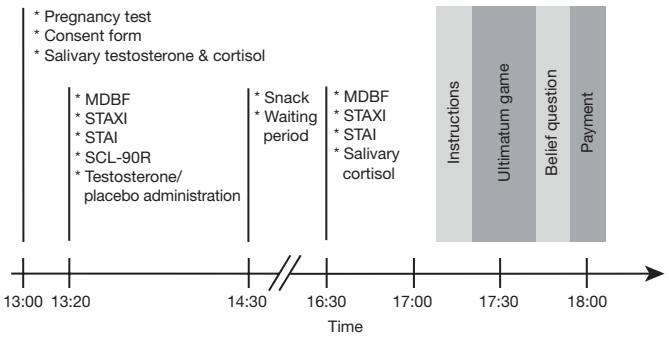

Figure 1 | Sequence of events in the double-blind study with testosterone and placebo administration. Every experimental session started at 13:00; the ultimatum game took place 4 h after testosterone or placebo administration, consistent with an established protocol of single-dose testosterone administration studies. MDBF, Mehrdimensionaler Befindlichkeitsfragebogen (multidimensional mood questionnaire); SCL-90R, 90-item symptom checklist (revised version); STAI, state-trait anxiety inventory; STAXI, state-trait anger expression inventory.

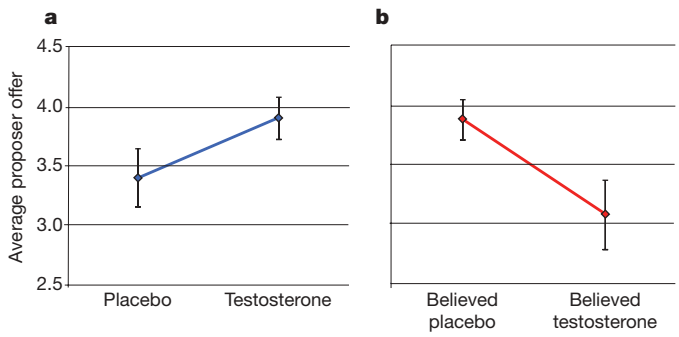

Figure 2 | The proposers' mean offers in the ultimatum game across treatments and beliefs. Error bars indicate s.e.m. **a**, Mean offers in the placebo and the testosterone group. Subjects who received testosterone make significantly fairer offers (ANOVA, $F = 4.92$, $P = 0.031$, two-tailed, $n = 60$). **b**, Mean offers for the subjects who believed that they received placebo compared to those who believed they received testosterone. Subjects who believed that they received testosterone make offers that are significantly more unfair (ANOVA, $F = 8.22$, $P = 0.006$, two-tailed, $n = 60$).

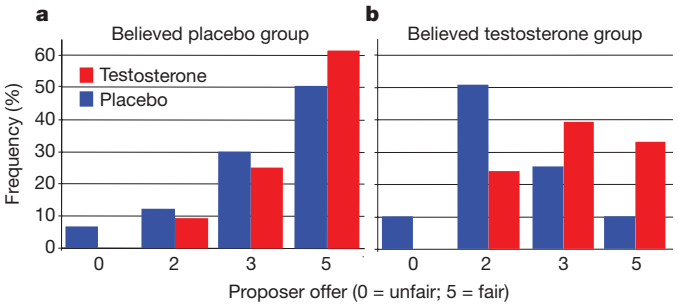

Figure 3 | Distribution of proposers' offers conditional on their beliefs. **a**, Distribution of offers for subjects who believed that they received placebo. **b**, Distribution of offers for subjects who believed that they received testosterone. Regardless of subjects' beliefs, those who actually received testosterone (red bars) made fairer offers compared with those who actually received placebo (blue bars). The figure also illustrates the belief effect; that is, subjects in the believed testosterone group (right panel) generally make offers that are less fair than the subjects in the believed placebo group (left panel), regardless of whether they actually received testosterone or placebo.

is also consistent with a recent study in which postmenopausal women, aged 50–65, received a testosterone treatment for 4 weeks[25]. In contrast to the present paper, however, this study cannot discriminate between the social status and the folk hypothesis because no data on how testosterone affects proposer behaviour are reported.

