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The Bull of Wall Street: Experimental Analysis of Testosterone and Asset Trading

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Abstract. Growing evidence shows that biological factors affect individual financial decisions that could be reflected in financial markets. Testosterone, a chemical messenger especially influential in male physiology, has been shown to affect economic decision making and is taken as a performance enhancer among some financial professionals. This is the first experimental study to test how testosterone causally affects trading and prices. We exogenously elevated testosterone in male traders and tested testosterone's effect both on their trading behavior in experimental asset markets and on the size and duration of asset price bubbles. Using both aggregated and individual trading data, we find that testosterone administration generated larger and longer-lasting bubbles by causing high bids and the slow incorporation of the asset's fundamental value.

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Keywords: asset trading • experimental markets • testosterone • neurofinance • bubbles

1. Introduction

Behavioral finance literature shows that financial markets meaningfully deviate from efficiency because of limits to arbitrage and behavioral biases, and that investors' decisions are influenced by mood, sunshine, sports events, and other nonmarket factors. Neurobiology affects investors' preferences and beliefs, yet little is known about the biological aspects of financial decision making. This is the first study to test the effects of testosterone—a potent male hormone—on males' trading decisions and the impact of those decisions on asset price bubbles. In this paper, we measure testosterone's causal effect on the size and duration of bubbles, and elucidate the mechanics of bubble formation by administering testosterone or placebo in a randomized, double-blind asset-trading experiment. This paper's primary hypothesis is that testosterone causes male traders to bid and ask at higher prices and neglect an asset's fundamental value, and that these behaviors will lead to larger and longer-lasting bubbles.

Growing evidence suggests that behavioral factors affect individual economic behavior, and some of these factors demonstrably influence financial markets. Research shows that behavioral factors drive inefficient market outcomes, such as asymmetric prospect theory preferences (Tversky and Kahneman 1992) underlying the disposition effect and consequent suboptimal asset buying and selling (Odean 1998, Shefrin and Statman 1985), inertia affecting time-varying risk aversion (Brunnermeier and Nagel 2008), and non-Bayesian updating associated with overreaction to news (De Bondt and Thaler 1985, Jegadeesh and Titman 1993). Various biological mechanisms, too, have been shown to compute and affect financial decision making and markets (Frydman and Camerer 2016). These include the identification of neural substrates predicting overpricing (De Martino et al. 2013, Smith et al. 2014), genes explaining asset allocation (Cesarini et al. 2010, Cronqvist and Siegel 2014), and hormones affecting both risk aversion (Kandasamy et al. 2014) and the choice of risky assets (Cueva et al. 2015).[1] We advance this growing literature by testing whether the sex hormone testosterone affects males' asset trading

and by measuring any associated impact on prices in experimental financial markets.

Named from the Greek verb *hormoa* meaning "to excite" (Starling 1905), hormones are chemical messengers that influence the brain and body to motivate both long-term physical and neurological (i.e., "developmental") features and short-term (i.e., "activational") behavioral changes.[2] Research on the intersection of hormones and behavior have historically focused on relatively simple behaviors in animals such mating, aggression, and feeding; only more recently has the role of hormones been studied within human economic decision making. In this paper, we focus on the sex hormone testosterone, because the majority of professional traders are male, and testosterone is especially influential in male physiology.[3] Testosterone plays significant roles in biological development, is a central biological driver of gender differences, and has been recently shown to influence various economic behaviors.[4] Men's testosterone levels vary cross-sectionally, are generally 5- to 25-fold higher than in women (Salameh et al. 2010), and likely contribute to both gender differences and variations in intramale behaviors. Research shows that relative to females, males hold an overwhelming majority of trading jobs in finance (Clarke 2013, Fabrikant 2010), overtrade and take more risks (Barber and Odean 2001, Croson and Gneezy 2009), exhibit greater overconfidence (Lundeberg et al. 1994) and associated acquisitiveness (Huang and Kisgen 2013, Levi et al. 2010), and generate larger price bubbles in experimental markets (Eckel and Füllbrunn 2015).

A field study showed that testosterone levels positively predict trading performance among professionals relative to their recent profit and loss (Coates and Herbert 2008), and experiments suggest risk taking is also affected by baseline levels of the hormone (Apicella et al. 2008, Stanton et al. 2011). Albeit correlational evidence that biological factors affect financial decision making (Apicella et al. 2008, Coates and Herbert 2008, Stanton et al. 2011), causal studies are needed to establish a direct effect (Frydman and Camerer 2016, Mazur 2017). Despite promising early findings, the field of hormonal neuroeconomics is developing, and studies in this area may require replication and corroboration for robustness, as done in other areas of experimental economics (Camerer et al. 2016).

Despite an abundance of data from large exchanges (e.g., NASDAQ), archival data do not lend themselves to cleanly identifying and quantifying the impact of individual and institutional factors among competing theories (Levitt and List 2007). Further, using a field study to test the causal effects of testosterone on trading should be avoided because of potentially significant market consequences. To this end, experimental financial markets provide concise frameworks for testing specific theories with a high degree of identification (Bossaerts and Plott 2004). The contribution of this paper is to advance understanding of the causal effects of biology on financial decision making in a controlled environment (Frydman and Camerer 2016).

We used the dynamic experimental market introduced in Smith et al. (1988) (SSW, henceforth) because this paradigm offers active trading, a transparent fundamental value of the asset being traded, real monetary incentives, and the ability to carefully manipulate specific variables in markets to identify their effect on trading and prices. Most financial market experiments seek to identify the effects of institutional, informational, or trait-based factors, yet none has tested the causal impact of hormones on trading behavior and associated prices. By externally administering testosterone or placebo in a double-blinded procedure, this study creates markets that differ only by the testosterone levels of the market participants (called traders), and tests for the causation of testosterone on trading behavior and prices.[5] We measure both testosterone and an associated hormone produced from testosterone called dihydrotestosterone (DHT) as manipulation checks and to analyze their effects on market measures such as amplitude, duration, and volume.[6] In addition to obtaining trading data and biological measures, we also surveyed traders prior to, between, and after trading rounds to identify primary psychological and belief channels.

Our chief hypothesis is that testosterone will cause traders to overbid for financial assets (as detectible from bidding data), which drives larger price bubbles—defined as upward deviations from an asset's fundamental value. Our results confirm these conjectures by showing that traders in cohorts that received testosterone bid higher amounts, which led to higher transaction prices relative to markets in which traders had received placebo. These findings advance our understanding of the hormone's effects on trading behavior and can inform strategies to potentially improve individual decision making, firm trading performance, and the ability to predict—and potentially stabilize—financial markets.

2. Literature Review and Hypothesis Development

2.1. Evolution of Economics Research

Traditional economic theory assumes that agents are rational and optimize "as if" they execute complex computations that approximate optimality, according to well-defined utility functions and Bayesian updating. However, evidence to the contrary has been consistent: for example, investors' myopic portfolio evaluation horizon (Gneezy et al. 2003, Gneezy and Potters

1997) can lead to behavior that defies expected utility theory. Similarly, according to finance theory, financial markets are informationally efficient, and prices accurately reflect asset fundamentals and relevant economic information (Fama 1970). Conventional theories maintain that bubbles and crashes (such as the Internet bubble of the late 1990s and the American housing market crash in the 2000s) can be explained by rational factors such as procyclical expansions of credit, institutional incentives and their associated systemic externalities, and innovations characterized by uncertain future cash flows (Allen and Gale 2000, Bernanke 2010, Brunnermeier 2008). However, prices have been shown to change because of reasons unrelated to intrinsic value or rational expectations thereof (De Bondt and Thaler 1985, Shiller 2015), such as sentiment (Baker and Wurlger 2006, Shiller 2015), sunshine (Hirshleifer and Shumway 2003), hours of daylight (Kamstra et al. 2003), columnist opinion (Dougal et al. 2012), and even professional sports outcomes (Edmans et al. 2007). Underlying many of these aggregate findings are, arguably, biological factors acting at the individual level (De Martino et al. 2013, Haracz and Acland 2015, Smith et al. 2014) and scaling to produce macroeconomic effects (Korniotis and Kumar 2011).[7]

2.2. Biological Causes Underlying Finance Research Findings

Experiments can test causal hypotheses and reveal the underlying mechanisms of phenomena observed in archival data. For example, Kamstra et al. (2003) show that sunlight cycles affect asset prices mediated by mood that affects risk aversion. This result is corroborated by Bassi et al. (2013) who demonstrate experimentally that sunshine and good weather affect asset prices through improvements in mood. Mood is a psychological channel that has an established biological connection to serotonin, a neurotransmitter that is demonstrably sensitive to sunlight and has been shown to affect consumer decision making (Lambert et al. 2002, Lichters et al. 2016).[8] Other studies corroborate that underlying biological mechanisms can lead to market-level events. For example, Smith et al. (2014) identify brain regions that encode bubble size and provide both a neurobehavioral metric of bubbles and an early detection of excessive price deviations. Also, financial crises and periods of low returns persist because of time-varying risk aversion produced by fear (Guiso et al. 2013). Fear and stress are driven by hormones (Rodrigues et al. 2009), and Kandasamy et al. (2014) show that chronically elevating stress hormones increases risk aversion—an important biological factor because stress has been shown to affect asset allocation decisions (Porcelli and Delgado 2009).

Similarly, evidence suggests that biological factors could underlie the reaction of asset prices to sports outcomes, which occur without concomitant changes in fundamentals (Edmans et al. 2007). Several studies show changes in testosterone levels among both competitors (Apicella et al. 2008, Booth et al. 1989) and spectators (Bernhardt et al. 1998) in response to wins and losses, a phenomenon known as the winner and loser effects of testosterone (Booth et al. 1989). Additionally, changes in testosterone have been associated with increased aggression (Carré et al. 2013) and the willingness to compete (Apicella et al. 2014).[9] A comprehensive review by Apicella et al. (2015) summarizes the multiple approaches to understanding testosterone's role in risky decisions and suggests that the hormone adaptively modulates risky behaviors.[10, 11] In addition to associational evidence regarding endogenous (i.e., produced in the body) levels and behavior, recent work has shown that exogenous testosterone administration changes beliefs and economic decision making (Boksem et al. 2013, Cueva et al. 2015) and encourages intuitive and impulsive cognition in lieu of deliberate thinking (Nave et al. 2017). Together, this literature led us to clear hypotheses and motivated us to test them in a controlled environment.

