Does Testosterone Increase Willingness to Compete, Confidence, and Risk-taking in Men? Evidence from Two Randomized Placebo-Controlled Experiments and a Meta-Analysis

Amos Nadler¹, Matthias Wibral², Thomas Dohmen³, Armin Falk⁴, Alessandro Previtero⁵, Bernd Weber⁶, Colin Camerer⁷, Anna Dreber⁸, Gideon Nave^{9*}

¹ Research Department, Poize, London, ON, Canada

² Department of Microeconomics and Public Economics, Maastricht University, The Netherlands

³ Department of Economics, University of Bonn, Bonn, Germany

⁴ Institute on Behavior and Inequality (briq) and Department of Economics, University of Bonn, Bonn, Germany

⁵ Finance Department, Kelley School of Business, Indiana University, Bloomington, IN, USA

⁶ Department of Epileptology, University Hospital Bonn, Bonn, Germany

⁷ Department of Humanities and Social Science, California Institute of Technology, Pasadena, CA, USA

⁸ Stockholm School of Economics, Stockholm, Sweden

⁹ Marketing Department, the Wharton School, University of Pennsylvania, Philadelphia, PA, USA

* Corresponding author. Email: gnav@wharton.upenn.edu

ABSTRACT

The sex steroid hormone testosterone regulates male-typical behaviors such as aggression and displays of dominance in non-human animals. According to the Challenge Hypothesis, these effects arise from context-sensitive testosterone elevations that facilitate inter-male competitions over resources, status, and mates. A growing literature documents similar testosterone effects on economic behaviors related to competition and risk-taking in humans, though findings have been mixed. Here, we report two randomized placebo-controlled experiments (total $N = 332$) investigating the effects of testosterone administration on men's willingness to compete, confidence, and risk-taking. Across the two experiments and their meta-analyses, we find no evidence for effects of testosterone on the behavioral constructs studied. Our findings cast doubt on the proposition that testosterone is a meaningful causal driver of the stereotypically "masculine" dimensions of economic behavior studied. Even if such effects existed, they are small and detecting them experimentally would be challenging.

Keywords: *hormones; testosterone; willingness to compete; confidence; risk; neuroeconomics; behavioral economics; meta-analysis*

TEASER

We find no evidence that testosterone affects men's competitiveness or risk-taking in two independent experiments.

INTRODUCTION

A core assumption of traditional economic theory is that preferences are stable across time and context. Although static preferences make economic models tractable, a growing literature shows that situational variation in people's physiological state systematically affects their decisions (1–4). A candidate biological mechanism to underlie such effects is fluctuations in hormonal levels. Hormones are chemical messengers that are released from glands into the bloodstream in response to environmental cues and changes in internal states such as hunger, stress, and sexual arousal. Many brain regions involved in cognitive and emotional processes contain hormonal receptors, and hormonal signals affect how they process information to influence decision-making (5–10).

Among hormones, the sex steroid testosterone has garnered significant attention due to its potential to provide a simple biological account for differences in preferences between and within sexes (10–18). According to the Challenge Hypothesis—a well-known theory supported by animal studies across species—testosterone levels rise in males amid contexts where status or reproduction is at stake (e.g., during the breeding season) to facilitate behaviors such as displays of dominance and aggression (19–22), that support competition for resources. Following a challenge, testosterone levels rise in winners—presumably to prepare them for further challenges—and drop in losers—putatively to motivate withdrawal from future competition (23). Humans show similar patterns, where men's testosterone levels rise in anticipation of competitions and after winning them (for reviews, (24, 25), and preliminary evidence suggests that these elevations can generate subsequent behavioral and psychological responses (26–28). To what extent this suggests that testosterone plays a role in decision-making is however unclear.

The current work reports two randomized placebo-controlled studies and a meta-analysis investigating the effects of testosterone on men's willingness to compete, confidence, and risk-taking. These behavioral outcomes are closely linked theoretically to the Challenge Hypothesis (29–31),

display behavioral differences between sexes (32–36), and their laboratory measures predict important real-life socioeconomic outcomes, such as career choice (37–39). Evidence for a possible link between testosterone and these outcomes comes from research using three methodological approaches: correlational studies, testosterone reactivity studies, and testosterone administration experiments.

A large number of studies have investigated correlations between baseline testosterone levels, measured in blood or saliva, and behaviors related to competition and risk (for reviews, (12, 14). To date, findings in such studies have been mixed. Several studies, of both men and women, observed correlations between baseline testosterone and risk-taking, willingness to compete, and confidence (e.g., (13, 17, 40). Other studies did not find significant correlations (e.g., (41), reported non-linear relationships (15), found effects only among participants with low cortisol (e.g., (42, 43), or detected effects in women but not in men (11). Although a recent meta-analysis found a small significant correlation between testosterone and risk-taking (16), the samples employed by its individual studies were an order of magnitude smaller than what would be required for detecting the aggregate meta-analytic effect ($r = 0.12$)—indicating low statistical power and limited capacity to quantify true underlying effects.

The mixed findings in correlational studies may be accounted for by the Challenge Hypothesis, which predicts that a transient context-sensitive elevation of testosterone, rather than its baseline levels, drives the hormone’s behavioral effects. Such effects are presumably more adaptive, as prolonged testosterone elevation causes immune-suppression, oncogenic effects, and increased risk of injury from physical aggression (44). A handful of studies addressed this issue by examining how testosterone changes following a competition predict subsequent behavior. One such study observed that testosterone increases after losing predicted men’s willingness to compete against the same partner again (26), and another study found that testosterone elevation following a competition increased men’s risk-taking, regardless if they won or lost (27). Nonetheless, results of testosterone reactivity studies have also been inconclusive. For example, one study found that testosterone elevation after a competition predicted men’s willingness to compete against a different partner—but only among participants who won decisively (28). Two other studies did not find an effect of testosterone reactivity on subsequent risk-taking (45, 46), though one of them reported an exploratory

analysis indicating that testosterone reactivity increased risk-taking among competition winners with independent self-construals (45).

Testosterone reactivity studies rely on endogenous hormone changes and do not utilize random assignment of testosterone. As testosterone reactivity might correlate with individual difference factors (e.g., (47), such studies are not ideal to establish whether the hormone's elevation causes a behavioral change. The gold-standard method for establishing such causal links is via randomized placebo-controlled testosterone administration experiments. A handful of such studies were conducted in women. One study could not detect a main treatment effect on women's willingness to compete, but found that testosterone influenced the outcome via an interaction with trait dominance (48). Three studies found no statistically significant effects of testosterone on women's risk-taking (49–51). However, men and women are hormonally distinct such that, based on evidence from animal studies and human testosterone reactivity studies, acute testosterone effects are expected to manifest predominantly in men.

One study to date, by Knight et al. (52), investigated how testosterone administration affected willingness to compete in men ($N = 115$). They did not observe a main treatment effect, but found that the testosterone administration influenced men's decision to compete via a three-way interaction with their cortisol levels and their opponents' gender. A larger number of studies investigated the effects of testosterone administration on outcomes related to men's risk-taking. Cueva et al. (53) reported that testosterone increased optimism and investments in high-variance assets ($N = 145$), and Nadler et al. (54) found that testosterone created larger and longer-lasting price bubbles in experimental asset markets ($N = 140$); yet, the micro-foundations of these effects, in terms of preferences, are unclear. Gourdriaan et al. (55) found that a seven-week pharmacological treatment that elevated men's testosterone and decreased their estradiol levels increased risk-taking in the Balloon Analogue Risk Task (BART), but had no effect on risk-taking in the Game of Dice Task (GDT), and the Iowa Gambling Task (IGT), ($N = 21$). Wu et al. (56) found that testosterone decreased men's reliance on expected-value and increased their use of anticipated regret when making risky decisions but did not affect risk-taking ($N = 64$). Wagels et al. (57) did not find a main effect of testosterone in the BART ($N = 103$), but noted a treatment effect in a subsample of participants who were carriers of the MAOA-

S variant of the MAOA genetic polymorphism (though the study is likely severely under-powered to investigate genetic effects; (58). Finally, Stanton et al. (41) did not find a main effect of testosterone on risk-taking, either in a study with a within-subject design of lottery choices ($N = 26$) or a between-subject design using the BART ($N = 117$).

In summary, the evidence on testosterone's effects on economic primitives related to competition and risk-taking is inconclusive across correlational studies, testosterone reactivity studies, and randomized administration experiments. The mixed evidence might reflect the patchwork nature of the literature that consists of studies that used relatively small samples, and potentially a high false discovery rate due to exploration of testosterone's effects across many different experimental conditions and sample subgroups (e.g., competition winners vs. losers, men vs. women, high vs. low cortisol) without correction for multiple comparisons (see (7) for more discussion).