Although the results on responder behaviour rule out that testosterone affects altruistic motivations, they are fully consistent with the social status hypothesis; that is, with the idea that testosterone increases the motivation to prevent a social affront. The reason is that, unlike proposers, responders have no behavioural option to avoid being turned down. Responders can only accept or reject a given offer but cannot affect the offer they receive. Therefore, the motive to prevent a social affront cannot become operative for the responders; that is, their behaviour cannot be affected by testosterone-induced changes in this motive. In other words, the social status hypothesis predicts a null effect on responder behaviour.

The fact that testosterone enhances aggression in many animals and the broad media coverage of results suggestive of a relationship between endogenous testosterone levels and antisocial behaviour has led public opinion to believe that testosterone may generally cause antisocial, selfish and aggressive behaviours. In this context, it is interesting that we observe a strong belief effect in our data; that is, subjects who merely believe they received testosterone made much lower bargaining offers. This belief effect may be interpreted in two ways. One interpretation is that subjects with a testosterone belief have an *ex ante* apology for making greedy offers. In a sense, their belief relieved them from the responsibility of making offers that comply with the prevailing fairness norm and allowed them to make greedy offers. Another interpretation is that subjects who tend to be selfish, aggressive, or dominant will make lower offers anyway and rationalize their selfishness *ex post*. If this interpretation holds then there should be a higher share of selfish, aggressive, or dominant subjects among those with a testosterone belief because selfish, aggressive, or dominant personalities would self-select into reporting this belief. We tested these implications with the help of personality measures. However, subjects with a testosterone belief are neither more Machiavellian (Mann–Whitney *U*-test test, $P = 0.392$, $n = 54$), more aggressive (Mann–Whitney *U*-test, $P = 0.720$, $n = 60$), nor more dominant (Mann–Whitney *U*-test, $P = 0.371$, $n = 54$) than subjects who reported a placebo belief.

Thus, although the folk hypothesis seems to give rise to a belief effect, our results cast serious doubts on this hypothesis because subjects with exogenously administered testosterone make much fairer offers in the bargaining game. As higher offers are associated with a large and significant increase in the acceptance rate (ANOVA, $F = 5.05$, $P = 0.000$, $n = 60$), they reduce bargaining conflicts and increase the efficiency of social interactions. Indirect effects of testosterone on emotional state—that is, on general mood, anxiety, anger and arousal—cannot explain these results. Furthermore, we find that testosterone administration has no effect on the endogenous cortisol level. We also observe that the endogenous testosterone level neither affects behaviour nor influences the effect of testosterone administration on behaviour in our setting. Finally, the increase in the fairness of bargaining offers can not be attributed to altruism, as this would imply a decrease in rejection rates, whereas testosterone had no effect on rejection behaviour. Thus, only the social status hypothesis is compatible with both major facts: the presence of a testosterone effect on bargaining offers and the absence of an effect on rejection behaviour.

The profound impact of testosterone on bargaining behaviour supports the view that biological factors have an important role in human social interaction[1–5,20,26,27]. This does, of course, not mean that psychological factors are not important. In fact, our finding that subjects' beliefs about testosterone are negatively associated with the fairness of bargaining offers points towards the importance of psychological and social factors. Whereas other animals may be predominantly under the influence of biological factors such as hormones, biology seems to exert less control over human behaviour. Our findings also teach an important methodological lesson for future studies: it is crucial to control for subjects' beliefs because the pure substance effect may be otherwise under- or overestimated. Thus, it is necessary to be aware of biological and socio-psychological factors in human social interaction for substantive and for methodological reasons.