2.3. Experimental Financial Markets

Experimental financial markets provide frameworks to test foundational theories, such as the impact of institutional design, liquidity, information, and financial derivatives, as well as individual differences and biological factors, on economic behavior. SSW-type experimental markets typically have a single asset with a variable dividend that has a positive expected value. All traders know the fundamental value of the asset, which allows for the unambiguous measurement of mispricing.[12] Because traders determine market prices endogenously in their respective markets, the individual buying and selling offers, together with associated volume, can reveal both the determinants of transaction prices and the differences between experimental treatments. These markets consistently exhibit brief initial underpricing followed by significant overpricing that dampens over successive rounds (Dufwenberg et al. 2005, Palan 2013). The majority of studies using the SSW framework focus on institutional variables, such as dividend uncertainty and futures trading (Porter and Smith 1995), the effect of short selling (Ackert et al. 2006, Haruvy and Noussair 2006), the cash-to-asset ratio (Caginalp and Ilieva 2008), and adding cash or changing the dividend distribution in experienced markets (Hussam et al. 2008).

Other studies have measured the effects of individual trader traits, such as gender (Eckel and Füllbrunn 2015), business experience (Smith et al. 1993), cognitive abilities (Bosch-Rosa et al. 2015), overconfidence (Biais et al. 2005, Michailova and Schmidt 2016), their own and others' irrationality (Cheung et al. 2014,

Hargreaves Heap and Zizzo 2012), and an individual proclivity to speculate (Janssen et al. 2015) on prices and trading patterns. Further, to quantify the effects of traders' psychological states on prices and trading behavior, recent studies have manipulated emotion (Andrade et al. 2015, Lahav and Meer 2012) and confusion (Kirchler et al. 2012). Similarly, this study is the first to directly manipulate a biological factor by exogenously administering testosterone in an attempt to isolate and test its influence on experimental asset trading in men (for a comparison of studies, see Table A.5 in the e-companion).

2.4. Hypotheses Development

Men generally show lower risk aversion than women (Eckel and Grossman 2002) and produce larger price bubbles in experimental markets (Eckel and Füllbrunn 2015). Additional experimental evidence shows that testosterone is associated with various types of risk taking (Apicella et al. 2015), such as basal testosterone levels (Stanton et al. 2011) and endogenous changes that predict subsequent risk taking (Apicella et al. 2014). Further, exogenous application of testosterone increases traders' willingness to invest in high-variance stocks and may increase optimism regarding future prices (Cueva et al. 2015). Testosterone is responsible for sexual characteristics that distinguish males from females and has both anxiolytic (anxiety-reducing) and analgesic (pain-reducing) properties (which may buffer traders from experiencing discomfort from risk and pain of losses) (Crawley et al. 1986). Therefore, in a risky market setting where traders might be unable to profitably resell overpriced assets, we expected that traders that have elevated testosterone would be willing to pay more and ask higher prices for assets, and as a result, would drive market prices to levels that exceed their fundamental values (i.e., cause bubbles).

Hypothesis 1 (H1). *The markets in which traders received testosterone will produce larger bubbles in aggregate as measured by* amplitude *and* market value *amplitude* (*defined in Section 4.2*).

Hypothesis (H2). *The markets will also produce longer-lasting bubbles in aggregate as measured by* duration (*Section 4.2*).

Hypothesis (H3). *Because of expected greater bidding activity and reduced attention to concordance with assets' fundamental values, we expect that markets in which traders received testosterone will trade at a higher volume as measured by* turnover (*Section 4.2*).

Second, the recent evidence, as shown by Cueva et al. (2015), that exogenous testosterone increases both optimism regarding future prices and the preference for high-volatility assets suggests that traders in the testosterone sessions will bid higher prices because of their belief in higher future prices and, thus, subsequent capital gains through resale (which will lead to larger bubbles as hypothesized in H1). Cueva and coauthors propose that testosterone increases the preference for high-volatility assets through increased optimism, so traders may expect that prices will be higher and will therefore bid higher.

Hypothesis (H4). *Individual traders who have received testosterone will bid higher prices relative to traders given placebo* (*Section 4.3*).

Hypothesis (H5). *The individual traders who have received testosterone will post higher ask prices relative to traders who received placebo* (*Section 4.3*).

Hypothesis (H6). *We expect that traders who have received testosterone will bid at higher volume relative to traders given placebo, as measured by the normalized number of offers to buy, called buying turnover* (*Section 4.3*).

Hypothesis (H7). *This hypothesis anticipates that relative to traders who have received placebo, traders who have received testosterone will, in an attempt to capitalize on capital gain opportunities, post sell offers at higher volumes, as measured by the number of offers to sell, called selling turnover* (*Section 4.3*).

Trading financial assets in a dynamic market is a complex cognitive task. It requires simultaneously and rapidly estimating, planning, learning, responding, and reoptimizing in an unpredictable setting. Therefore, financial cognition is a broad skill set that is likely correlated with other types of intelligence underlying trading behavior, and this aptitude presumably affects performance. Indeed, Bosch-Rosa et al. (2015) show larger bubbles in markets composed exclusively of traders with low cognitive sophistication as measured by a battery of tests, including cognitive reflection test (CRT) scores (Frederick 2005). Stemming from recent evidence of exogenous testosterone promoting intuitive decision making and a decrease in deliberate thinking (Nave et al. 2017), we expect changes in an asset's fundamental value to be imperfectly incorporated among testosterone markets. The parallel between testosterone's effects on financial cognition and CRT performance is that testosterone shifts decision making to rapid, reactive (so-called "system 1") processes and away from excogitated and deliberate decision-making ("system 2") processes (Kahneman 2003).

Hypothesis (H8). *This hypothesis tests whether traders who received testosterone will incorporate changes in fundamental value less accurately, relative to traders who received placebo* (*Section 4.4*). *Additionally, our experimental design included interround surveys of price expectations to test differences between treatment groups.*

Hypothesis (H9). *Because Haruvy et al.* (2007) *showed that expectations of future prices are predictive of future prices, we hypothesized that traders who received testosterone will have expectations consistent with attendant higher prices and expect higher prices* (*Section* 5).

3. The Experiment

We conducted 17 *sessions* of continuous double-auction markets, each consisting of three *rounds* of 12 trading *periods*, which each lasted 1.5 minutes, during which traders bought, sold, bid, and asked for shares of a financial asset. Only one asset type was traded throughout the session (described below). Ten cohorts (84 traders; each cohort composed of traders in the same session) received testosterone gel, and seven cohorts (56 traders) received gel containing no testosterone (placebo); cohorts ranged in size between five and 14 because of variation in recruiting responses and show-up rates.[13] All prices were denominated in experimental currency units (ECUs), which were converted to U.S. dollars at the end of the session and paid in cash according to trading performance. Participants were informed of the exchange rate of one ECU for US$0.01.

3.1. Experimental Setting and Design

We created a market for trading an asset by using a simple and predictable fundamental value structure. Each share of the asset paid a dividend of 0 or 18 ECUs at the conclusion of each period with equal probability (i.e., the expected value of 9 ECUs per share for each of 12 periods) and followed an independent and identically distributed (i.i.d.) random process (see Section 1 of the e-companion). Through random assignment, traders were endowed, at the start of every round, with either six stocks and 216 ECUs or two stocks and 648 ECUs (both allocations worth 864 ECUs). At the start of each round, the fundamental value of the asset began at 108 ECUs, decreasing by 9 each period and reaching zero at the end of each round. Participants were provided with a complete table of the asset's fundamental (i.e., expected) value for each period over the course of an entire round, and the fundamental value structure was the same in all three rounds of trading (see Section 1 of the e-companion). Using seven-point Likert scales, surveys were conducted prior to trading, following each trading round, and at the conclusion of trading to assess mood, perception of prices, self-evaluation, rating of trading performance, and beliefs and associated certainty about which treatment was received.

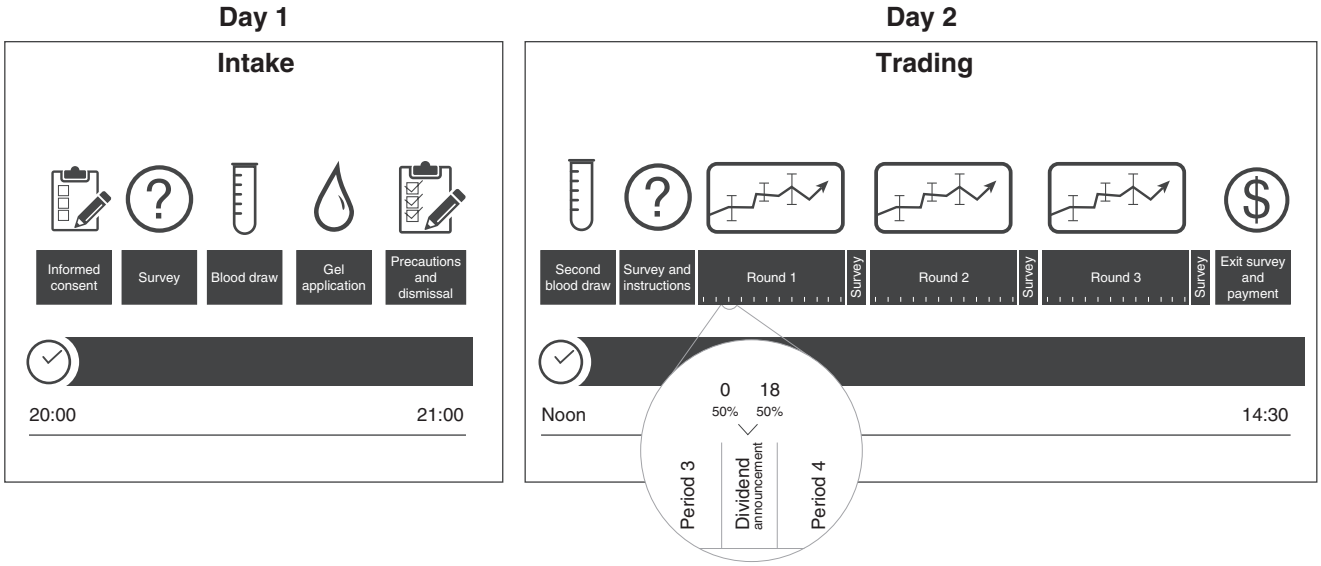
3.2. Study Design and Participant Demographics

We conducted a double-blind experiment in which 140 male traders 23 years old on average (min = 18, max = 65, SD = 7.0) received a topical gel containing testosterone or placebo prior to participating in an experimental asset market. Sessions took place between April 5, 2012, and November 11, 2012. We used a between-group design, where all traders in a cohort were assigned to either the testosterone or placebo treatment. Each trader participated only once. Traders' characteristics were evenly distributed between treatment groups, such as age (two-tailed t-test between treatment groups $p = 0.14$, t-statistic (137) = 1.49), proportion of subjects who had trading experience ($p = 0.20$, z-statistic = 1.28), and proportion of economics and business majors ($p = 0.43$, z-statistic = 0.78).[14]

Each session took place over two days to allow testosterone levels to increase and stabilize following exogenous application on the first day. Recent single-dose studies show a rapid increase occurring shortly after administration (Carré et al. 2015, Eisenegger et al. 2013), so we timed the trading sessions when traders were at stable and elevated testosterone levels rather than while experiencing rapid elevation (see Figure 1).[15] Because hormone levels vary cyclically throughout the day (Brambilla et al. 2009) and in response to environmental factors (such as the presence of attractive potential mates) (Ronay and Hippel 2010), we adhered to a strict experimental procedure that had a uniform time schedule and clear operational protocols (such as male-only research assistants) to minimize changes in testosterone.