We aim to help resolve the inconsistencies here, via two independently-designed randomized placebo-controlled experiments (Table 1 summarizes their characteristics) and their meta-analysis. Our research systematically investigates the effects of testosterone administration on (1) Willingness to compete—operationalized either via preference for a competitive (versus piece-rate) compensation scheme in a real-effort task, or via investment of resources in a competition that does not involve skill or effort; (2) Confidence—one's evaluation of one's own performance relative to others; and (3) Risk-taking—one's preference for a risky financial lottery over a certain payoff.

The combined sample size of our studies is substantially larger than any previous investigation on the topic to date. Study 1 included 91 European men, which provides 90% statistical power to detect a large effect size of $d = 0.68$ and 50% power to detect a medium effect size of $d = 0.41$ at the $\alpha = 0.05$ level. Study 2 included $N = 241$ American men, about twice the size of the largest testosterone administration study previously conducted on risk-taking and willingness to compete. This sample provides 90% power to detect a medium effect ($d = 0.42$), and 50% power to detect a small effect ($d = 0.25$) at $\alpha = 0.05$ level. The convergent results across our studies do not support the proposition that testosterone affects the behavioral constructs tested, and their meta-analysis rejects treatment effects that are “small” in size ($d > 0.3$). If such effects existed, detecting them experimentally would require studies that administer testosterone to very large samples, with thousands of participants.

Table 1. Characteristics of the two studies

	Study 1	Study 2
Location	Bonn, Germany	Claremont, CA, USA
Sample size	91 (46 Testosterone, 45 Placebo)	241 (123 Testosterone, 118 Placebo)
Statistical power ($\alpha = .05$, two-sided)	$d = 0.68$ (90% power) $d = 0.41$ (50% power)	$d = 0.42$ (90% power) $d = 0.25$ (50% power)
Participants per session	11-24	12-16
Randomization	Participant level	Session level
Experimental session time	Approx. 150 minutes	Approx. 120 minutes
Age (SD)	24.3 (2.7)	23.4 (7.3)
Exclusion criteria	Benign prostate hypertrophy, prostate cancer, heart failure, renal failure, hepatic failure, epilepsy or migraine history, and exogenous uptake of cortisone or ACTH	Klinefelter's syndrome, brain tumor, cancer, psychiatric diagnosis, high blood pressure, liver disease, kidney disease, angina, cancer, hepatitis, renal/kidney impairment, history of epileptic seizures, hypersensitivity to soy/alcohol, subjects using prescription drugs that may interfere with the study (oxyphenbutazone, insulin, corticosteroids, opioids), subjects who self reported consuming illegal drugs or alcohol in excess in the last 24 hours, and non-native English speakers
Administration method and dosage	Topical gel application: 1 packet of Testogel® containing 5 g of total gel and 50 mg testosterone (1% concentration)	Topical gel application: 2 packets of Vogelxo® Gel each containing 5 g of total gel and 50 mg testosterone (1% concentration)
Drug loading time	21 - 24 hours	4 hours
Testosterone measure	Serum (blood)	Saliva
Total compensation	Show-up fee of €40 plus experimental earnings.	Show-up fee of \$10 plus experimental earnings. Participants whose experimental earnings were below \$30 were paid a total compensation of \$40.
Other publications from the same experimental battery	(59, 60)	(22, 61–63)

STUDY 1

Ninety-one healthy men completed the behavioral tasks of this study, which took place over two consecutive days (see timeline in Figure 1). On the first day, participants were randomly assigned to receive either a gel containing 50 mg of 1% testosterone or a placebo gel, following a double-blind

protocol. Participants returned to the lab on the following day and completed a battery of tasks, including those reported. After the experiment, we collected a blood sample from each participant for measurement of total testosterone. Participants also answered sociodemographic and personality questionnaires, where a subset ($N = 51$) were asked if they believed they had received testosterone or placebo. Supplemental Figure 2 shows the empirical distributions of the study's main behavioral outcomes.

Figure 1. Experiment 1 Timeline

Manipulation check

Post-treatment testosterone increased in the treatment group relative to placebo ($d = 0.48$, 95% CI[0.06, 0.90], $t(89) = 2.23$, $p < 0.025$; Figure 2A). We find no evidence for a difference in treatment expectancy between the groups ($d = 0.02$, 95% CI [-0.58, 0.54], $t(49) = 0.076$, $p > 0.93$).

Real-effort Tournament

In this task, adopted from ref (64), participants solved a series of math problems that involved multiplying one-digit numbers by two-digit numbers, over a period of five minutes. Before solving, participants decided whether to receive a fixed compensation (400 Experimental Points, or EPs) or compete against a randomly chosen anonymous partner, who also decided to compete. Among a pair of competitors, the participant who provided more correct answers won the tournament and earned

1,300 EPs, while the loser received zero EPs. Ties were resolved by random draw, and if an odd number of participants chose to compete in the session, a randomly drawn participant's score was used for a second time, to calculate the unmatched participant's payoff. We elicited a measure of arithmetic skill in a follow-up two-minute task, where participants received a payoff of 10 EPs for every correct answer on similar math problems (in both the five-minute and the two-minute math tasks, all participants went through the exact same sequence, which contained problems of different difficulty levels). We also used this task for measuring participants' confidence (see below). Participants were informed about their performance and payoff at the end of the competition.

In this task, sixty-five percent of the testosterone group chose the tournament over a fixed wage compared to sixty percent of the placebo group (Figure 2B). This effect is in the hypothesized direction, yet small and statistically insignificant ($h = 0.11$; 95% CI [-0.30, 0.52]; $z = 0.51$, $p > 0.30$; for regressions with additional controls, see Supplemental Table 1). There is also no significant treatment effect on competition performance, quantified as the average number of problems solved by participants who self-selected into a competition ($d = 0.03$, 95% CI [-0.50, 0.46], $t(55) = 0.11$, $p > 0.91$). As expected, arithmetic skill positively predicted willingness to compete ($r = 0.36$, 95% CI [0.17, 0.53], $t(89) = 3.67$, $p < 0.001$).

Confidence

The study included two measures of participants' beliefs about their performance relative to others. First, we asked participants to guess their rank within the session in the two-minute arithmetic skill task (see 'Real-effort Tournament'). To measure confidence, we rely on these guessed ranks to calculate participants' belief about their performance percentile in the session (e.g., .90 indicates that the participant believed he scored higher than 90% of the participants in the session), such that a higher percentile implies greater confidence. Second, participants completed a 20-question trivia quiz, and similarly guessed their rank.¹

¹ In the trivia task, each question had two possible answers, and participants had to choose the correct one (there were no financial incentives for answering the questions). In the math task, participants were paid 200EPs if they were exactly correct about their rank within the session, 100EPs if they were off by 1, and 0 otherwise. In the trivia task, participants who correctly guessed their rank received 400 EP. No feedback was provided about performance in this task until the end of the experimental battery.

On average, participants guessed that they had performed slightly better than their session median (51st percentile in the math task and 56th percentile in the trivia task). As expected, participants' actual performance predicted their confidence level (Math: $r = 0.78$, 95% CI [0.69, 0.85], $t(89)=11.90$, $p < 0.001$; Trivia: $r = 0.39$, 95% CI [0.20, 0.55], $t(89) = 3.39$, $p < 0.001$). However, we find no evidence for treatment effects on confidence in either task (Math: $d = -0.03$, 95% CI [-0.45 -0.39], $t(89) = -0.15$, $p > 0.88$; Trivia: $d = -0.06$, 95% CI [- 0.48 0.35], $t(89) = -0.31$ $p > 0.75$). The absence of effects persists in regressions that control for performance and additional individual-difference controls (see Supplemental Table 2).

Two-stage Elimination Tournament

This two-stage task, adopted from ref (65), measured willingness to compete when winning did not require non-strategic skills (e.g., arithmetics). Participants completed this task in groups of four. In the first stage, they competed by choosing a number e ("investment") between 0 and 125. Each investment had an associated cost (measured in EPs) according to the function $c(e) = e^2 / 2250$, provided in a table. Then, a random shock [-60, 60] was added to each participant's investment. The two lowest-scoring participants were then eliminated, and received low wages of 573 EPs. The two remaining participants advanced to the second stage, and competed for high and medium wages (1,211 and 2,000 EPs, respectively) akin to the first stage. During both stages, participants first entered their investment decisions and were then asked about their expectations about the other participants' investments. After the first stage, participants were informed on the realization of their own shock and whether they had been promoted to the second stage. After the second stage, participants learned about the realization of their own shock and whether they had won.

We find a small insignificant treatment effect on willingness to compete, in terms of participants' first round investment ($d = 0.26$, 95% CI [-0.16, 0.68], $t(89) = 1.25$, $p > 0.20$; for regression models with additional controls, see Supplemental Table 3). As expected, participants' expectations about their partners' investments predicted their investment ($r = 0.59$, 95% CI [0.44, 0.71], $t(89) = 6.86$, $p < 0.001$), though we find no significant treatment effects on expectations ($d = 0.05$, 95% CI: ([-0.36, 0.46], $t(89) = 0.23$, $p > 0.81$).