METHODS SUMMARY

A total of 121 healthy women (mean age (±s.d.) of 25.16 ± 6.40 years), who did not use hormonal contraceptives, participated in a double-blind, placebo-controlled single-dose testosterone administration study. None of them used hormonal contraceptives; all of them had a regular menstrual cycle and were in the early follicular phase of the cycle, when the endogenous level of sex steroids tends to be low and stable. 0.5 mg of testosterone or placebo was applied sublingually 4 h before subjects played the ultimatum game. This is a well established single-dose testosterone administration procedure[21] that has been reliably shown to generate behavioural effects[28–30] in young women (see Methods). Subjects were assigned the role of either a proposer or a responder in the ultimatum game and did not know the identity of their interaction partners. They were sitting in carrels and were unable to see each other during the experiment. The proposer could propose an offer of 5, 3, 2 or 0 MUs out of 10 MUs to the responder. This ensured a clear separation between an offer that is regarded as fair (5 MUs) and offers perceived to be unfair (3, 2 or 0 MUs). Every proposer made three proposals while paired with three different randomly selected interaction partners. The proposer did not receive feedback about the responders' choices until the end of the experiment. Each MU in the ultimatum game was worth one Swiss franc. In an additional experiment without substance administration (robustness check, see Supplementary Information) another 180 female subjects participated in an identical ultimatum game. All statistical tests are two-tailed and robust to controls for repeated measurements. Standard errors were bootstrapped (20,000 replications) in the Mann–Whitney *U*-tests and *t*-tests.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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METHODS

Subjects. All 121 subjects provided written informed consent to the study, which the local ethics committee had previously approved. Only women were recruited because the parameters (quantity and time course) for inducing neurophysiological effects after a single sublingual administration of testosterone are known in women[21], whereas these parameters are unknown in men. Before admission to the study, all subjects were screened in a telephone interview to exclude medication intake, somatic diseases, or any neurological or psychiatric disorders. They were further instructed to abstain from alcohol or caffeine intake and smoking 24 h before the experiment. We conducted a pregnancy test before the beginning of the experiment to preclude pregnancy. Subjects were all invited to the experiment within 10 days after the beginning of the menstrual cycle, when endogenous levels of sex hormones tend to be low and stable. A physician was at the experimenter's disposal during the course of the whole experiment. Six subjects were excluded from the analysis because they had an overall score of two standard deviations above the mean in the global severity index of the symptom checklist for psychopathological symptoms[31].

Experimental procedure. All experiments took place at the experimental laboratory of the Institute for Empirical Research in Economics, in Zurich, Switzerland, where a total of ten sessions were conducted. All sessions started at 13:00 and lasted approximately 5 h. After oral instructions at the beginning of each session, subjects were randomly assigned to the testosterone or placebo group and to the proposer ($n = 62$) or the responder ($n = 59$) role (double-blind, placebo-controlled study design). Six subjects were excluded, two in the proposer role and four in the responder role. Subjects received one single dose of testosterone or placebo, sublingually. Owing to the established time lag of 4 h for behavioural effects to appear after sublingual application of 0.5 mg testosterone in young, healthy women[21,28,29], a 4 h waiting period between substance administration and the ultimatum game experiment was implemented. During this period, our subjects were required to remain in the laboratory room and read newspapers. This was to ensure that no social interaction outside the laboratory took place.

The testosterone preparation contained 0.5 mg of testosterone base with hydroxypropyl-β-cyclodextrin as a carrier[32]. The placebo contained no testosterone but was otherwise identical. Both preparations were manufactured by Laboswiss AG.

The ultimatum game is played with two types of players, a proposer and a responder, who have to agree on the division of 10 MUs. The proposer can decide upon the distribution of the 10 MUs. In our experiment, the proposer could propose an offer of 5, 3, 2, or 0 MUs to the responder. This ensured a clear separation between an offer that is regarded as fair (5 MUs) and offers that are perceived as unfair (3, 2 or 0 MUs). The responder then had to either accept or reject this proposal. If the responder accepted the proposer's offer, the proposed allocation was implemented. However, the responder could also reject the proposal; in this case neither party earned anything.

Subjects were randomly and anonymously assigned to the role of either the proposer or the responder and did not know the identity of the persons with whom they were matched in the experiment. After subjects read the instructions (available from the authors upon request), we checked whether they had understood the payoff structure by having them complete several control questions. All subjects answered these control questions correctly. In addition, we summarized the experimental procedure orally. In the experiment, every proposer made three propositions on the distribution of MUs while paired with three different randomly selected interaction partners. No pair of subjects interacted twice. The proposer did not receive feedback about the responder's choices until the end of the experiment. All decisions in the ultimatum game were implemented in zTree software and presented on computer screens[33]. Subjects received a base fee of one hundred Swiss francs for participation in the experiment. Each MU in the ultimatum game was worth one Swiss franc. Each subject received her earnings consisting of the base fee plus the earned MUs in private at the end of the experiment.