The first day of a session consisted of a medical screening, blood drawn by a licensed phlebotomist, double-blind gel application, and demographic survey at 8:00 P.M. Traders were informed that they were receiving either testosterone or an inert placebo with equal probability. Trading took place immediately after the second blood draw at noon on the second day. Testosterone has been shown to vary from baseline naturally over the short term, decreasing to as low as 60% (Kreuz et al. 1972) among officers in training and increasing as much 72% after sexual activity (Escasa et al. 2011). The experimental dose of 10 mg (two packets of 50 g of 1% AndroGel®) increased traders' blood testosterone levels to "high normal," comparable with the normal range of variation for men in their respective age group (Salameh et al. 2010).[16] To rule out the possibility of a group-specific influence of random exogenous factors, and to support the claim that differences in trading are caused by a single dose of testosterone, we used a clinical dosage; a double-blind, randomized experimental design; temporally proximal trading sessions; and multiple blood measures. All research assistants, in addition to completing Protecting Human Research Participants training and receiving corresponding certification by the National Institute of Health, participated in several mandatory training sessions and ran multiple pilot

Figure 1. Structure of Intake and Drug Administration and Trading Sessions



Notes. Participants arrived the evening prior to their trading session to sign informed consent forms and take pretrading surveys prior to their blood draws and gel administration (day 1). Trading took place in three rounds of 12 periods each in each session the following day (day 2). After each period a dividend of either 0 or 18 was issued to every share of the asset (i.e., every share in the entire market received the same dividend). After each round, a survey was used to assess participants' market perceptions and their attribution of performance. The survey included questions such as, "What do you think determined your performance?" where traders rate on a 1–7 scale the effects of specific factors such as luck, talent, and their calculations. In addition, traders were asked whether prices and price fluctuations were higher or lower than expected.

studies at the lab prior to starting the study. The phlebotomist was strictly in charge of all blood acquisitions, and a licensed psychiatrist conducted the medical intakes. The institutional review board approved this study, and extensive safety, sterility, and participant-protection measures were maintained throughout. No adverse events occurred during the study.

3.3. Trading

The double-auction format allows participants to simultaneously post bid and ask prices, as well as to immediately buy and sell assets. Traders could buy or sell using a standard electronic limit order book where outstanding orders were fulfilled by selecting the desired price. They could see all transacted prices in the current period, standing sell and buy orders, and their current cash and stock holdings (see Section 2 of the e-companion). Posted offers could be retracted with a "Remove" button, allowing traders to rescind offers as market conditions changed. Limit orders needed to be integers between 0 and 500 ECUs, and were shown on all screens without trader identification. The trading screen showed the amount of time remaining and the current period (out of 36). Trading took place in real time in a large behavioral laboratory with private computer terminals using z-Tree software (Fischbacher 2007). All keyboards and computer mice were calibrated to the same tracking motion speed.

4. Testosterone and Asset Trading Results

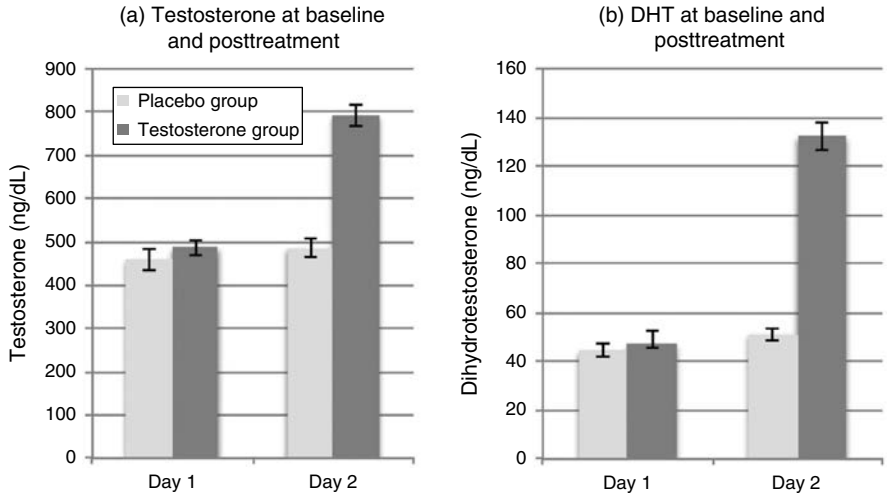
We find that testosterone gel increased traders' blood levels of testosterone relative to their baseline levels in comparison to placebo gel. Transaction data suggest that traders used the trading platform correctly by posting bids to buy that were lower than offers to sell, and thus they were poised to profit from their transactions. We test for differences in prices and then analyze differences in individual trading patterns between testosterone- and placebo-treated traders.

4.1. Testosterone Treatment Manipulation Check

We measured testosterone and DHT twice to obtain baseline and posttreatment levels. Baseline testosterone levels were similar between groups, with the testosterone group's average testosterone level at 486 nanograms per deciliter (ng/dl)[17] (SD = 17.4), and the placebo group average was 459 ng/dl (SD = 24.9) (two-tailed p-value = 0.36, $t(138) = 0.92$)[18]; baseline DHT levels were also similar, with the testosterone group's average DHT level at 47.3 ng/dl (SD = 16.2) and the placebo group averaging 44.5 ng/dl (SD = 18.9) (two-tailed p-value = 0.35, $t(138) = 0.93$).

Postadministration testosterone and DHT levels were significantly higher in the testosterone group compared with the placebo group. The testosterone group's average increase in testosterone was 63% from 486 to 791 ng/dl (t-test relative to baseline: $p < 0.001$, $t(83) = 13.1$),

Figure 2. Manipulation Check: Testosterone and DHT Levels at Baseline and Posttreatment



Notes. Panel (a) shows testosterone and panel (b) DHT levels for all cohorts by treatment condition (testosterone $n = 84$; placebo $n = 56$). Both testosterone and DHT baseline levels are comparable between the two cohorts (day 1). Postadministration levels on day 2 show that the testosterone-treated groups' average testosterone level increased 63%, and that their average DHT level increased 180%, while the placebo group average did not significantly increase. The small increase in the placebo group's hormone levels between days 1 and 2 accord with the natural daily cycle (diurnal), which is highest in the morning and steadily decreases throughout the day so that it is expected to be higher at the time of the second blood draw.

placing many traders near the upper end of the natural male range (known as "high normal") with only five traders exceeding this range, and only slightly so. The level of testosterone in the placebo group was statistically similar to their initial levels and experienced an expected small increase due to typical daily variation ($p = 0.16$, $t(55) = 1.42$).[19] Because of natural heterogeneity in baseline testosterone levels (146–1,125 ng/dl in the total sample) and range of change in testosterone (−76–632 ng/dl in the testosterone group), hormone levels partially overlap across treatment groups, meaning that some traders had similar second-day levels despite being in different treatment groups (see Figure A.2 in the e-companion). Similar to testosterone levels, DHT levels increased 180% from 47 to 132 ng/dl in the testosterone-treated group ($p < 0.01$, $t(83) = 13.1$), while placebo group levels increased slightly as expected given DHT's daily cycle (44.0 ng/dl on evening of day 1, 51.2 ng/dl at noon on day 2, $p = 0.05$, $t(55) = 1.99$) (see Figure 2).

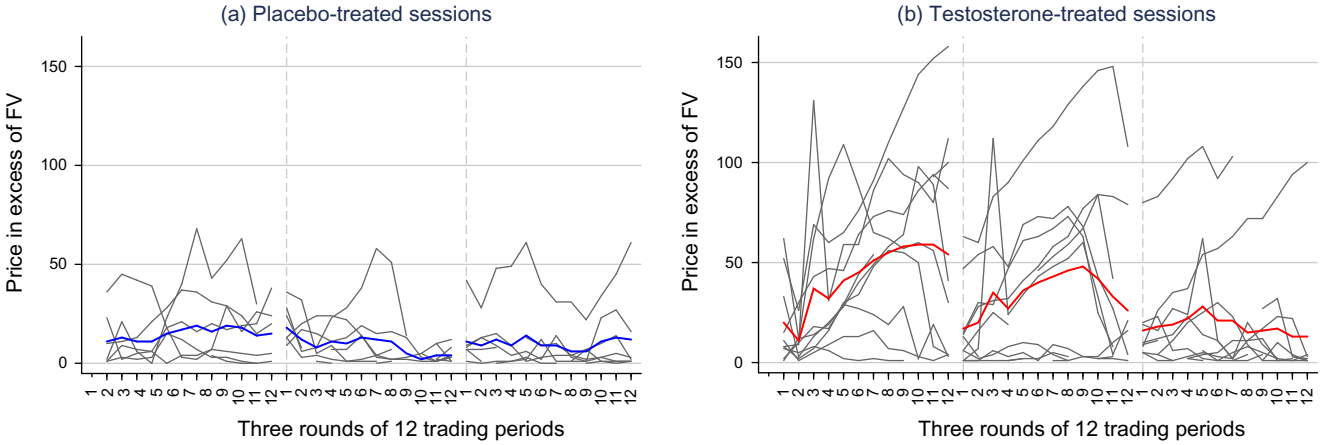
Traders were asked which treatment they believed they had received (testosterone or placebo) and how confident they were that they had received it (using a Likert scale with 1 = "don't know" and 7 = "certain"). Both treatment groups had statistically similar proportions of traders who believed that they had received testosterone (test of equality in proportions of subjects believing in receiving testosterone: testosterone group mean = 0.70, placebo group mean = 0.73; $p = 0.70$, $t(120) = 0.38$). Traders were systematically incorrect about whether they had received testosterone or placebo, with correct guessing over the entire sample being virtually random (49% overall; 55% among the testosterone-treated traders, and 41% among placebo-treated traders). The placebo group was weakly more certain of their beliefs at the 10% level (testosterone group mean = 2.8, placebo group mean = 3.4; $p = 0.06$, $t(105) = 1.9$).[20] We tested whether beliefs in treatment affected actual testosterone levels and find no reliable evidence.[21]