Figure 2. Experiment 1 results. (A) Post-treatment testosterone levels (logged). (B) Real effort tournament task: Proportion of participants choosing a competitive compensation scheme. (C) Confidence, measured via participants' guessed performance percentile in a math task. (D) Confidence, measured via participants' guessed performance percentile in a trivia task. (E) Two-stage elimination task: Investment in the first stage. (F) Risk-taking level, inferred from two choices between a sure payoff and a risky lottery.

Twenty-three participants from each treatment group advanced to the second round. The investments and expectations of these two selected groups did not differ statistically significantly, though the statistical power for testing such differences was small (investment: $d = 0.38$, 95% CI [-0.21, 0.99], $t(44) = 1.31$, $p > 0.19$; expectation: $d = 0.20$, 95% CI [-0.39, 0.80], $t(40) = 0.68$, $p > 0.49$).

Risk-taking

Participants made two decisions that measured their attitudes towards risk: (1) a choice between 200 EPs for sure and a 50% chance of receiving 600 EPs and zero otherwise; (2) a choice between 300 EPs for sure and a 50% chance of receiving 600 EPs and zero otherwise. Both choices were paid (if the lottery was chosen, it was determined at the end of the session). When analyzing data from this task, we exclude participants who showed intransitive preferences (i.e., chose the safe option in the first

lottery and the risky option in the second). Akin to ref (66), we classify the remaining participants to three risk-taking levels: (1) risk averse (chose the safe option twice); (2) slightly risk averse (choosing the risky lottery in the first lottery and the safe option in the second); and (3) risk loving (choosing the risky lottery twice).

We excluded four participants who showed inconsistent choices from the analysis. Both treatment groups displayed similar and statistically comparable risk-taking levels ($d = -0.02$, 95% CI [-0.45, 0.40], $t(85) = -0.12$, $p > 0.89$; for additional regression models, see Supplemental Table 4).

Equivalence Tests

Table 2 (right columns) summarize the TOST Equivalence tests results, which reject effects greater than $d = 0.62$ at the $\alpha = 0.05$ level for all behavioral outcomes.

Table 2. Experiment 1 treatment effects and statistical tests.

Dependent variable [unit and range]	Mean difference [95% CI]	Effect size [95% CI]	Statistics (df) <i>p</i> -value	Equivalence test ($d < -0.68$)	Equivalence test ($d > 0.68$)
Willingness to compete (real effort tournament) [Proportion, 0-100%]	0.05 [-0.17, 0.27]	$h = 0.11$ [-0.30, 0.52]	$z = 0.51$ $p > 0.30$	$z = -7.23$ $p < .001$	$z = 6.20$ $p < 0.001$
First stage tournament investment [investment, 0-125]	9.95 [-5.91, 25.82]	$d = 0.26$ [-0.16, 0.68]	$t(89) = 1.25$ $p > 0.21$	$t(89) = -4.49$ $p < 0.001$	$t(89) = 1.95$ $p < 0.025$
Confidence (Math) [Guessed performance percentile, 0-1]	-0.02 [-0.12, 0.10]	$d = -0.03$ [-0.45 -0.39]	$t(89) = -0.15$ $p > 0.88$	$t(89) = -3.10$ $p < 0.002$	$t(89) = 3.39$ $p < 0.001$
Confidence (Trivia) [Guessed performance percentile, 0-1]	-0.01 [-0.08, 0.06]	$d = -0.06$ [-0.48 0.35]	$t(89) = -0.31$ $p > 0.75$	$t(89) = -2.93$ $p < 0.003$	$t(89) = 3.55$ $p < 0.001$
Risk-taking [level, 1-3]	-0.02 [-0.36, 0.32]	$d = -0.03$ [-0.45, 0.40]	$t(85) = 0.12$ $p > 0.89$	$t(85) = 3.04$ $p = 0.002$	$t(85) = -3.29$ $p = 0.002$

STUDY 2

Two-hundred and forty-one healthy men completed the behavioral tasks in this experiment over two sessions within the same day (timeline in Figure 3). In the morning session, participants had their hands scanned for 2D:4D measures, and were randomly assigned to self-administer either a

topical gel containing 10 g of testosterone 1%, or a volume equivalent of inert placebo, following a double-blind protocol. Participants returned to the lab in the afternoon to complete a battery of tasks, including those reported. Due to a technical error, fifteen participants did not complete the fourth round of the real-effort tournament task and did not report their beliefs about winning and rank, and are excluded from analyses that involve these outcomes. During the experiment, we collected four saliva samples that were used for measuring levels of 14 hormones using LC-MS/MS. After the experiment, participants indicated their beliefs about the treatment they had received. Supplemental Figure 4 displays the distributions of the main behavioral outcomes.

Figure 3. Experiment 2 timeline

Manipulation check

Saliva testosterone increased in the treatment group relative to the placebo group in the first post-treatment measure ($d = 2.38$, 95% CI [2.03, 2.71], $t(239) = 18.43$, $p < 0.0001$; Figure 4A) and remained elevated in the two other post-treatment measures (note that testosterone levels in saliva tend to be substantially more elevated than their levels in blood serum following topical testosterone administration). For further discussion, see supplemental materials of ref (62). We find no statistical differences between treatment groups in their beliefs about the treatment they had received ($d = -0.20$,

95% CI [-0.46, 0.05], $t(237) = -1.55$, $p > 0.12$) or their post-treatment affective state (positive: $d = 0.04$, 95% CI [-0.22, 0.29], $t(234) = 0.28$, $p > 0.78$; negative: $d = 0.01$, 95% CI [-0.25, 0.27], $t(236) = 0.08$, $p > 0.93$).

Real Effort Tournament

We relied on the four-round task by Niederle and Vesterlund (32). This task generates large sex differences in willingness to compete and predicts real-world outcomes such as career choice (37). In the first three rounds, participants had five minutes to correctly add as many sets of five randomly drawn two-digit numbers as they could. In the first round (“piece rate”), participants received \$1 for each correct answer, regardless of others’ performance. In the second round (“tournament”), we divided participants into groups of four anonymous competitors. The participant who solved most problems in each group (“winner”) received \$2 for each correct answer and the other competitors received no payoff.² In the third round (“choice”), participants decided, before the task, what percentage of their payout would be calculated according to a tournament scheme, where the rest would be paid based on the piece rate scheme (in case of a tie, the winner was chosen at random).³ This percentage is our main measure of willingness to compete. In the last round (“choice of competition scheme for past performance”) participants did not perform the task, but instead indicated what percentage of their first round performance would be paid according to a tournament scheme. This round quantified their preferences for a competitive compensation scheme in the absence of future performance. Participants did not receive any feedback about their partners’ performance or their payoffs until the end of the full experimental battery, when they were paid for one randomly selected round.

As expected, piece-rate (first round) performance predicted performance amid competition (second round) across treatment groups ($r = 0.81$, 95% CI [0.76, 0.85], $t(241) = 21.22$, $p < 0.001$).

² To mitigate potential ceiling effects, tournament rewards were initially set to \$3—lower than Niederle and Vesterlund (2005). As a relatively large proportion of participants (across treatment groups) still invested all their endowment in competition (round 3) in the first four sessions, we reduced the reward to \$2 in the remaining sessions. All effects hold when controlling for tournament reward (Supplemental Table 6).

³ In the original design of Niederle and Vesterlund (2005), the decision to compete was binary. In order to reduce the potential of ceiling effects (75% of men chose to compete in the original study) and obtain a more fine-grained measure of willingness to compete, we asked participants to choose a convex combination of a compensation scheme, akin to Gneezy and Pietrasz (2013).

Furthermore, performance in the second round was significantly better than performance in the first round ($d = 0.25$, 95% CI [0.16 0.32], $t(241) = 5.86$, $p < 0.001$; paired two-tailed t-test in the full sample), indicating either a learning effect and/or increased motivation to perform amid competition. However, we find no evidence for a treatment effect on competition performance ($d = 0.002$, 95% CI [-0.25, 0.26], $t(239) = 0.02$, $p > 0.98$; Fig. 4A; for regression models with additional controls see Supplemental Table 5).

Our main measure of willingness to compete is the amount of investment in the competitive compensation scheme in the third (choice) round. As expected, task performance is predictive of willingness to compete ($r = 0.29$, 95% CI [0.17, 0.41], $t(240) = -0.77$, $p < 0.001$). However, we find no evidence for a treatment effect on this outcome ($d = 0.06$, 95% CI [-0.19, 0.32], $t(239) = 0.49$, $p > 0.62$; Fig. 4B; for regression models with additional controls see Supplemental Table 6).