Salivary measurements. We measured salivary testosterone concentrations before administration of 0.5 mg of sublingual testosterone or placebo. We deliberately measured salivary testosterone levels because taking blood is highly invasive and could induce stress in subjects. Salivary testosterone has proven to be a reliable measure of the biologically active, non-protein-bound proportion (free testosterone) of testosterone in blood serum. Moreover, salivary hormone levels of cortisol and testosterone have been shown to correlate with economic interactions[34]. Before sublingual application of either testosterone or placebo, mean baseline salivary testosterone concentration was 42.06 pg ml^{-1} (±37.11 pg ml^{-1} s.d.) in the group randomly assigned to receive the placebo and 39.02 pg ml^{-1} (±37.90 pg ml^{-1} s.d.) in the group randomly assigned to receive testosterone.

We additionally analysed salivary cortisol levels before testosterone or placebo administration and immediately before the ultimatum game was played. Before administration of testosterone or placebo, salivary cortisol concentrations were 10.68 nmol l^{-1} (±5.11 nmol l^{-1} s.d.) in the placebo group and 9.66 nmol l^{-1} (±4.47 nmol l^{-1} s.d.) in the testosterone group. Before the ultimatum game was played, salivary cortisol concentrations were 4.32 nmol l^{-1} (±2.68 nmol l^{-1} s.d.) in the placebo group and 4.40 nmol l^{-1} (±2.45 nmol l^{-1} s.d.) in the testosterone group. We used the IBL SaliCaps Kit (IBL-Hamburg) for saliva specimen collection; subjects were requested to transfer 1 ml of saliva into the test tubes, which were then immediately frozen at −80 °C. Saliva analysis was performed by IBL-Hamburg using commercially available chemiluminescence-immunoassay with an intra- and inter-assay coefficient of variation lower than 10%.

There are no significant differences in cortisol levels and cortisol changes across the testosterone and placebo group (Mann–Whitney *U*-tests: before testosterone administration $P = 0.726$, before playing the ultimatum game $P = 0.961$, Mann–Whitney *U*-test for changes in cortisol levels across treatments, $P = 0.549$, $n = 58$).

Questionnaires. Subjects completed the validated German versions of the following questionnaires: the 90-item symptom checklist (revised version)[31], the multidimensional mood questionnaire[35], the state-trait anxiety inventory[36], and the state-trait anger expression inventory[37]. Psychological well-being was assessed at the beginning of the experiment by the 90-item symptom checklist (revised version). This is a multidimensional self-report instrument designed to screen for a broad range of psychological problems and symptoms of psychopathology. The inventory contains a total of 90 items, each of which is rated on a 5-point scale indicating the degree of distress associated with each symptom[31]. The global severity index is calculated from the sum of all ratings divided by the number of rated items. This global severity index forced the exclusion of six subjects from the analysis, due to an overall score of two standard deviations above the mean.

We assessed which treatment group subjects believed themselves to be in by asking them at the end of the experiment whether they believed they received testosterone or placebo.

We measured mood and arousal at the beginning of the study and immediately before the ultimatum game (that is, 4 h after substance administration) by means of the multidimensional mood questionnaire (MDBF). The MDBF consists of three subscales, termed elevated versus depressive mood, wakefulness versus sleepiness, and calmness versus restlessness. Subjects rate these items on a 5-step scale ranging from 1 (not at all) to 5 (very strongly). Subscale scores are calculated by summing up the respective item ratings[35]. The placebo and testosterone group were identical in all these dimensions (Mann–Whitney *U*-tests: wakefulness $P = 0.942$, mood $P = 0.863$, calmness $P = 0.278$, $n = 60$). There were also no differences between the testosterone and the placebo group immediately before playing the ultimatum game (Mann–Whitney *U*-tests: wakefulness $P = 0.365$, mood $P = 0.151$, calmness $P = 0.411$, $n = 60$). We also measured changes between the first and the second measurement and found no differences (Mann–Whitney *U*-tests: wakefulness $P = 0.764$, mood $P = 0.325$, calmness $P = 0.735$, $n = 60$). These results indicate that testosterone neither influenced subjects' mood and arousal, nor did it affect changes in these variables during the experiment.