4.2. Testosterone Effect on Prices

Given the challenges of establishing the causality of testosterone amid the conflation of cause and effect in correlational studies, we focus our analyses on the differences between the two treatment groups to quantify the causal effect of testosterone.[22] The sessions with traders who received placebo exhibited price bubble sizes comparable with the sessions that had similar parameters, such as Sutter et al. (2012) (see Figure A.2 and Table A.5 in the e-companion). Consistent with other papers using the SSW paradigm, we anticipated that bubbles would monotonically decrease and differences between testosterone and placebo groups would diminish as traders gained experience in the market.[23] Figure 3 shows the price deviations from fundamental values by treatment condition, and that the deviations were greater in testosterone sessions than placebo sessions.

We use measures of pricing bubble traits common in the experimental literature, including *amplitude*, *market value amplitude* (MVA), *duration*, and *turnover*, to test whether high-testosterone cohorts created larger bubbles than their placebo counterparts.[24] Bubble size was measured by amplitude, the maximum normalized difference between average prices and fundamental value during a trading period (Porter and Smith 1995), and

Figure 3. (Color online) Price Bubbles: Prices in Excess of Fundamental Value



Notes. This figure depicts overpricing by showing price minus fundamental value for the entire experiment by treatment condition. Grey lines show prices in excess of the asset's fundamental value for a particular cohort across three rounds of each session. The average of all placebo cohorts is shown in blue in panel (a), and the average of all testosterone cohorts is shown in red in panel (b). Consistent with virtually all other asset trading experiments, bubbles decrease in size with each round and approach the asset's fundamental value in the third round. The diminutive size of the bubble in the placebo condition is due to the low uncertainty in our design, regarding the asset's fundamental value, as dividends could be only 0 or 18, creating a narrow range of expected values similar to Porter and Smith (1995). These graphs show that increasing testosterone causes higher prices without any indication of high future prices and despite knowledge of future decreasing fundamental values.

MVA, the volume-weighted average price above the asset's fundamental value (Hussam et al. 2008). *Duration* measures the number of consecutive periods over which the difference between average price and fundamental value grew. *Turnover*, similar to volume in large exchanges such as the NYSE, captures relative trading activity and is measured by the number of trades divided by the number of shares in the market (Porter and Smith 1995) (all measures defined in Table A.1 in the e-companion).

Aggregating across all three rounds of trading, we observe a 114% larger amplitude ($p = 0.01$, $z = 2.5$ using Mann–Whitney test)—the primary measure of bubble size—between testosterone and placebo sessions, and an associated Cohen's d of 1.10 (Cohen 1992); in round 1, we observe a 120% larger amplitude ($d = 2.03$) (see Table A.2 in the e-companion). To contextualize our results with other papers in the first round of trading, our treatment effect lies between Janssen et al. (2015), who observed a 130% larger amplitude between low and high speculators, and Lahav and Meer (2012), who found a 100% larger amplitude caused by positive relative to neutral emotional induction (see Table A.5 in the e-companion).

By estimating a linear regression controlling for trading group size and round fixed effects, we find that testosterone treatment increased amplitude ($\beta = 0.34$, $p < 0.01$, $t(46) = 3.45$), MVA ($\beta = 3.35$, $p = 0.02$, $t(46) = 3.76$), and duration ($\beta = 1.52$, $p = 0.02$, $t(46) = 2.47$), but not turnover ($p = 0.53$), and that effects were largest in round 1 (see Table 1 for regression results and Table A.2 in the e-companion for summary statistics and nonparametric t-tests).[25]

In addition to treatment effects, we also test post hoc whether testosterone levels in markets affected the degree of mispricing and find that cohorts' average testosterone levels positively correlated with amplitude ($r = 0.27$, $p = 0.05$, $t(49) = 1.96$) and market value

Table 1. Market-Level Regressions

	Amplitude	MVA	Duration	Turnover
Treatment	0.344**	3.346**	1.520**	−0.0177
	(0.141)	(1.308)	(0.607)	(0.028)
Round = 2	−0.188***	−2.891***	−0.588	−0.029**
	(0.052)	(0.692)	(0.681)	(0.011)
Round = 3	−0.299***	−4.646***	−1.294	−0.059***
	(0.086)	(1.219)	(0.752)	(0.017)
Size	−0.017	0.395	0.081	0.005
	(0.029)	(0.260)	(0.087)	(0.004)
Constant	0.597**	0.994	3.030***	0.209***
	(0.272)	(2.216)	(0.770)	(0.051)
N	51	51	51	51
R^2	0.278	0.373	0.178	0.169

Notes. Ordinary least-squares (OLS) regressions of market measures are shown as dependent variables; and a binary variable (*Treatment*) is shown for testosterone (1) and placebo (0), dummy variables are shown for rounds (*Round* = 1 omitted), and the number of traders in cohort (*Size*) is included. Each session produced three observations, one for each round of trading ($N = 51$). Results show that testosterone-treated groups had larger and longer periods of prices exceeding fundamental value while controlling for cohort size. Robust standard errors are reported in parentheses.

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

amplitude ($r = 0.33$, $p = 0.02$, $t(49) = 2.45$) (see Figure A.3 in the e-companion).[26] In summary, results confirm H1 and H2, and disconfirm H3.

4.3. Testosterone Effect on Bids and Asks

4.3.1. Buying and Selling Prices. We find significantly higher average bidding prices among traders in the testosterone group in rounds 1 and 2 ($p < 0.01$), and greater but insignificant higher average bidding prices in round 3 ($p = 0.15$), which is consistent with H4 (see Table 2 and Figure 4). This empirical result explains why prices were higher in markets populated by testosterone-treated traders: markets in which buyers willing to pay more will trade at higher transaction prices.[27] Similarly, ask prices were higher among testosterone-treated traders compared with placebo-treated traders in all three rounds ($p < 0.01$) (see Table 2), confirming H5.

Buying turnover and *Selling turnover* measure the number of bids and asks divided by the total number of shares. *Buying turnover* was significantly higher among placebo sessions ($p = 0.02$, $p = 0.04$, and $p < 0.01$), disconfirming H6. This outcome may have been caused by a high quantity of below-fundamental-value bids (see below). *Selling turnover* is significantly higher among testosterone-treated traders ($p < 0.01$, $p < 0.01$, and $p = 0.03$), confirming H7. Also, we find that spreads (i.e., the difference between buying and selling prices) were significantly higher among testosterone markets in all three rounds ($p = 0.01$, $p = 0.02$, $p < 0.01$), suggesting that traders in this group attempted to "buy high" and to "sell higher," as illustrated by the high asking prices. The spread in round 3 drastically widened in the testosterone sessions, which was likely due to traders attempting to recapture losses sustained in earlier rounds through their efforts, in the final round of trading, to sell assets at prices above their fundamental values (as high asking prices carry no risk of loss). A higher spread is associated with lower trading volume, which, coupled with lower bid prices, may have precipitated the bursting of bubbles in later periods (see Table 2).

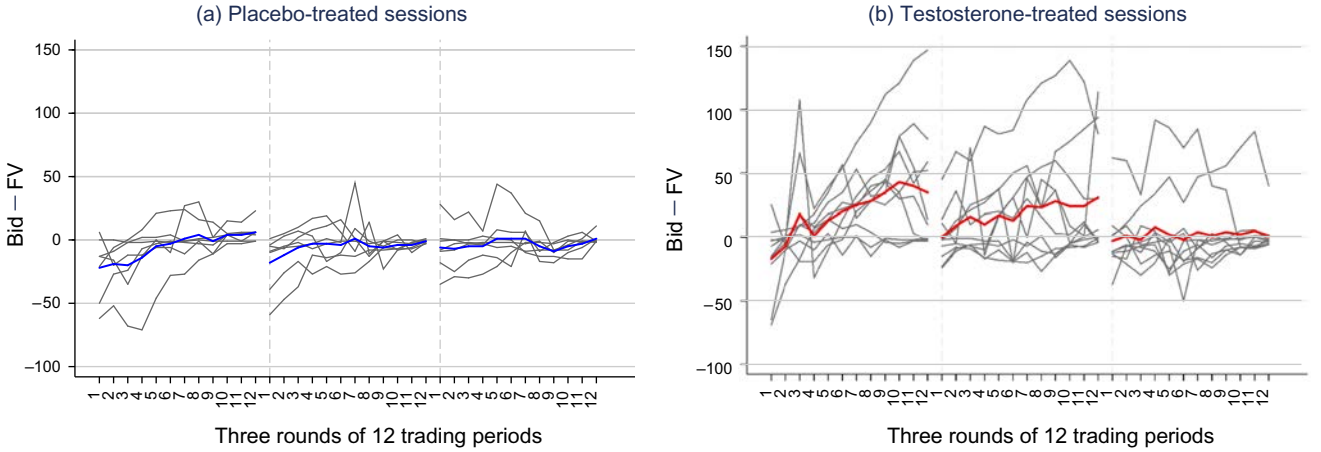
4.3.2. Influence of Testosterone on Bidder Type. Haruvy and Noussair (2006) and Caginalp and Ilieva (2008) uniquely categorize traders by type to depict the evolution of prices, cash holdings, and trading strategies among traders within trading sessions. Adapting a