The amount invested in the fourth round (choice of competition scheme for past performance) allows us to quantify the treatment effect on preferences for a competitive compensation scheme when payoff does not depend on a future competition. Akin to the third round, task performance is predictive of the fourth round investment ($r = 0.35$, 95% CI [0.23, 0.46], $t(223) = 5.57$, $p < 0.001$), but there is no evidence for a treatment effect on this outcome ($d = 0.02$, 95% CI [-0.24, 0.28], $t(223) = 0.14$, $p > 0.89$; Fig. 4B; for regression models with additional controls see Supplemental Table 7).

Confidence

Following the final round of the real-effort tournament, participants guessed their rank in the second round (“competition”) and received \$1 for guessing correctly. We also elicited their beliefs about winning the competitions using the incentive-compatible method of (67). We used these two measures for estimating their confidence. We reversed-coded the guessed rank such that a higher number implied greater confidence.

As expected, performance amid competition (second round) predicted participants’ beliefs that they had won it ($r = 0.43$, 95% CI [0.32, 0.53], $t(224) = 7.21$, $p < 0.001$), and their guessed rank ($r = -0.53$, 95% CI [-0.52, -0.43], $t(224) = -9.45$, $p < 0.001$). Beliefs and guessed rank also correlate with participants’ decision to compete in the third round (beliefs: $r = 0.36$, 95% CI [0.24, 0.47], $t(224) = 5.83$, $p < 0.001$; guessed rank: $r = -0.42$, 95% CI [-0.30, -0.52], $t(224) = 6.28$, $p < 0.001$). In line with

previous studies using the same paradigm (32), we also find that the study's male participants over-estimate both their relative performance. The mean guessed winning probability is 60% (more than double the objective probability of 25%) and about half of the participants guessed that they had the highest score in their group (the actual proportion was a quarter). However, we find no evidence for treatment effects on either beliefs ($d = 0.06$, 95% CI [-0.20, 0.33], $t(223) = 0.48$, $p > 0.63$; Figs. 4C) or guessed rank ($d = -0.10$, 95% CI [-0.37, 0.15], $t(223) = -0.80$, $p > 0.42$; Fig. 4D). These results hold when controlling for participants' task performance (for regression models with additional controls, see Supplemental Tables 8 and 9).

All Pay Auction

Participants completed three rounds of an all pay auction. This task is commonly used as a measure of rent-seeking—investment of resources in a competition in which losers are not compensated for their effort. Over-bidding relative to the Nash equilibrium commonly emerges in this task, and bids increase with the level of competition among bidders (68). In each round, we endowed participants with 100 EPs, and randomly divided them into groups using a stranger protocol. The group size in the first round was two participants, in the second round four participants, and in the last round the size of the entire session (12 or 16 participants). In each round, participants decided which part of their endowments to bid, knowing that all players in the group had to pay their bids, and only the highest bidder would earn a reward of 100 EPs. Participants received no feedback on their payoffs and their partners' bids until the end of the entire experimental battery, when they were paid according to one randomly selected round using an exchange ratio of \$1 = 10 EP.

As predicted by economic theory and consistent with previous findings (68), auction bids decreased with the group size (see Supplemental Table 11). We find no evidence for treatment effects on the average bid ($d = 0.07$, 95% CI [- 0.17, 0.33], $t(239) = 0.62$, $p > 0.54$; Fig 4E; see Supplemental Tables 10 for regressions with additional controls, and Supplemental Table 11 for an alternative specification using linear mixed-models).

Risk-taking

Participants made a series of ten choices between (A) a sure payoff of \$1 or (B) a lottery that would yield \$3 with a varying probability between 0.1 and 1 (in increments of 0.1) but \$0 otherwise.

Participants initially (when the probability of winning \$3 was 0.1) chose the certain reward, and switched to the lottery in the later decisions, as the chances of winning \$3 increased. Our measure of risk-taking is based on the number of questions after which a participant switched to the riskier payoff, i.e., the lottery (27, 69). For participants who always chose the risky lottery or the sure payoff, this number was set to 1 and 10, respectively. Finally, we reverse coded this measure such that a greater value indicates greater risk-taking. Participants completed the task twice, in the morning (to assess their baseline) and in the afternoon. We excluded all participants who showed inconsistent preferences (i.e., had more than one switching point) when analyzing this task.

Twenty-nine participants showed inconsistent preferences in the afternoon risk task, and were excluded from further analysis. Of the remaining, 19 participants showed inconsistent pre-treatment (morning) risk-preferences, and were excluded from analyses that involve this baseline measure. The average participant in the experiment chose the safe option in the first 4.1 questions ($SD = 1.6$) before switching, indicating overall risk aversion in the sample. As expected, pre-treatment risk-taking predicted post-treatment risk-taking ($r = 0.56$, 95% CI [0.45, 0.65], $t(191) = 9.27$, $p < 0.001$). We find no statistical evidence for a treatment effect on the task, with the point estimate of the effect indicating lower risk-taking in the testosterone group ($d = -0.06$ 95% CI [-0.33, 0.21], $t(210) = 0.46$, $p > 0.64$, Fig 4F; for linear and ordered logistic regression models with additional controls see Supplemental Tables 12 and 13).

Equivalence Test

The results of our TOST Equivalence tests for the main treatment effects are available in Table 3. These tests reject an effect size that is greater than $d = 0.42$ for all of the behavioral outcomes of interest at the $\alpha = 0.05$ level.

Testosterone $\times$ Cortisol Interactions

The Dual Hormone Hypothesis proposes that testosterone's effects on behaviors related to social status are stronger when cortisol levels are low (70). We explore such effects via regressions that include interactions between the treatment and logged cortisol levels, controlling for task-related covariates (see Supplemental Tables 5, 6, 7, 8, 9, 10, 12). As interaction effects in non-linear models

do not have a straightforward interpretation (71), we include these interactions only in linear regression models.

We find no evidence for interactive effects between testosterone administration and cortisol in any of our analyses (see column 4 in Supplemental Tables 5, 6, 7, 8, 9, 10, 12).

Developmental biomarkers

A related research stream investigates the effects of putative developmental biomarkers of testosterone exposure on later-life on economic preferences (12, 72, 73). We explore such effects via regressions that include the 2D:4D measures, a putative proxy of prenatal testosterone exposure, as a covariate. We find no evidence for 2D:4D effects in any of our analyses (see Supplemental Tables 5-13).

Figure 4. Experiment 2 results. (A) Pre- and post-treatment testosterone levels (logged) (B) Performance under piece-rate (round 1) and competitive (round 2) compensation schemes in the real-effort tournament task. (C) Investment in a competitive compensation scheme for an upcoming task (round 3) and for past performance (round 4) in the real-effort tournament task. (D) Confidence, measured via participants' belief of winning the competition (round 2). (E) All pay auction bidding average for the three rounds. (F) Risk-taking, measured via the switching point from a sure payoff to a risky lottery (reverse-coded).

Table 2. Experiment 2 treatment effects and statistical tests.

Dependent variable [unit]	Mean difference [95% CI]	Effect size [95% CI]	Statistics (df) p-value	Equivalence test ($d < -0.42$)	Equivalence test ($d > 0.42$)
Performance amid competition (round 2) [num questions solved]	0.01 [-1.12, 1.14]	$d = 0.002$ [-0.25, 0.26]	$t(239) = 0.02$ $p > 0.98$	$t(239) = 3.27$ $p < 0.001$	$t(239) = 3.24$ $p < 0.001$
Competitive scheme investment (round 3) [investment, 0-100]	2.21 [-6.76, 11.19]	$d = 0.06$ [-0.19, 0.32]	$t(239) = 0.92$ $p > 0.62$	$t(239) = -3.74$ $p < 0.001$	$t(239) = 2.77$ $p = 0.003$
Competitive scheme investment (round 4) [investment, 0-100]	0.69 [-9.08, 10.46]	$d = 0.02$ [-0.24, 0.28]	$t(223) = 0.14$ $p > 0.89$	$t(223) = -3.28$ $p < 0.001$	$t(223) = 3.01$ $p = 0.001$
All pay bidding [Average bid, 0-100]	2.28 [-4.97, 9.53]	$d = 0.08$ [-0.17, 0.33]	$t(239) = 0.62$ $p > 0.53$	$t(239) = -3.88$ $p < 0.001$	$t(239) = 2.63$ $p < 0.001$
Beliefs winning [Probability, 0-100]	1.79 [-5.53, 9.11]	$d = 0.06$ [-0.20, 0.33]	$t(223) = 0.48$ $p > 0.63$	$t(223) = -3.63$ $p < 0.001$	$t(223) = 2.67$ $p = 0.004$
Guessed rank [1-4, reverse-coded]	-0.10 [-0.35, 0.15]	$d = -0.11$ [-0.37, 0.15]	$t(223) = -0.81$ $p > 0.42$	$t(223) = 2.34$ $p = 0.01$	$t(223) = -3.95$ $p < 0.001$
Risk-taking [switching question, reverse-coded 1-10]	-0.11 [-0.54, 0.34]	$d = -0.05$ [-0.33, -0.21]	$t(210) = -0.46$ $p > 0.64$	$t(210) = 2.60$ $p = 0.005$	$t(210) = -3.51$ $p < 0.001$

META ANALYSIS

We meta-analyzed testosterone's effects across the two studies on the following behavioral outcomes: (1) willingness to compete in real-effort tasks (binary choice in Study 1, investment in competitive scheme in Study 2); (2) willingness to compete in tasks that do not involve skill or effort (investment in the two-stage elimination tournament in Study 1, average all pay auction bid in study 2); (3) confidence regarding one's own math performance (guessed performance percentile in Study 1, guessed rank in Study 2), and (4) risk-taking. To aggregate the effects, we converted them to a common metric (Cohen's d) using the raw data, and conducted a fixed-effect meta-analysis (akin to (61)) using the meta package in R (74). In addition, we report equivalence tests that compare the meta-analytic effect size against a "small" effect ($|d| > 0.3$).