Anxiety was measured by the state-trait anxiety inventory[36]. The inventory is measured by a 40-item self-rated psychometric instrument. The state-trait anxiety measure consists of items rated on four-point intensity scales (1 = not at all; 2 = somewhat; 3 = moderately; 4 = very much). Trait anxiety was assessed at the beginning of the experiment, whereas state anxiety was assessed immediately after the administration of the substance and before the start of the ultimatum game. State anxiety denotes a transitory emotional state characterized by subjective feelings of tension and apprehension. Trait anxiety indicates individual differences in anxiety proneness and refers to a general tendency to respond to perceived threats in the environment with anxiety.

Anger was measured by the state-trait anger expression inventory[37]. The inventory is measured by a 20-item self-rated psychometric instrument. The state and trait anger measure consists of items rated on four-point intensity scales (1 = not at all; 2 = somewhat; 3 = moderately; 4 = very much). Trait anger was again assessed at the beginning of the experiment, and the state measure was assessed twice, once immediately after the substance administration and once at the beginning of the behavioural task. State anger denotes the intensity of angry feelings experienced 'right now, at this moment'. Trait anger represents individual differences in general proneness to react angrily in anger-provoking situations.

We found no significant differences between the testosterone and placebo group with regard to the trait measures (Mann–Whitney *U*-tests: trait anger, $P = 0.403$; trait anxiety, $P = 0.809$, $n = 60$). It is a priori rather unlikely that testosterone increased fair behaviour owing to an increase in subjects' anxiety because the literature points in the opposite direction. If anything, testosterone

tends to reduce anxiety[29] and increase risk-seeking behaviour[30] which should lead to a decrease in ultimatum game offers. We find no significant differences between the placebo group and the testosterone group with regard to any of the state measures. We neither find differences across treatment groups after substance administration (Mann–Whitney *U*-tests: state anger, $P = 0.787$; state anxiety, $P = 0.615$, $n = 60$) nor before the beginning of the ultimatum game (Mann–Whitney *U*-tests: state anxiety, $P = 1.000$; state anger, $P = 0.522$, $n = 60$), nor is there a treatment difference in the changes in these variables between the two time points of the measurements (Mann–Whitney *U*-tests: state anger, $P = 0.641$; state anxiety, $P = 0.340$, $n = 60$).

To assess how subjects believed that the hormone testosterone influences behaviour, we conducted an online post-hoc survey. First, subjects were asked how testosterone administration would modify any given person's behaviour. They were asked to answer this question without the aid of class books or any other information material. Second, they were asked whether they expect the administration of testosterone would modify their behaviour if they were to receive it. Third, they were given a list of 13 two-poled opposed items, where they could indicate the expected behaviour modification after application of testosterone ranging from 'none', 'weak behaviour modification' to 'strong behaviour modification'.

We also measure subjects' personality traits with regard to the dimensions 'selfishness and opportunism' (with the Machiavelli questionnaire[38]), 'dominance'[39], and 'aggression'[31]. These individual difference measures enable us to examine whether there is a higher share of selfish or dominant or aggressive individuals among the subjects who believed that they received testosterone.

Statistical analysis. Our statistical analysis is based on non-parametric Mann–Whitney *U*-tests and parametric *t*-tests with bootstrapped standard errors (20,000 replications) and an analysis of variance (ANOVA). All tests are two-tailed tests and control for repeated measurements by taking each subject's average offer across the three ultimatum games as the unit of observation. The results remain the same if we take each individual offer as the unit of observation and control for repeated measurements in the ANOVA. The data on proposer and responder behaviour are available in the Supplementary Information. We examined the impact of testosterone (with a binary indicator for testosterone indicating whether the subject received testosterone (=1) or placebo (=0)) and the impact of belief about testosterone administration (with a binary indicator for subjects who believed that they received testosterone (=1) or placebo (=0)) in a univariate ANOVA on proposers' mean offer in the ultimatum game. We also examined (1) the impact of baseline levels of salivary testosterone on proposer behaviour (we grouped subjects into four equally sized groups); (2) the interaction between baseline testosterone and testosterone administration; and (3) the interaction between testosterone administration and believed testosterone with a univariate ANOVA. For the responders, we examined the influence of the same variables and interactions on rejection behaviour using ANOVAs.

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