Table 2. Summary of Bids, Asks, and Spreads Between Placebo (P) and Testosterone (T)

	Round 1		Round 2		Round 3	
Variable	P	T	P	T	P	T
Bid price						
Mean	53.2	78.1	52.9	76.8	55.1	60.5
SD	27.5	34.9	31.4	43.0	33.0	40.0
p-value	<0.01		<0.01		0.15	
t-statistic	5.7		4.6		1.0	
Buying turnover						
Mean	0.38	0.32	0.52	0.46	0.50	0.34
SD	0.22	0.18	0.2	0.3	0.29	0.28
p-value	0.02		0.04		<0.01	
t-statistic	2.28		2.1		3.8	
Ask price						
Mean	88.9	147.2	83.1	143.9	111.9	234.9
SD	44.4	144.1	53.6	178.0	183.9	391.6
p-value	<0.01		<0.01		<0.01	
t-statistic	4.2		3.5		3.0	
Selling turnover						
Mean	0.45	0.55	0.49	0.64	0.54	0.63
SD	0.21	0.28	0.21	0.32	0.32	0.36
p-value	<0.01		<0.01		0.03	
t-statistic	2.98		3.8		1.9	
Spread						
Mean	35.5	69.1	30.1	67.1	56.8	174.4
SD	36.0	142.2	43.6	175.9	183.2	392.0
p-value	0.01		0.02		<0.01	
t-statistic	2.5		2.2		2.9	

Notes. Complementing Figure 3, this table shows that traders in the testosterone groups bid and asked higher prices in most rounds of trading, relative to traders in the placebo groups. The *t*-test results are one-tailed (i.e., the null hypothesis being that testosterone is greater than placebo) tests because of the directional hypothesis of the testosterone bid and ask prices being expected to exceed those of the placebo groups (computed with assumption of unequal variance). Since prices transact at the intersections of buyers' willingness to pay and sellers' willingness to sell, higher prices will transact in markets with higher bids and offers, as observed in testosterone-treated markets. Standard deviations shown below. Degrees of freedom equals 202 with per-period averages as observations.

Figure 4. (Color online) Bidding Above Fundamental Value

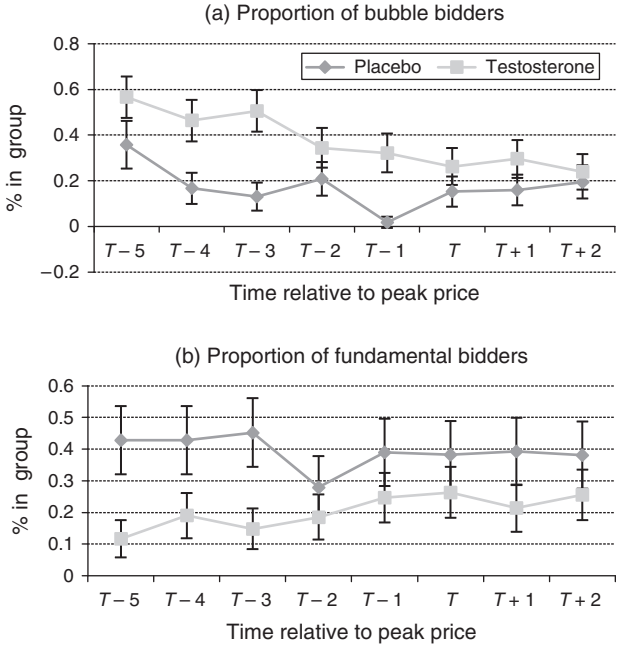


Notes. Average bids minus the fundamental value are shown by round separately, by treatment condition, for every session. Grey lines show overpricing for cohorts across three rounds of the session and show the average in blue in panel (a) for placebo-treated sessions and in red in panel (b) for testosterone-treated sessions. We see statistically significant and meaningfully higher bid prices among testosterone cohorts, relative to placebo, even in early periods of trading within a round, suggesting that testosterone increases optimism about future prices without feedback trading and leads to bidding in excess of fundamental value and causes overpricing. This trend continues as many traders sell overpriced shares and continue to bid despite obvious upward deviations from the asset's fundamental value.

similar framework, we identify traders as either *bubble* or *fundamental* bidders by assigning, for each trader, a positive point for every fundamental bid (i.e., below the asset's fundamental value) and a negative point for every momentum bid (i.e., above the asset's fundamental value). A trader is categorized as a fundamental bidder in a period if the summed points in that period are positive, and as a bubble bidder if the summed points are less than zero (and as a neutral bidder if the summed points equal zero). The rationale for using bids to establish a type is threefold: bids bind buyers to a contract, indicate expectations of future prices, and carry the risk of capital losses through an inability to resell. We use an event window of seven periods—five periods prior to the peak price to two periods following the peak price—and depict the period-by-period proportions of momentum and fundamental traders similar to the depiction used by Caginalp and Ilieva (2008). Corroborating findings that testosterone traders do not "track" fundamental value, we find that, relative to placebo markets, testosterone-treated markets are constituted primarily by bubble bidders in every period, and the opposite for the proportion of fundamental bidders (see Figure 5).

We quantified the effects of being in the testosterone group on the likelihood of bidding above an asset's fundamental value using a logistic regression for each round with standard errors clustered at the individual level. *Bidding type* was the dependent variable: 1 = bubble bid, 0 = fundamental bid as categorized above. The regressions control for lagged deviations from the fundamental value (Price – FV), the change in price from $t-2$ to $t-1$ (Delta – Price), and the number of periods prior to and after that particular round's price peak. The last two control variables account for market timing and the period's fixed effects. We find that the marginal effect of being in the testosterone group increases the odds of bidding above the asset's fundamental value by about a factor of 1.65 in rounds 1

Figure 5. Composition of Bidder Types by Treatment Condition



Notes. This figure shows the proportion of traders, by type, for the testosterone and placebo treatment groups in the five periods preceding and two following the peak price during a trading round (with standard error bars). We see a consistently high proportion of bubble traders and a correspondingly low proportion of fundamental traders among testosterone-treated cohorts and the opposite for placebo sessions. The proportions do not add to one because of a quantity of traders who were classified as neither bubble bidders nor fundamental bidders (i.e., neutral traders).

and 2 ($p < 0.10$), thereby corroborating other results (see Table A.6 in the e-companion).[28] In round 3, the effect is no longer significant.

Next, we estimate how traders' bidding responded to rising prices and dividend payments. We identify periods of rising average prices by using a binary variable called *Priceup*, which equals 1 when the price in a period is greater than the preceding period, and 0 otherwise. *Pay* captures the number of consecutive trading periods of dividend payouts, and *NoPay* indicates the number of consecutive periods of zero dividend payouts, as traders' perception of asset fundamental value affects prices (Noussair et al. 2001). The results show that traders who received placebo did not increase their buying prices as prices increased. Conversely, traders who received testosterone posted higher buying prices, as market prices increased in round 1 by an average of 22 ECUs ($p = 0.01$), in round 2 by an average of 40 ECUs ($p < 0.01$), and in round 3 by an average of 19 ECUs ($p = 0.02$). We ran a similar regression for average selling price and found no significant differences across treatments, meaning that serial price appreciation did not increase selling prices on average within a round. We find that the placebo group decreased bidding prices in response to "streaks" of zero dividends, but that the testosterone group did not (see Table 3).[29]

4.4. Rational Expectations

We show that bidding prices changed in response to price changes and dividends, yet how accurately did traders incorporate the asset's declining fundamental value over time? SSW proposed that the mean price change between periods could be decomposed into (a maximum of) three components: a decline in fundamental value, an adjustment for risk,[30] and a revealed excess demand for shares arising from capital gains expectations. They postulated that excess demand is correlated with excess bids that have endogenously expected capital gains, and thus a "surrogate" for excess demand, and use the following "rational expectations" equation:

$$\bar{P}_t - \bar{P}_{t-1} = \alpha + \beta(B_{t-1} - O_{t-1}) + \varepsilon_t,$$

where $\bar{P}_t - \bar{P}_{t-1}$ is the change in mean price from period $t-1$ to period t, and $\beta_{t-1} - O_{t-1}$ is the difference between the number of buying and selling offers known as *excess bids* in period $t-1$. A positive β coefficient reflects participants' expectations of forthcoming upward price movements in their prior excess demand. The intercept, α, represents the average expected differences in fundamental value between periods as well as risk aversion on the part of traders. An α of 9 ECUs is the expected change in the fundamental value between periods, while an alpha of less (more) than 9 reflects risk aversion (seeking) in regard to dividends.[31] We hypothesized that the intercept term would be significant and approximate the change in the fundamental value of 9 ECUs per period among placebo sessions because of the tight tracking of prices with fundamental values, and poorly track fundamental value for testosterone sessions.[32] Because of evidence of high bid prices and volume among testosterone groups, we anticipated that excess bids would predict changes in prices between periods, especially in earlier rounds. We ran separate regressions for testosterone and placebo treatment groups, using price adjustment between periods as the dependent variable and lagged excess bids as the explanatory variable, and found that the constant term is significantly negative ($p < 0.001$, $t(74) = -7.19$ for round 1, $t(74) = 11.27$ for round 2, $t(74) = 24.35$ for round 3) for the placebo group in all three rounds at magnitudes that are notably close to the decline in fundamental value of 9 ECUs per period as found in

Table 3. Bidding in Response to Price Changes

	Placebo			Testosterone		
	Round 1	Round 2	Round 3	Round 1	Round 2	Round 3
Priceup	3.831	3.092	3.856	22.01**	40.17***	19.31**
	(6.906)	(8.197)	(8.709)	(7.143)	(12.21)	(6.432)
Pay	6.243	−3.011	−4.102	6.428***	−11.67	3.347
	(3.746)	(2.094)	(3.884)	(1.709)	(6.869)	(5.640)
NoPay	0.0679	−9.460***	−5.338***	0.871	−5.968	−2.410
	(4.352)	(1.605)	(0.920)	(4.813)	(3.429)	(2.713)
Constant	40.79***	60.95***	56.61***	56.92***	78.51***	49.98***
	(8.969)	(7.654)	(5.707)	(8.661)	(14.79)	(11.14)
N	70	70	70	98	99	100
Adjusted R^2	0.0640	0.238	0.0349	0.213	0.176	0.0199

Notes. This table reports OLS regression results using the bidding prices as the dependent variable and each trading period as an observation, with standard errors clustered at the session level. *Priceup* is a dummy variable that is equal to 1 if the price increased in the previous period, and *Pay* (*NoPay*) is equal to the number of consecutive periods with dividend payment (no dividend payment). Standard errors are clustered at the session level in parentheses.