Figure 5 shows the meta-analytic results. The aggregate effect estimates for both willingness to compete measures are positive, yet they are small and insignificant (real effort tasks: $d = 0.07$, 95% CI = [-0.14 0.29], $z = 0.67$, $p > 0.49$; non-effort tasks: $d = 0.13$, 95% CI = [-0.09 0.35], $z = 1.16$, $p > 0.24$).

The aggregate effects of testosterone on confidence ($d = -0.08$, 95% CI = $[-0.31; 0.14]$, $z = -0.73$, $p > 0.46$) and risk-taking ($d = -0.05$; 95% CI = $[-0.28; 0.17]$; $z = -0.45$, $p > 0.65$) are negative and also insignificant. Equivalent tests reject effects that are larger than $|d| = 0.3$ for willingness to compete in a real-effort competition ($Z = -2.04$, $p < 0.021$), confidence ($Z = 1.908$, $p = 0.029$), and risk-taking ($Z = 2.12$, $p < 0.017$). For non-effort competition, we reject effects larger than $|d| = 0.3$ with 94% confidence ($Z = -1.54$, $p = 0.061$).

Figure 5. Meta analysis of testosterone's effects across the two studies.

GENERAL DISCUSSION

Based on animal studies, the Challenge Hypothesis proposes that testosterone regulates behaviors related to competition, risk-taking, and the pursuit of status in men. However, findings in human studies supporting this hypothesis have been mixed, and causal evidence has remained scarce. We investigated the effects of testosterone administration on willingness to compete, confidence, and risk-taking—three dimensions of economic behavior that are theoretically linked to the Challenge Hypothesis, vary by sex, and predict important real-life outcomes. The two studies that were designed and conducted independently by separate research groups find no evidence for effects of testosterone on these outcomes.

Although the point estimates for some treatment effects are in the hypothesized direction, their magnitudes are small and they are not statistically distinguishable from zero in any of the studies. The largest meta-analytic effect that we observed was $d = 0.13$. Obtaining 90% power to detect this effect would require 2,490 participants—an order of magnitude greater than the largest behavioral testosterone administration study to date (18). Even if one would assume that the effect of testosterone on the outcomes of interest is the “small” effect ($|d| = 0.3$) that our meta-analysis rejects, a sufficiently powered study would require 470 participants—a sample that is larger than (18) and substantially greater than a typical study in the current literature. These findings cast doubt on the proposition that testosterone is a meaningful driver of these stereotypically “masculine” economic behaviors, and suggest that even if true effects existed, detecting them experimentally via pharmacological studies would be challenging.

Consistent with two recent studies (72, 73), we find no evidence for a relationship between any of the outcomes and 2D:4D, a putative biomarker of developmental testosterone exposure (see Supplemental Tables 5-13), though the validity of this biomarker is questionable (75). We also find no indication for interactions between testosterone treatment and participants’ cortisol, echoing a recent meta-analysis that found limited support for the Dual Hormone Hypothesis (70). It is possible that testosterone may affect economic preferences only via interactions with other variables, and our studies did not measure and test all variables that could potentially interact with the treatment. For example, a recent study observed that testosterone administration interacted with a personality risk score and genetic variation in the androgen receptor gene, to influence aggression (18).

However, we caution that establishing such interactions is expected to be even more difficult than detecting a main treatment effect. Obtaining sufficient statistical power to detect interactions requires much larger samples—between 4 to 16 times greater—than what is required for detecting main effects (76). Furthermore, reliably exploring a large number of potential interactions would require correcting the alpha level for multiple testing, which would result in further decrease of statistical power. Thus, studying potential interactions might be impractical, as it would require administering testosterone to a very large number of participants. In addition, when interaction effects have not been pre-registered they are an example of so-called “researcher degrees of freedom” in the analysis (e.g., (77)). That is,

without a pre-analysis plan researchers might have flexibility to explore many interaction effects, to exclude observations or to study subgroups, and somewhere in the analysis something will eventually be statistically significant by pure chance.

The convergent findings across independently designed studies using various incentivized measures of the same constructs suggest that our results would generalize to other incentivized measures of these constructs. However, our findings do not preclude testosterone effects on behaviors that involve willingness to compete, confidence, or risk-taking, via mechanisms that do not play a role in our tasks. For example, studies implicated testosterone in physical risk-taking when performance advanced sexual opportunity to male athletes (78), and in willingness to compete on the attention of potential mates (79). Such effects could result from testosterone's influence on other psychological processes, such as men's motivation to obtain mates or social status (21, 22), or heavier reliance on intuitive decision processes (62). However, we note that the testosterone administration literature is in its infancy, and that some of its early results did not replicate or robustly generalize (e.g., (63)). We recommend that future studies of testosterone's psychological effects employ large samples and include replications in independent samples, as well as pre-analysis plans.

Finally, we highlight several constraints of the generalizability of our findings. Our samples consisted of healthy men from Western, Educated, Industrialized, Rich and Democratic (WEIRD) societies, most of whom were less than 25 years old. We have no reason to believe that our results would not generalize to similar populations, yet future studies should evaluate their generality to other populations. Moreover, while our results were consistent across two commonly-used testosterone administration protocols that previously generated behavioral effects on other tasks (59, 61, 62), it is possible that administration via other delivery methods or over a longer time period would generate different findings.

MATERIALS AND METHODS

Participants and Protocol

Study 1. Ninety-two healthy men were recruited and pre-screened for medical exclusion

criteria (summarized in Table 1), 91 of these completed the tasks (see CONSORT chart in Supplemental Figure 1). Power analysis using G*Power (80) shows that the study has 90% statistical power to detect a large effect size of $d = 0.68$ and 50% power to detect a medium effect size of $d = 0.41$ at the $\alpha = 0.05$ level. Each participant took part in two sessions of 11-24 participants each over two consecutive days (see timeline in Figure 1). On the first day, participants arrived at the lab between 10AM and 1PM and were randomly assigned (at the participant level) to a treatment. A research assistant then applied a gel containing 50 mg of 1% testosterone or a placebo gel on their upper right arm, following a double-blind protocol. Participants returned for the second session the following day at 10AM, and read self-paced instructions in private cubicles. The experiment had a battery of 10 tasks, including those reported here. Details of other tasks and their results are presented in Table 1. We collected a blood sample from each participant in a separate room at the end of each session. All samples were processed on the following day for measurement of total testosterone. After the experiment, participants answered sociodemographic and personality questionnaires, where a subset ($N = 51$) were asked if they believed they had received testosterone or placebo. Participants were then paid a show-up fee of €40 plus experimental earnings, which were converted into Euros at a rate of €0.005 for each experimental point (EP) earned. There was no deception in any part of the experiment, and no adverse events occurred. The ethics committee of the University of Bonn medical department approved the study and all participants provided informed consent.

Study 2. Two-hundred and forty-four healthy men were recruited and pre-screened for medical exclusion criteria (Table 1), of which 241 completed the tasks (see CONSORT chart in Supplemental Figure 3). The study has 90% power to detect a medium effect ($d = 0.42$), and 50% power to detect a small effect ($d = 0.25$) at $\alpha = 0.05$ level, based on G*Power. Each participant took part in two sessions of 12-16 participants within the same day (timeline in Figure 3). In the morning session, participants had their hands scanned for 2D:4D measures (see ref (62) for details) and were then randomly assigned to complete self-paced questionnaires in isolated cubicles. Then, participants proceeded to another room and self-administered either 10 g of topical testosterone 1% or a volume equivalent inert placebo under researcher supervision, under a double-blind protocol. Participants returned to their cubicles in the afternoon to complete a battery of unrelated tasks, including those

reported here (for details of other tasks see Table 1). During the experiment, we collected four saliva samples (in the beginning of each session and in the middle and end of the afternoon session) that were used for measuring levels of 14 hormones using LC-MS/MS (see a comprehensive summary of the assay methods and their results in (62)). After the experiment, participants indicated their beliefs about the treatment they had received, and were then paid a show-up fee of \$10 plus experimental earnings, where participants whose experimental earnings were below \$30 were paid a total compensation of \$40. There was no deception and no adverse events occurred. The ethics committees of Claremont Graduate University and Caltech approved the study and all participants provided informed consent.

Statistical Analysis

Our analyses include all participants who have available measures of the relevant outcomes. We estimate the treatment effect size via Cohen's d for continuous outcomes and Cohen's h for binary outcomes, with standard deviations pooled across treatment groups. We test for differences between treatment groups via two-sided two-sample t-test for continuous outcomes and z-test for binary outcomes. We also provide regression models that quantify the treatment effect as the regression coefficient of a binary treatment indicator. These regressions control for task-specific covariates (e.g., baseline performance), and individual-difference factors. In Study 1, these factors include treatment expectancy (testosterone = 1; placebo = 0; not measured = 0.5), age, disposable income after rent, last high-school math grade (0-15), and self-reported impatience, impulsivity, and willingness to take risks in general (all 0-10 scales). In Study 2, these factors include treatment expectancy (5-point scale), mood, right-hand 2D:4D, and logged measures of hormones that are not affected by testosterone treatment from the first post-treatment saliva sample. We impute missing hormonal values by the sample means.

We also provide equivalence tests that compare the observed treatment effects to the smallest effect that the study has 90% statistical power to detect ($|d| = 0.68$ in Study 1 and $d = |0.42|$) in Study 2), via the Two One-Sided Tests (TOST) Equivalence Testing procedure (72).

Data and Code Availability

Data and code are available in the project's Open Science Framework (OSF) page:

https://osf.io/rwd26/?view_only=20c2299a65ef4497917be28825d46065.

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Supplemental Materials:

Does Testosterone Increase Willingness to Compete, Confidence, and Risk-taking in Men? Evidence from Two Randomized Placebo-Controlled Experiments and a Meta-Analysis

Amos Nadler, Matthias Wibrall, Thomas Dohmen, Armin Falk, Alessandro Previtro, Bernd Weber,
Colin Camerer, Anna Dreber⁸ Gideon Nave

Supplemental Figure 1: CONSORT chart, Experiment 1.

Supplemental Figure 2: Empirical distributions of behavioral outcomes, Experiment 1.

Supplemental Figure 3: CONSORT chart, Experiment 2.

Supplemental Figure 4: Empirical distributions of behavioral outcomes, Experiment 2.

Supplemental Table 1. Logistic Regressions. DV: Willingness to compete in real-effort tournament (Experiment 1).

	(1)	(2)
Treatment (Testosterone = 1)	0.141 (-0.799, 1.080)	-0.019 (-1.108, 1.069)
Math Skill	0.096*** (0.043, 0.149)	0.109* (0.015, 0.203)
Correct Answers (task)		-0.023 (-0.203, 0.157)
Age		-0.016 (-0.220, 0.187)
Treatment Expectancy		0.125 (-1.545, 1.794)
Disposable Income		-0.001 (-0.004, 0.002)
Math Grade (0-15)		0.046 (-0.121, 0.213)
General Risk-taking		0.404** (0.104, 0.704)
Impatience		-0.071 (-0.296, 0.153)
Impulsivity		-0.221 (-0.488, 0.046)
Intercept	-1.355* (-2.475, -0.234)	-1.907 (-7.478, 3.664)
Observations	91	91
Log Likelihood	-51.132	-45.176
Akaike Inf. Crit.	108.265	112.352

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 2. Linear Regressions. DV: Confidence (Experiment 1).

	Confidence (Math)		Confidence (Trivia)	
	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	-0.024 (-0.093, 0.044)	-0.060 (-0.133, 0.012)	-0.004 (-0.067, 0.060)	-0.001 (-0.069, 0.067)
Correct Answers	0.036*** (0.030, 0.042)	0.036*** (0.030, 0.042)	0.028*** (0.014, 0.042)	0.025** (0.011, 0.040)
Age		0.016* (0.003, 0.028)		0.005 (-0.007, 0.018)
Treatment Expectancy		0.065 (-0.034, 0.165)		0.140** (0.048, 0.233)
Disposable Income		-0.00001 (-0.00004, 0.00003)		0.00000 (-0.00003, 0.00003)
Math Grade (0-15)		0.007 (-0.003, 0.018)		-0.003 (-0.012, 0.007)
General Risk-taking		-0.010 (-0.028, 0.009)		-0.004 (-0.021, 0.013)
Impatience		0.014 (-0.0004, 0.028)		0.013* (0.0003, 0.026)
Impulsivity		-0.008 (-0.024, 0.009)		0.006 (-0.009, 0.021)
Intercept	0.131** (0.052, 0.210)	-0.284 (-0.644, 0.075)	0.208* (0.025, 0.392)	0.018 (-0.320, 0.356)
Observations	91	91	91	91
R ²	0.616	0.675	0.152	0.273
Adjusted R ²	0.608	0.639	0.133	0.192
Residual Std. Error	0.167 (df = 88)	0.160 (df = 81)	0.154 (df = 88)	0.149 (df = 81)
F Statistic	70.663*** (df = 2; 88)	18.686*** (df = 9; 81)	7.914*** (df = 2; 88)	3.373** (df = 9; 81)

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 3. Linear Regressions. DV: Investments in two-stage elimination tournament (Experiment 1).

	Round 1		Round 2	
	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	9.952 (-5.687, 25.591)	11.209 (-5.796, 28.214)	9.696 (-7.790, 27.181)	10.141 (-8.866, 29.147)
Age		0.725 (-2.228, 3.679)		0.174 (-3.583, 3.932)
Treatment Expectancy		-9.263 (-32.587, 14.060)		-2.847 (-27.598, 21.904)
Disposable Income		-0.003 (-0.011, 0.005)		-0.001 (-0.008, 0.006)
Math Grade (0-15)		0.098 (-2.314, 2.511)		-1.770 (-4.605, 1.065)
General Risk-taking		3.572 (-0.756, 7.899)		4.613 (-0.334, 9.561)
Impatience		0.259 (-3.005, 3.524)		2.121 (-1.627, 5.869)
Impulsivity		2.216 (-1.564, 5.996)		-0.085 (-4.308, 4.138)
Intercept	71.200*** (60.081, 82.319)	25.165 (-58.350, 108.680)	91.087*** (78.723, 103.451)	68.794 (-38.763, 176.351)
Observations	91	91	46	46
R ²	0.017	0.114	0.026	0.196
Adjusted R ²	0.006	0.028	0.004	0.022
Residual Std. Error	38.057 (df = 89)	37.638 (df = 82)	30.254 (df = 44)	29.980 (df = 37)
F Statistic	1.556 (df = 1; 89)	1.323 (df = 8; 82)	1.181 (df = 1; 44)	1.126 (df = 8; 37)
Note:	*p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses			

Supplemental Table 4. Ordinal Logistic Regressions. DV: Risk-taking (Experiment 1).

	(1)	(2)
Treatment (Testosterone = 1)	-0.065 (-0.839, 0.710)	0.002 (-0.871, 0.875)
Age		0.017 (-0.131, 0.166)
Treatment Expectancy		-0.485 (-1.649, 0.680)
Disposable Income		-0.001 (-0.003, 0.001)
Math Grade (0-15)		-0.031 (-0.154, 0.091)
General Risk-taking		0.126 (-0.110, 0.361)
Impatience		-0.006 (-0.166, 0.154)
Impulsivity		-0.002 (-0.204, 0.200)
Observations	87	87
Log Likelihood	-95.109	-92.198

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parenthesis

Supplemental Table 5. Linear Regressions. DV: Competition performance (Experiment 2).