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

Table 4. Rational Expectations Regressions

	Placebo			Testosterone		
	Round 1	Round 2	Round 3	Round 1	Round 2	Round 3
Lagged excess bids	2.310	3.239	−0.583	9.927	7.955***	5.111*
	(4.423)	(3.845)	(1.006)	(6.581)	(1.947)	(2.775)
Constant	−6.466***	−8.373***	−8.414***	−1.393	−6.144***	−6.750***
	(0.900)	(0.743)	(0.346)	(1.523)	(0.858)	(1.435)
N	76	75	77	106	107	104
R^2	0.003	0.002	0.001	0.024	0.040	0.028

Notes. This table reports OLS regressions with the price change from period $t-1$ to period t as the dependent variable, and the lagged excess bids (the difference between the buying offer turnover and the selling offer turnover in period $t-1$) as the independent variable. Standard errors are clustered at the session level and are shown in parentheses.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

some stable price markets in SSW (6.47, 8.37, and 8.41, respectively). Following SSW's interpretation of this term, this result suggests that traders in the placebo sessions systematically incorporated the declining fundamental value into their trading decisions and did not expect capital gains in future rounds, as evidenced by being unable to reject the hypothesis that $\beta = 0$ ($p > 0.10$). In testosterone markets, we find a nonsignificant intercept (i.e., we cannot reject the hypothesis $\alpha = 0$) in round 1 ($p = 0.17$), confirming H8, and we find intercepts in rounds 2 and 3 that more poorly estimate a declining fundamental value relative to placebo markets (6.14 and 6.75, $p < 0.001$). Lagged excessive bids significantly positively correlate with price changes in round 2 ($p < 0.01$, $t(74) = 4.08$), and a weaker such correlation is found in round 3 ($p = 0.10$, $t(74) = 1.84$) (see Table 4) in testosterone markets only.

4.5. Testosterone's Effect on Trading Behavior Prepeak and Postpeak

We have shown that testosterone caused traders to bid higher for assets, which led to higher transaction prices relative to markets composed of traders who received placebo. Because most price paths rise, then fall, we analyzed the differences between treatment conditions in relation to price peaks within trading rounds. We find that placebo-treated traders posted a greater quantity of buying offers at lower prices, relative to testosterone-treated traders, and this "buy low to sell high" behavior was consistent both before and after price peaks. Conversely, testosterone-treated traders bid in excess of an asset's fundamental value to "buy high to sell higher" both before and after price peaks. Specifically, buying turnover was 23% lower among testosterone-treated relative to placebo-treated traders prior to price peaks ($p < 0.01$, $t(357) = 3.84$) as well as after price peaks ($p = 0.02$, $t(251) = 2.70$). Average buying price was 34% higher among testosterone traders prepeak ($p < 0.001$, $t(357) = 6.82$) and 52% higher postpeak ($p < 0.001$, $t(251) = 4.0$). The notable differences between buying and selling prices were measured as significantly larger spreads in testosterone sessions both before (143% larger, $p = 0.01$, $t(357)$) and after (158% larger, $p = 0.02$, $t(251)$) price peaks. We found similar selling offers among testosterone-treated traders before prices peaked but significantly more after prices peaked (58% higher, $p < 0.01$, $t(251)$) and at higher prices (72% higher prepeak, $p < 0.01$, $t(357) = 2.61$, and 112% higher postpeak, $p < 0.01$, $t(251) = 2.79$), relative to placebo-treated traders, likely because testosterone-treated traders were attempting to sell assets for which they had overpaid during the run up to peak price (see Table 5).

Further, we tested the influence of the buying and selling volume on overpricing (measured by price minus fundamental value) before and after price peaks. We regressed the price minus fundamental value on bid and ask volumes, bid and ask prices, while controlling for rounds and cohort size. We find that bid volume has opposite effects on testosterone and placebo markets, as it predicted a decrease in prices in the placebo markets due to coupling with below-fundamental-value bidding (despite higher volume) (placebo $\beta = -9.91$, $p = 0.05$, $t(149) = 1.94$) and an increase in prices in testosterone markets due to above-fundamental-value bidding (testosterone $\beta = 20.7$, $p = 0.02$, $t(192) = 2.42$) prior to price peaks. We found that bid prices significantly predicted overpricing for both placebo and testosterone markets, yet the magnitude of the latter was five times higher (placebo $\beta = 0.14$, $p < 0.01$, $t(149) = 2.88$; testosterone $\beta = 0.698$, $p < 0.001$, $t(192) = 10.34$) prior to the peak. However, selling (i.e., ask) volume did not significantly influence overpricing before price peaks in either placebo- or testosterone-treated sessions (both groups $p > 0.10$). Postpeak, we find no effect of bids or offers on mispricing yet a strong prediction of bid price for both groups (placebo $\beta = 0.398$, $p < 0.0014$, $t(86) = 4.27$; testosterone $\beta = 0.645$, $p < 0.001$, $t(150) = 10.42$), again with a much higher beta coefficient for testosterone (see Table A.7 in the e-companion).

Table 5. Differences in Trading Behavior Relative to Peak Prices

	Prepeak			Postpeak		
	P	T	Statistics	P	T	Statistics
Buying turnover	0.47 (0.26)	0.36 (0.25)	p-value < 0.01 t-statistic = 3.84 DF = 357	0.47 (0.31)	0.36 (0.29)	p-value = 0.02 t-statistic = 2.71 DF = 251
Average buying price	66.3 (28.0)	88.8 (33.2)	p-value < 0.01 t-statistic = 6.82 DF = 357	33.0 (22.4)	50.0 (37.7)	p-value < 0.01 t-statistic = 3.99 DF = 251
Selling turnover	0.51 (0.26)	0.53 (0.28)	p-value = 0.60 t-statistic = 0.51 DF = 357	0.45 (0.23)	0.71 (0.35)	p-value < 0.01 t-statistic = 6.32 DF = 251
Average selling price	102.3 (85.7)	176.2 (236.1)	p-value < 0.01 t-statistic = 3.73 DF = 357	82.0 (149.4)	174.2 (297.8)	p-value < 0.01 t-statistic = 2.79 DF = 251
Average spread	35.9 (81.9)	87.4 (236.3)	p-value = 0.01 t-statistic = 2.61 DF = 357	48.1 (147.1)	124.2 (297.9)	p-value = 0.02 t-statistic = 2.32 DF = 251

Notes. Differences in buying and selling offers before and after peak prices use two-sample t-test between testosterone-treated (T) and placebo-treated (P) traders. Standard deviations are listed below in parentheses. Two-tailed p-values are shown. DF, degrees of freedom.

4.6. Testosterone Effect on Trading Performance, Trader Mood, and Sentiment

In addition to transaction prices and bidding patterns, we ran post hoc analyses of how testosterone affected individual traders' earnings, moods, and sentiments regarding market prices. We ranked traders' earnings within their cohort and used individual testosterone levels, changes thereof, and cohort size to determine the effects of the hormone on performance. Correlations (uncorrected for multiple hypotheses) among testosterone-treated traders show day 2 DHT levels positively correlated with percentile earnings ($r = 0.26$, $p = 0.02$) and a similar relationship between day 2 testosterone levels ($r = 0.19$, $p = 0.08$). We find no significant correlations among placebo cohorts (see Table A.7 in the e-companion). Regressing ranked earnings on day 2 DHT levels, percent change in DHT levels, and cohort size separately by treatment groups, we find that day 2 DHT levels marginally ($p = 0.06$) and weakly ($\beta = 0.15$) positively correlated with trading earnings among testosterone cohorts (see Table A.9 in the e-companion).

We find that testosterone treatment had little effect on traders' self-rating of their performance and overconfidence.[33] Testosterone-treated traders were marginally *less* (testosterone mean = 4.56, SD = 0.12; placebo mean = 4.93, SD = 0.15; $p = 0.064$, $t(418) = 1.89$) confident about their performance prior to starting the trading session (a measure that is unrelated to performance) and statistically similar to placebo about expectations of future performance thereafter (see Table A.10.a in the e-companion) as well as perception of past performance (see Table A.10.b in the e-companion).

We surveyed traders' attributions of their performance and opinions of prices and bidding, and found some evidence that testosterone-treated traders unconditionally attributed their trading performance more to their own "talent" (overall testosterone mean = 4.4, SD = 0.10, placebo mean = 4.2, SD = 0.12; $p = 0.07$, $t(418) = 1.80$) and less to "luck" (overall testosterone mean = 4.0, SD = 0.11, placebo mean = 4.4, SD = 0.13; $p = 0.03$, $t(418) = 2.15$) (see Table A.10.b in the e-companion). However, round-by-round measures are not statistically different, and these subjective measures are affected by a multitude of factors including endogenous variations unique to each trading round, warranting further investigation with clear controls.

Research has suggested that increasing testosterone in men who have low levels of testosterone can have a positive effect for both mood and libido, whereas elevating testosterone in men who have normal levels of testosterone does not affect their mood (Alexander et al. 1998, Anderson et al. 1992, Pope et al. 2000). Therefore, we did not expect to find a difference in mood from a single exogenous administration and indeed find no significant differences between treatment groups.

Testosterone-treated traders perceived prices on average as lower than expected in two out of the three rounds and overall (overall testosterone average = 4.2, SD = 2.0, placebo average = 3.6, SD = 1.8; $p < 0.01$, $t(418) = 3.22$). Further, beliefs about others' buying and selling prices were consistent and opposite by treatment, with testosterone-treated traders indicating that others were buying "too low" and placebo-treated traders indicating that others were buying "too high." Fittingly, traders in the placebo groups thought others were "selling too high" and "buying too high," relative to the testosterone group. It is important to keep

in mind that these results emerged despite the testosterone sessions experiencing objectively higher prices than the placebo sessions. Differences in price sentiment likely drove differential trading behavior and, ultimately, higher prices between treatments, as these results directly aligned with their fundamental trading strategies (all survey results are in Tables A.10.a–A.10.d in the e-companion).