	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	0.035 (-0.633, 0.703)	0.235 (-0.458, 0.929)	0.247 (-0.474, 0.968)	0.072 (-0.600, 0.744)
Incentives	0.441 (-0.319, 1.200)	0.516 (-0.286, 1.317)	-0.011 (-1.036, 1.015)	0.437 (-0.324, 1.197)
Piece-rate performance	0.879*** (0.798, 0.960)	0.879*** (0.794, 0.964)	0.878*** (0.789, 0.967)	0.877*** (0.795, 0.958)
Age		-0.030 (-0.079, 0.020)	-0.023 (-0.075, 0.028)	
Negative affect		-0.054 (-0.697, 0.589)	-0.082 (-0.754, 0.591)	
Positive affect		-0.140 (-0.507, 0.226)	-0.140 (-0.519, 0.239)	
2D:4D (right)		-1.123 (-11.140, 8.895)	-1.818 (-12.112, 8.475)	
Treatment Expectancy		0.358 (-0.019, 0.734)	0.369 (-0.018, 0.756)	
Estrone			-0.196 (-0.774, 0.383)	
Estradiol			0.486 (-0.174, 1.146)	
DHEA			0.435 (-0.302, 1.173)	
Progesterone			-0.003 (-0.583, 0.577)	
Deoxycortisol 11			-0.142 (-0.794, 0.510)	
Treatment x Cortisol				-0.571 (-1.563, 0.422)
Cortisol			-0.202 (-1.325, 0.921)	0.386 (-0.298, 1.071)
Cortisone			-0.018 (-1.037, 1.002)	
Corticosterone			0.347 (-0.250, 0.945)	
Aldosterone			0.210 (-0.275, 0.696)	
Melatonin			-0.378 (-1.147, 0.390)	
Intercept	2.194*** (1.149, 3.239)	3.343 (-6.325, 13.012)	1.903 (-8.801, 12.608)	2.196*** (1.149, 3.242)
Observations	241	231	231	241
R ²	0.654	0.660	0.670	0.656
Adjusted R ²	0.650	0.648	0.642	0.649
Residual Std. Error	2.643 (df = 237)	2.628 (df = 222)	2.649 (df = 212)	2.646 (df = 235)
F Statistic	149.399*** (df = 3; 237)	53.959*** (df = 8; 222)	23.962*** (df = 18; 212)	89.737*** (df = 5; 235)

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 6. Linear Regressions. DV: Willingness to compete (Round 3, Experiment 2).

	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	-0.917 (-9.294, 7.459)	0.045 (-8.680, 8.770)	0.493 (-8.707, 9.694)	-1.029 (-9.463, 7.404)
Incentives	19.909*** (10.479, 29.339)	22.124*** (12.164, 32.084)	18.894** (6.059, 31.728)	19.894*** (10.424, 29.364)
Piece-rate performance	1.348* (0.305, 2.391)	1.214* (0.130, 2.298)	1.052 (-0.074, 2.178)	1.357* (0.308, 2.406)
Winning beliefs	0.375*** (0.220, 0.530)	0.399*** (0.237, 0.561)	0.387*** (0.219, 0.556)	0.376*** (0.220, 0.533)
Age		-0.538 (-1.165, 0.090)	-0.610 (-1.258, 0.039)	
Negative affect		2.684 (-5.530, 10.897)	2.123 (-6.543, 10.789)	
Positive affect		2.119 (-2.422, 6.661)	2.324 (-2.367, 7.015)	
2D:4D (right)		13.311 (-112.062, 138.684)	6.377 (-124.200, 136.954)	
Treatment Expectancy		-0.207 (-4.914, 4.500)	0.350 (-4.543, 5.243)	
Estrone			-3.710 (-10.985, 3.566)	
Estradiol			5.858 (-2.546, 14.262)	
DHEA			-6.076 (-15.237, 3.084)	
Progesterone			-0.551 (-8.215, 7.113)	
Deoxycortisol 11			3.541 (-4.690, 11.772)	
Treatment x Cortisol				2.194 (-10.336, 14.724)
Cortisol			0.949 (-13.224, 15.122)	-1.388 (-9.669, 6.893)
Cortisone			1.163 (-11.443, 13.770)	
Corticosterone			-0.433 (-7.988, 7.121)	
Aldosterone			0.499 (-5.596, 6.594)	
Melatonin			-1.805 (-14.089, 10.479)	
Intercept	7.467 (-6.864, 21.797)	-2.490 (-124.358, 119.377)	32.932 (-103.367, 169.231)	7.370 (-7.059, 21.800)
Observations	225	216	216	225
R ²	0.207	0.235	0.256	0.207
Adjusted R ²	0.192	0.202	0.184	0.186
Residual Std. Error	31.878 (df = 220)	31.649 (df = 206)	32.007 (df = 196)	32.014 (df = 218)
F Statistic	14.348*** (df = 4; 220)	7.048*** (df = 9; 206)	3.550*** (df = 19; 196)	9.507*** (df = 6; 218)

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 7. Linear Regressions. DV: Willingness to compete for past performance (Round 4, Experiment 2).

	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	-1.072 (-9.446, 7.302)	1.942 (-6.706, 10.589)	3.502 (-5.620, 12.625)	-1.019 (-9.451, 7.412)
Incentives	15.978** (6.465, 25.490)	16.545** (6.584, 26.505)	16.425* (3.502, 29.348)	15.976** (6.420, 25.532)
Piece-rate performance	2.369*** (1.278, 3.461)	2.329*** (1.219, 3.439)	2.228*** (1.074, 3.382)	2.363*** (1.265, 3.462)
Winning beliefs	0.432*** (0.265, 0.598)	0.475*** (0.303, 0.646)	0.470*** (0.292, 0.647)	0.432*** (0.265, 0.599)
Age		-0.301 (-0.924, 0.322)	-0.316 (-0.961, 0.329)	
Negative affect		1.611 (-6.533, 9.755)	1.600 (-6.998, 10.197)	
Positive affect		0.811 (-3.705, 5.327)	0.816 (-3.845, 5.477)	
2D:4D (right)		-6.715 (-131.096, 117.667)	-4.276 (-133.591, 125.039)	
Treatment Expectancy		2.740 (-1.924, 7.404)	3.297 (-1.553, 8.147)	
Estrone			-2.647 (-9.846, 4.552)	
Estradiol			-0.373 (-8.669, 7.923)	
DHEA			1.750 (-7.322, 10.822)	
Progesterone			-2.996 (-10.616, 4.623)	
Deoxicortisol 11			2.710 (-5.453, 10.872)	
Treatment x Cortisol				-1.081 (-13.578, 11.416)
Cortisol			-0.522 (-14.577, 13.533)	0.648 (-7.633, 8.928)
Cortisone			-2.332 (-14.843, 10.179)	
Corticosterone			1.668 (-5.848, 9.183)	
Aldosterone			4.697 (-1.341, 10.735)	
Melatonin			-4.449 (-16.546, 7.648)	
Intercept	-10.187 (-23.782, 3.408)	-12.647 (-133.488, 108.194)	-31.359 (-166.688, 103.970)	-10.169 (-23.835, 3.497)
Observations	225	216	216	225
R ²	0.275	0.308	0.326	0.275
Adjusted R ²	0.262	0.278	0.261	0.255
Residual Std. Error	31.869 (df = 220)	31.368 (df = 206)	31.735 (df = 196)	32.012 (df = 218)
F Statistic	20.874*** (df = 4; 220)	10.187*** (df = 9; 206)	4.991*** (df = 19; 196)	13.797*** (df = 6; 218)

Note: *p<0.05; **p<0.01; ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 8. Linear Regressions. DV: Confidence (winning belief, Experiment 2).

	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	0.824 (-5.706, 7.354)	-0.237 (-7.032, 6.557)	-0.423 (-7.502, 6.657)	0.926 (-5.626, 7.478)
Incentives	9.462* (2.229, 16.695)	8.942* (1.289, 16.594)	5.414 (-4.432, 15.261)	9.424* (2.184, 16.664)
Piece-rate performance	2.792*** (2.053, 3.530)	2.554*** (1.784, 3.325)	2.475*** (1.684, 3.266)	2.780*** (2.038, 3.522)
Age		0.223 (-0.268, 0.714)	0.257 (-0.243, 0.758)	
Negative affect		0.105 (-6.293, 6.502)	0.813 (-5.854, 7.479)	
Positive affect		2.367 (-1.140, 5.873)	2.351 (-1.220, 5.922)	
2D:4D (right)		-62.653 (-159.985, 34.679)	-69.593 (-169.577, 30.391)	
Treatment Expectancy		1.151 (-2.510, 4.812)	0.835 (-2.928, 4.599)	
Estrone			-1.961 (-7.546, 3.624)	
Estradiol			3.314 (-3.138, 9.767)	
DHEA			2.004 (-5.033, 9.041)	
Progesterone			-2.660 (-8.537, 3.216)	
Deoxycortisol 11			-1.030 (-7.341, 5.281)	
Treatment x Cortisol				-3.914 (-13.638, 5.811)
Cortisol			-1.648 (-12.515, 9.220)	-0.711 (-7.160, 5.738)
Cortisone			-5.458 (-15.091, 4.175)	
Corticosterone			3.665 (-2.121, 9.451)	
Aldosterone			0.683 (-4.010, 5.376)	
Melatonin			-8.276 (-17.651, 1.099)	
Intercept	22.434*** (12.318, 32.551)	71.391 (-22.702, 165.484)	86.306 (-17.563, 190.176)	22.623*** (12.487, 32.759)
Observations	225	216	216	225
R ²	0.215	0.210	0.250	0.220
Adjusted R ²	0.204	0.179	0.182	0.203
Residual Std. Error	24.854 (df = 221)	24.652 (df = 207)	24.614 (df = 197)	24.876 (df = 219)
F Statistic	20.128*** (df = 3; 221)	6.871*** (df = 8; 207)	3.654*** (df = 18; 197)	12.377*** (df = 5; 219)

Note:

*p<0.05; **p<0.01; ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 9. Ordinal Logistic Regressions. DV: Confidence (guessed rank, reversed, Experiment 2).