5. Discussion

We showed that testosterone increased the prices of financial assets in an experimental setting and now discuss potential channels underlying the effect.

5.1. Risk Aversion

Decreased risk aversion is an appealing candidate for explaining why testosterone-treated traders paid more for assets in experimental financial markets, leading to larger bubbles. As discussed earlier, some evidence suggests that basal testosterone, and changes thereof, reduces risk aversion (Apicella et al. 2015, Stanton et al. 2011), that higher testosterone traders earn more money (Coates and Herbert 2008), and that exogenous application increases willingness to purchase risky assets (Cueva et al. 2015). Thus, changes in risk aversion may have led to increased bid prices for financial assets among testosterone-treated traders. However, active double-auction trading is a noisy paradigm with endogenous factors that complicate unambiguous measurement of risk preferences, and therefore further work is needed to carefully isolate and better understand the influence of testosterone on this central economic primitive.

5.2. Overconfidence

Several aspects of our analysis shed light on the link between testosterone and overconfidence. First, in surveys administered between rounds, we observed that testosterone-treated traders (unconditionally) attributed their performance overall more to their "talent" and less to "luck" than placebo-treated traders, which reflects the definition of attribution bias presented by Gervais and Odean (2001). The elevation in self-attribution may have contributed to the pronounced overpricing by taking larger positions as predicted by the model, yet further work is needed to disentangle the effect of testosterone on overconfidence in complex environments. Second, Barber and Odean (2001) argue that overconfidence is a cause of excessive trading and find that male retail traders overtrade more relative to women.[34] However, we find similar trading volume between treatment conditions (likely due to the paucity of the crossing of supply and demand evidenced by larger spreads among testosterone-treated sessions), yet this finding is affected by differences in endogenous market conditions and not necessarily due to lack of effect on preferences for trading frequency. Third, traders' elicited expected rankings show no systematic differences from their actual rankings between groups, meaning that testosterone did not systematically lead traders to overpredict their own performance in our experiment.

Together, we find weak evidence that testosterone increased traders' confidence in their trading skills during trading and did not increase confidence in expectations of trading performance. Despite stereotypes regarding testosterone's positive effect on overconfidence among men, we found no clear evidence that testosterone causally affects overconfidence per se, and our data present context-dependent evidence toward this open question in need of further exploration.

5.3. Beliefs

Testosterone may have changed beliefs toward comparatively higher future prices and thereby motivated bidding above assets' fundamental values (in an attempt to capitalize on future capital gains by speculating), leading to the overpricing observed in this experiment.[35] Survey data in this study support the possibility that testosterone affected beliefs, as we observed significant differences in expectations about future prices between treatment groups, with testosterone-treated traders expecting higher prices than their placebo-treated counterparts (see Table A.10.c in the e-companion), confirming H9. Future research using SSW's interround price forecasts could further test this channel of influence and quantify the effects of testosterone on beliefs. Another useful method of testing testosterone's effect on beliefs per se could be the paradigm introduced by Bloomfield and Hales (2002), wherein participants predict price changes in a fixed environment where they have no influence on prices. Relatedly, Frydman and Nave (2017) demonstrated a common computational model forming extrapolative economic *and* perceptual beliefs. Given their results, the mechanism itself is likely governed by a common neural process, which may be affected by testosterone.

Trading in markets with other people necessitates forming higher-order beliefs (i.e., simulating other traders' beliefs). De Martino et al. (2013) show that greater activation in areas of the brain associated with theory of mind is correlated with "riding" bubbles with deleterious consequences to traders.[36] Testosterone has been shown to have mixed influences on the perception of others' intentions (Bos et al. 2016, Carré et al. 2015, van Honk et al. 2011), so further research is needed to elucidate whether bubble formation occurred because of changes in the beliefs regarding others' intentions or optimism per se.

5.4. Cognition and Self-Control

Testosterone has been shown to play a role in cognition (O'Connor et al. 2001) and impulsivity (Coccaro

et al. 2007, Dolan et al. 2001), and therefore may have affected bidding through these channels. Nave et al. (2017) show that exogenous testosterone reduces cognitive reflection as measured by CRT scores. Further, Bosch-Rosa et al. (2015) show that traders with lower cognitive abilities as measured by CRT scores (and three other tasks) exhibit larger price bubbles in experimental markets. In the same paper, Nave et al. show that testosterone had no effect on mathematical abilities, suggesting that overpricing might not be driven by impairment in the capacity of performing calculations, but rather in the probability of using explicit calculations as a cognitive strategy.

Given testosterone's role in impulsivity—a trait central to rapid financial decision making—testosterone likely affects trading behavior by biasing toward intuitive, impulsive, and rapid cognition that excludes complex and relevant information. Biais et al. (2005) show that traders with higher self-monitoring earned more and were less likely to fall subject to the winners' curse because of higher inhibition of impulsive responses and game theoretic reasoning. Further, Kocher et al. (2016) show that traders with depleted self-control created larger bubbles, supporting the possibility that testosterone increased impulsivity and biased beliefs in higher prices and that this led to changes in bidder type (as shown in Section 4.3.2).

5.5. Status Seeking

Obtaining high social status is a universal human desire, and testosterone has been shown to correlate with status-seeking behavior (Kenrick et al. 2010, Mazur and Booth 1998). The crucial elements of (nonaggressive) status are that it can be reliably signaled to others and easily identified by competitors and potential mates (Zahavi 1975). However, as this experiment was anonymous, rankings were not known by traders, and trading stations were private, which eliminated the display of status through achieved earnings and thereby reduced the probability of status seeking as a chief channel. The same trading paradigm could easily be modified to include a salient ranking component to ascertain sensitivity to group status in future research.

5.6. Mood

Andrade et al. (2015), Lahav and Meer (2012), and Hargreaves Heap and Zizzo (2011) show that mood per se affected bubble size in a similar experimental paradigm, and Kuhnen and Knutson (2005) show that such an effect influences beliefs, preferences, and decisions.

We tested whether exogenous testosterone affected mood and find no effect, which is consistent with research suggesting that androgens do not reliably affect mood for hormonally typical males even over medium-term treatment regimens (Anderson et al. 1992, O'Connor et al. 2001). Concordantly, we find no significant differences between treatment groups' affect, which strongly suggests that mood is not the channel through which trading behaviors differed between testosterone and placebo markets (see Table A.10.f in the e-companion).

6. Concluding Remarks

In this paper, we show that exogenously increasing testosterone in men increases bid prices and asset price bubbles, and slows the incorporation of fundamental value. We also demonstrate how the changes in buying and selling pressures give rise to bubbles and subsequent crashes. These results demonstrate the effects of a specific hormone, testosterone, on male traders in experimental markets and likely have attendant implications outside of the laboratory.

Much like sentiment, which causes entire asset classes to move in the same direction, endogenous changes in testosterone can cause synergistic comovements in financial markets: traders winning in bull markets likely experience an increase in the endogenous production of testosterone (Booth et al. 1989, Coates and Herbert 2008). The resulting increase of testosterone can fuel overpricing and bubble formation as shown in this experiment. Possibly exacerbating such scenarios is the associated biased price expectations that accompany a rise in testosterone levels. Even more troubling is the easy access of testosterone supplementation, the proliferation of its use among financial professionals, and the concomitant lack of public knowledge of testosterone's behavioral effects (Wallace 2012).[37] We hope that this study increases awareness of testosterone's behavioral effects among both users of exogenous testosterone and the scientific community, although these findings are likely also applicable to nonusers of exogenous testosterone as endogenous levels affect behavior (Apicella et al. 2014, Coates and Herbert 2008, Stanton et al. 2011).

This research suggests the need to consider hormonal influences on decision making in professional settings because biological factors can exacerbate capital risk; firms may, therefore, benefit from a better understanding of when and how hormones assert their influence—such as through exceptionally positive feedback cycles that are unsupported by fundamentals or technical indicators—and, as a result, provide appropriate decision support where feasible. Perhaps the simplest recommendation is to implement "cool-down" periods to interrupt exceptionally positive feedback cycles and return the focus to assets' fundamental valuations to reduce the possibility of biased decision making.

In line with Eckel and Füllbrunn (2015), who show that female traders produce significantly smaller bubbles than males, this study suggests that testosterone

may be an important biological driver of gender differences in rapid financial decision making; however, it is unknown whether these experimental results and implications would replicate and generalize to women. Closer examination of gender differences in financial trading would improve our understanding; however, this area is difficult to study empirically because of the paucity of female traders. Pursuantly, women have significantly lower levels and lower variance of testosterone than men (Salameh et al. 2010) and are less likely to experience the same behavioral effects from the hormone. Coupled with empirical data showing that females outperform males in retail trading (Barber and Odean 2001), and experimental evidence that female traders create smaller speculative price bubbles than their male counterparts (Eckel and Füllbrunn 2015), compelling rationale exists for increasing female participation in financial trading.

The chief objective of this paper was to test for a causal relationship between testosterone and trading, yet future projects ought to identify specific changes in economic primitives such as discounting and more distinctly disentangle beliefs and preferences. Further, future experiments could have both testosterone- and placebo-treated traders in the same session to test whether androgen increases both heterogeneity in trading strategies and performance within rounds. Also, future work could measure posttrading testosterone levels to test the winner and loser hypotheses of testosterone to approximate the hormonal response caused by engaging in competitive markets and the resulting effect of performance on testosterone levels.

Marshall (1890) once said, "The Mecca of the economist lies in economic biology rather than in economic dynamics." Here, we have shown how biology affects economic dynamics by providing compelling evidence of a hormone's effect on financial decision making. These results stand to inform retail and professional asset traders, regulators, and policy makers, as it is likely that testosterone significantly affects decisions that meaningfully impact the economy.

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Endnotes

[1] Brain activation studies of financial decisions have also elucidated neural processes underlying market phenomena such as bubbles (Smith et al. 2014), social cognition and the theory of the mind's influence on trading and prices (De Martino et al. 2013), and learning about gains and losses (Kuhnen 2015). (For a review of psychology and neuroscience in financial decision making, see Frydman and Camerer 2016.)

[2] Testosterone is a steroid hormone (meaning it enters cells to affect change) that is released in regular cycles, in response to social and environmental factors and from readily available prescription drugs (Wallace 2012).