	(1)	(2)	(3)
Treatment (Testosterone = 1)	-0.427 (-0.964, 0.109)	-0.371 (-0.938, 0.197)	-0.329 (-0.930, 0.273)
Incentives	0.890** (0.290, 1.489)	0.836* (0.189, 1.482)	0.172 (-0.653, 0.997)
Piece-rate performance	0.382*** (0.294, 0.470)	0.372*** (0.281, 0.463)	0.395*** (0.299, 0.492)
Age		-0.0001 (-0.042, 0.041)	0.001 (-0.042, 0.045)
Negative affect		0.084 (-0.438, 0.606)	-0.023 (-0.592, 0.545)
Positive affect		-0.291 (-0.587, 0.005)	-0.322* (-0.630, -0.013)
2D:4D (right)		-2.254 (-10.346, 5.838)	-1.597 (-10.252, 7.057)
Treatment Expectancy		0.131 (-0.176, 0.439)	0.175 (-0.145, 0.494)
Estrone			-0.042 (-0.521, 0.436)
Estradiol			0.605* (0.037, 1.173)
DHEA			-0.267 (-0.873, 0.339)
Progesterone			0.016 (-0.500, 0.532)
Deoxicortisol 11			-0.248 (-0.770, 0.273)
Cortisol			0.398 (-0.530, 1.327)
Cortisone			-0.804 (-1.706, 0.098)
Corticosterone			0.344 (-0.154, 0.841)
Aldosterone			0.360 (-0.047, 0.766)
Melatonin			-0.044 (-0.717, 0.628)
Observations	225	216	216

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 10. Linear Regressions. DV: Average all pay auction bid (Experiment 2).

	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	2.278 (-4.930, 9.486)	3.956 (-3.553, 11.464)	3.215 (-4.517, 10.948)	2.476 (-4.786, 9.738)
Age		0.263 (-0.256, 0.782)	0.136 (-0.392, 0.663)	
Negative affect		-0.049 (-6.988, 6.890)	-1.889 (-9.096, 5.319)	
Positive affect		-0.951 (-4.898, 2.997)	-1.150 (-5.166, 2.867)	
2D:4D (right)		49.309 (-58.476, 157.094)	68.496 (-40.913, 177.905)	
Treatment Expectancy		-0.220 (-4.289, 3.849)	0.044 (-4.094, 4.181)	
Estrone			3.558 (-2.544, 9.660)	
Estradiol			1.428 (-4.535, 7.392)	
DHEA			-0.955 (-8.844, 6.934)	
Progesterone			-3.878 (-9.886, 2.131)	
Deoxicortisol 11			-0.209 (-7.126, 6.709)	
Treatment x Cortisol				-3.176 (-13.902, 7.550)
Cortisol			11.124 (-0.777, 23.025)	3.148 (-4.247, 10.542)
Cortisone			-7.768 (-18.368, 2.832)	
Corticosterone			-7.308* (-13.700, -0.917)	
Aldosterone			-0.565 (-5.724, 4.594)	
Melatonin			3.357 (-4.883, 11.596)	
Intercept	28.497*** (23.348, 33.647)	-22.226 (-125.651, 81.199)	5.146 (-108.159, 118.452)	28.301*** (23.117, 33.485)
Observations	241	231	231	241
R ²	0.002	0.015	0.062	0.005
Adjusted R ²	-0.003	-0.012	-0.008	-0.008
Residual Std. Error	28.540 (df = 239)	28.452 (df = 224)	28.402 (df = 214)	28.618 (df = 237)
F Statistic	0.384 (df = 1; 239)	0.553 (df = 6; 224)	0.883 (df = 16; 214)	0.359 (df = 3; 237)

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 11. Linear Mixed model Regressions. DV: All pay-auction bidding (Experiment 2).

	(1)	(2)
Treatment (Testosterone = 1)	2.278 (-4.930, 9.486)	3.956 (-3.553, 11.464)
Group size = 4	-15.170*** (-20.514, -9.826)	-15.589*** (-21.130, -10.048)
Group size = session	-23.954*** (-29.299, -18.610)	-24.303*** (-29.844, -18.762)
Age		0.263 (-0.256, 0.782)
Negative affect		-0.049 (-6.988, 6.890)
Positive affect		-0.951 (-4.898, 2.997)
2D:4D (right)		49.309 (-58.476, 157.094)
Treatment Expectancy		-0.220 (-4.289, 3.849)
Intercept	41.539*** (35.536, 47.542)	-8.929 (-112.403, 94.546)
Observations	723	693
Log Likelihood	-3,594.769	-3,438.899
Akaike Inf. Crit.	7,201.537	6,899.797
Bayesian Inf. Crit.	7,229.038	6,949.748

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 12. Linear regressions. DV: Risk-taking (Experiment 2).

	(1)	(2)	(3)	(4)
Treatment (Testosterone = 1)	-0.041 (-0.417, 0.336)	-0.088 (-0.479, 0.303)	-0.031 (-0.424, 0.362)	-0.046 (-0.422, 0.330)
Risk-taking (morning)	0.573*** (0.451, 0.695)	0.549*** (0.425, 0.673)	0.606*** (0.478, 0.734)	0.600*** (0.476, 0.724)
Age		-0.012 (-0.040, 0.016)	-0.013 (-0.041, 0.014)	
Negative affect		0.212 (-0.131, 0.555)	0.154 (-0.201, 0.509)	
Positive affect		-0.087 (-0.305, 0.130)	-0.082 (-0.300, 0.135)	
2D:4D (right)		-4.279 (-9.846, 1.288)	-4.362 (-9.966, 1.242)	
Treatment Expectancy		-0.136 (-0.350, 0.079)	-0.109 (-0.323, 0.106)	
Estrone			-0.238 (-0.581, 0.105)	
Estradiol			0.171 (-0.133, 0.476)	
DHEA			0.444* (0.039, 0.849)	
Progesterone			0.152 (-0.149, 0.453)	
Deoxycortisol 11			0.166 (-0.191, 0.523)	
Treatment x Cortisol				0.001 (-0.548, 0.550)
Cortisol			-0.210 (-0.826, 0.406)	0.271 (-0.108, 0.649)
Cortisone			0.299 (-0.219, 0.818)	
Corticosterone			-0.114 (-0.447, 0.219)	
Aldosterone			0.116 (-0.150, 0.382)	
Melatonin			0.033 (-0.370, 0.436)	
Intercept	2.278*** (1.461, 3.094)	7.065* (1.661, 12.470)	3.548 (-2.409, 9.505)	2.098*** (1.263, 2.933)
Observations	193	186	186	193
R ²	0.311	0.333	0.391	0.324
Adjusted R ²	0.303	0.306	0.330	0.309
Residual Std. Error	1.332 (df = 190)	1.336 (df = 178)	1.313 (df = 168)	1.327 (df = 188)
F Statistic	42.801*** (df = 2; 190)	12.671*** (df = 7; 178)	6.351*** (df = 17; 168)	22.476*** (df = 4; 188)

Note:

*p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses

Supplemental Table 13. Ordered logistic regression. DV: Risk-taking (Experiment 2).

	(1)	(2)	(3)
Treatment (Testosterone = 1)	-0.179 (-0.692, 0.335)	-0.290 (-0.825, 0.246)	-0.262 (-0.818, 0.294)
Risk-taking (morning)	0.902*** (0.677, 1.127)	0.880*** (0.650, 1.110)	0.952*** (0.710, 1.195)
Age		-0.012 (-0.050, 0.025)	-0.016 (-0.054, 0.022)
Negative affect		0.214 (-0.259, 0.688)	0.196 (-0.306, 0.699)
Positive affect		-0.022 (-0.322, 0.279)	-0.027 (-0.334, 0.279)
2D:4D (right)		-6.709 (-14.381, 0.964)	-7.280 (-15.286, 0.725)
Treatment Expectancy		-0.245 (-0.537, 0.046)	-0.241 (-0.541, 0.059)
Estrone			-0.272 (-0.760, 0.216)
Estradiol			0.162 (-0.257, 0.580)
DHEA			0.538 (-0.041, 1.116)
Progesterone			0.237 (-0.186, 0.660)
Deoxycortisol 11			0.155 (-0.382, 0.692)
Cortisol			-0.169 (-1.102, 0.764)
Cortisone			0.500 (-0.568, 1.568)
Corticosterone			-0.323 (-0.786, 0.141)
Aldosterone			0.050 (-0.329, 0.430)
Melatonin			0.134 (-0.401, 0.668)
Observations	193	186	186
Log Likelihood	-294.313	-282.214	-276.661

Note: *p<0.05 **p<0.01 ***p<0.001; 95% confidence intervals are in parentheses