[3] Women comprise 35.2% of all employees in investment banking and securities dealing, just 15% of executive or senior-level positions, according to figures from the U.S. Equal Opportunities Commission in 2013 (Clarke 2013).

[4] For sexual differentiation in nonhuman animals, see MacLusky and Naftolin (1981); and for effects on human behavior, see Rubin et al. (1981).

[5] We apply the same drug taken by more than 2 million men annually and used extensively by financial professionals (Wallace 2012). With the proliferation of advertising aiming to remedy "low testosterone syndrome" or "andropause" and the ease of receiving a medical prescription, a large and growing population of men currently use AndroGel® (and similar generics). Further, men also inject anabolic steroids at (remarkably) higher doses than those delivered by topical gel (Baillargeon et al. 2013, Handelsman 2013). In fact, the rise in use and high penetration rates of this drug among financial professionals enable our experiment to mimic the "testosterone shock" in real-world asset markets such as the New York Stock Exchange.

[6] DHT is relevant because compared with testosterone, it binds faster to the cell (known as androgen receptor affinity) (Liao et al. 1973), stays in the cell significantly longer (Grino et al. 1990), and thus is likely to have stronger behavioral effects.

[7] In addition to progressive changes in theory, new methods are now used for studying core questions in economics questions, including field studies (Fehr and Goette 2007, Gneezy et al. 2009, Gneezy and List 2006), experimental studies (Smith et al. 1988), neuroscience studies (Frydman et al. 2014, Kuhnen 2015, Smith et al. 2014), genetics studies (Cesarini et al. 2010, Cronqvist and Siegel 2014), and hormonal studies (Coates and Herbert 2008, Cueva et al. 2015, Kandasamy et al. 2014). Together, complementary methods contribute to a more complete and data-driven discipline.

[8] Relatedly, sunshine affects vitamin D levels, which covary with testosterone levels (Wehr et al. 2010).

[9] However, other studies show little predictive power of baseline testosterone levels (Cueva et al. 2015, Schipper 2015); thus, more work is needed to clarify these relationships. Crucially, our study is distinct from Cueva et al. (2015) in that we test the causal relationship between testosterone and trading, whereas Cueva et al. correlated baseline testosterone levels with trading behavior (with the aforementioned null result).

[10] Apicella et al. (2008) also show that markers of prenatal testosterone do not correlate with financial risk taking. This area of research tests whether prenatal androgen exposure (measured by second-to-ring-finger digit ratio, known as the 2D:4D ratio) affects economic and social behavior. Although work has been published in high-profile journals (Sapienza et al. 2009; van Honk et al. 2001, 2011; Williams et al. 2000), a clear connection between androgen exposure

and the 2D:4D and behavioral effects has not been consistently established (Berenbaum et al. 2009); in fact, a relationship opposite to the theory has been found in some populations (Apicella et al. 2016).

[11] Testosterone increases levels of dopamine—a rewarding, excitatory neurotransmitter (Rupprecht 2003) that affects neural processing and sensation seeking in men (Campbell et al. 2010)—which may explain the downstream effects of the hormone on brain function and resulting behavioral effects. Smith et al. (2014) show that the nucleus accumbens—a part of the brain with both major inputs from dopamine neurons and high androgen receptor density (Kritzer 2004)—shows higher activation during excessive prices in experimental stock markets.

[12] In our experiment, a table of fundamental value was provided along with trading instructions (see Section 2 of the e-companion).

[13] The distributions of traders between treatment groups (i.e., the number of individual traders in testosterone cohorts (six, seven, nine, 12, five, 11, 10, eight, seven, and nine) and placebo cohorts (seven, 14, six, six, seven, six, and 10)) are similar as judged by t-test (two-tailed p-value = 0.76, $t(15) = 0.32$; nonparametric test Mann–Whitney p-value = 0.49) and comparable in range to other studies (Lei et al. 2001). A Kolmogorov–Smirnov test suggests that there is no significant difference in the distributions of group sizes (exact p-value = 0.69).

[14] We find slightly higher body mass index among the testosterone group (23.7 relative to 25.1 in placebo group, $p = 0.03$, uncorrected for multiple comparisons), yet we find no immediate theoretical ramification on analysis or interpretation of results for measures in our range (Gunstad et al. 2007).

[15] An extensive clinical literature exists on testosterone and its manipulation, and on a commercial, widely prescribed synthetic drug (e.g., AndroGel® and Vogelxo™) used to increase testosterone in men. The process by which the body absorbs, processes, and eliminates the drug is clearly documented, as are the time course of levels of the drug in the body after administration. However, there is no standardized administration protocol for testosterone in the behavioral sciences, which is a presently a limitation in the literature.

[16] Only males were included because the United States Food and Drug Administration approved the synthetic testosterone drug used in the experiment (AndroGel®) only for use in men, and our primary question is about the effects of testosterone in men on asset trading.

[17] Nanograms per deciliter is a standard measure of testosterone in blood.

[18] These levels are within the normal range of 250–1,200 ng/dl for this age group (Salameh et al. 2010).

[19] Testosterone follows a diurnal cycle, whereby it is highest in the morning and declines throughout the day. Given that the first measurement was in the evening when levels are lowest and the second at noon the following day, shortly after morning peak, observed variation occurred in the expected direction. Intraday variability for young men has been shown to be between 20% and 61% (Brambilla et al. 2009, Diver et al. 2003).

[20] Multiple elements would need to coincide for beliefs in the treatment received to have an effect. First, for beliefs per se to have an effect on trading, traders must have an a priori notion about what testosterone is intended to cause them to do differently. Of all traders, 84% were trading for the very first time in *any* trading paradigm, and none had taken exogenous testosterone, and therefore they had no foundation on which to base an expectation about how they would be affected by an exogenous hormone. Second, traders' belief about treatment would affect their expectations of others' behaviors, yet for similar reasons, they cannot form reliable predictions of others' behaviors in an entirely new context. In short, there is no baseline from which to establish a benchmark; plus there is no clear prediction as to how testosterone would affect their trading. In additional analysis, we tested whether beliefs about treatment affected bidding or actual testosterone levels and found no reliable support.

[21] To test whether beliefs affected actual testosterone levels, we combined the binary belief in treatment variable with the associated confidence variable to create a scale from −7 to 7 with the negative numbers representing the strength of belief in *not* having received testosterone and positive numbers representing strength of belief of having received testosterone (i.e., −7 means "I am certain I did not receive testosterone" and 7 means "I am certain that I received testosterone"). Pairwise correlation between belief in treatment and postadministration testosterone levels among those who received placebo was insignificant ($p = 0.15$) and in a direction suggesting that the stronger the belief in having received testosterone, the *lower* the testosterone levels were ($r = -0.20$).

[22] In unreported analyses, we tested whether baseline levels are predictive of behavior in both the placebo and testosterone groups, and verified that they are not.

[23] Mispricing among placebo groups is lower relative to similar markets. See Figure A.2 in the e-companion for a comparison to prices in Sutter et al. (2012).

[24] We test for differences in bubble size using every published measure and obtain the same pattern in results, which we report in Table A.2 in the e-companion (see Table A.1 in the e-companion for definitions and formulae of all measures used).

[25] Thanks to the suggestions of two anonymous reviewers, we reran the regressions in Table 1 for robustness checks using dummy variables for group size instead of a continuous variable and using standard errors clustered at the session level; using this alternative specification, we found larger coefficients at higher level of significance (see Table A.3 in the e-companion). We ran additional robustness tests by excluding the session with the two largest amplitudes in the testosterone session, and the treatment binary variable remained significant for both amplitude and MVA. We also tested the same specification while excluding the session with the largest amplitude among testosterone and the session with the smallest amplitude among placebo sessions, and the results are significant for amplitude, MVA, and duration.

[26] We found similar positive correlations between DHT levels and amplitude ($r = 0.36$, $p = 0.01$, $t(49) = 2.70$) and market value amplitude ($r = 0.38$, $p = 0.007$, $t(49) = 2.79$). Figure A.3 in the e-companion exhibits the correlations between amplitude and market value amplitude and DHT for all participants.

[27] The correlation between bid prices and transacted prices aggregated at the session level is greater than 0.94 for all periods for each round for both testosterone- and placebo-treated traders ($p < 0.001$, $t(70) < 23$).

[28] Eisenegger et al. (2010) suggest both that placebo effects can meaningfully affect behavior and that the belief of receiving treatment is sufficient to change behavior. Pursuantly, we test whether belief in treatment received (testosterone or placebo) affected trader type by replicating the analysis in Table A.6 in the e-companion with controlling for belief in treatment and find that beliefs have no significant explanatory power.

[29] We tested for the effects of price changes on the volume of bidding during periods of serial price increases and did not find significant results for either treatment group.

[30] The adjustment for risk is obtained by soliciting expectations of future prices, which was not done in our experiment, and thus the three components cannot be cleanly disentangled from the data.

[31] SSW hypothesized that under REM (i.e., rational expectations as depicted by Muth, 1961, in which outcomes support predictions of a particular theory), the change in prices is a combination of an expected change in the asset's fundamental value and an adjustment

for risk aversion (which can be disentangled using traders' price forecasts, which we did not measure in our experiment). In this application, the REM theory is that traders will have forward-looking expectations of future prices that rationally reflect the fundamental value over time.

[32] SSW explicitly solicited expectations of future prices and formally tested the two components of the intercept, whereas we do not, and thus can quantify the significance of only the intercept and not its constituent elements.

[33] Overconfidence was measured as the difference between traders' self-rating and actual ranking (t-test between groups; self-rating, $p = 0.95$, $t(138) = 0.05$; overconfidence, $p = 0.89$, $t(138) = 0.14$), and unreported regressions controlling for actual aggregate performance confirmed these null results and left the p-values virtually unchanged.

[34] Eckel and Füllbrunn (2015) find that women trade at higher volume than men but only in the first period of a single-round experimental design.

[35] Future work will test this hypothesis by surveying traders' opinions of future prices prior to each round of trading.

[36] Theory of mind is the ability to attribute mental states to beliefs, intentions, desires, pretending, and knowledge; see Sanfey (2007) for a review.

[37] One of them is John, a 40-year-old venture capitalist quoted in a *Financial Times* article saying that he now has "a bit more of an alpha male personality . . . . It's the positive side of aggression . . . . You change your mentality and start looking positively at the future." (Wallace 2012).

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