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

By

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Abstract

Financial markets deviate from efficiency due to behavioral causes and there is growing evidence that biological factors affect individual financial decisions that could be reflected in markets. Many behavioral influences on asset prices have underlying biological mechanisms associated with fluctuations in the levels of the male sex hormone testosterone. Testosterone, a chemical messenger especially influential in male physiology, varies cyclically and in response to challenge, fluctuates according to victory and defeat, and is taken as a performance-enhancer among some financial professionals, yet no study has tested how it causally affects trading decisions. We exogenously elevated testosterone in traders in an experimental asset market and found that it causes significantly higher and longer-lasting asset overpricing compared to placebo. Using both aggregated and individual trading data we demonstrate that testosterone administration generates bubbles by causing persistently high bids and slow incorporation of asset fundamental value among traders.

JEL classification: G11, G12, C23, C91, C92, D87

Keywords: Asset price bubbles, Experiment, Testosterone

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1. Introduction

Growing evidence suggests psychological and biological factors affect individual economic behavior and that some of these factors demonstrably influence financial markets. From the disposition effect capturing non-optimal buying and selling decisions (Odean 1998) to under- and over-reaction to news (Bondt and Thaler 1985; Jegadeesh and Titman 1993), there is strong evidence that psychological factors explain non-Bayesian behavior. Biological factors, too, have also shown to affect financial decision making and markets, such as hours of sunlight affecting stock returns (Kamstra, Kramer, and Levi 2003), and genetics explaining significant variation in asset allocation (Cesarini et al. 2010; Cronqvist and Siegel 2014). Also, brain activation studies of financial decisions have elucidated neural processes underlying market phenomena such as bubbles (Smith et al. 2014) and learning about gains and losses (Kuhnen 2015) (For a review of psychology and neuroscience in financial decision making see Frydman and Camerer (2016)).

Named from the Greek verb *hormoa* meaning ‘to excite’ (Starling 1905), hormones are chemical messengers that assert influence on the brain to motivate both long term physical and neurological (‘developmental’) features and short term (‘activational’) behavioral changes.⁵ Research in the intersection of hormones and behavior historically focused on relatively simple behaviors in animals such mating, aggression, and feeding and only more recently has the role of hormones been studied within human economic decision making. Men’s testosterone levels vary cross-sectionally and are generally 5- to 25-fold higher than women (Salameh et al. 2010) and likely contribute gender differences and variation within males. The sex hormone 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.⁶ Research shows males hold an overwhelming majority of trading jobs in finance (Fabrikant 2010), overtrade and take more risks (Barber and Odean 2001; Croson and Gneezy 2009), exhibit greater overconfidence (Lundeberg, Fox, and Punccohar 1994) and associated acquisitiveness (Huang and Kisgen 2013; Levi, Li, and Zhang 2010), and generate larger price bubbles in experimental markets (Eckel and Füllbrunn 2015) relative to women.

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 (Stanton, Lienen, and Schultheiss 2011; Apicella et al. 2008). In addition to associational evidence regarding endogenous (i.e., produced in the body) levels and behavior, recent work has shown exogenous testosterone administration changes beliefs

⁵ Testosterone is a steroid hormone (meaning it enter cells to affect change) released in regular cycles, in response to social and environmental factors and from readily available prescription drugs (Wallace 2012).

⁶ For sexual differentiation in non-human animals see MacLusky and Naftolin (1981) and for effects on human behavior see Rubin, Reinisch, and Haskett (1981).

and economic decision making (Cueva et al. 2015; Boksem et al. 2013) and encourages intuitive and impulsive cognition in lieu of deliberate thinking (Nave, Nadler, and Camerer 2016).

Albeit there is correlational evidence that biological factors affect financial decision making (Apicella et al. 2008; Coates and Herbert 2008; Stanton, Liening, and Schultheiss 2011), causal studies are needed to demonstrate effect (Mazur 2016). Despite 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 (Sunder 2007). Further, testing the effects of testosterone on trading cannot be done in a field study because effects could include significant market consequences. Therefore, experimental financial markets provide concise frameworks to test specific theories with high degree of identification (Bossaerts and Plott 2004). Neurofinance is in its early days and clear identification is needed to understand the effects of biology on financial decision making (Frydman and Camerer 2016), which is the contribution of this paper.

We used the dynamic experimental market introduced in Smith, Suchanek, and Williams (1988) (SSW henceforth) because this paradigm offers active trading, 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 have tested the causal impact of hormones on trading behavior and associated prices. By creating markets that differ only by the testosterone levels of the participants (called traders) that constitute them, this study tests for causation of testosterone on trading behavior and prices.⁷ We measure both testosterone and an associated hormone produced from testosterone called dihydrotestosterone (DHT) as manipulation checks and to analyze vis-à-vis market measures such as *amplitude*, *duration*, and *volume*.⁸ In addition to obtaining trading data and biological measures, we also survey traders prior to and between trading rounds to identify candidate psychological and belief channels.

Our chief hypothesis was that testosterone would cause traders to overbid for financial assets detectible in bidding data and motivate larger price bubbles, defined as size of upward deviation from fundamental value. Our results confirm these priors by showing that traders in cohorts that received testosterone bid higher amounts which led to higher transaction prices relative to markets with traders who were given

⁷ We apply the same drug taken by over 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 ease of receiving medical prescription, a large and growing proportion of men is currently using AndroGel® (and similar generics), and further more inject anabolic steroids at (remarkably) higher doses (Baillargeon et al. (2013); Handelsman (2013)). In fact, the rise and high penetration rates of this drug among financial professionals allows our experiment to mimic the ‘testosterone shock’ in real-world asset markets such as the NYSE.

⁸ DHT is relevant because it binds faster to the cell (known as androgen receptor affinity) than testosterone (Hemat 2004), stays in the cell significantly longer (Grino, Griffin, and Wilson 1990), and thus likely to have strong behavioral effects.

placebo. These findings advance understanding of the hormone's effects on trading behavior and can improve individual decision making, firm trading performance, and ability to predict—and potentially stabilize—financial markets.

The remainder of this paper is organized as follows. In section 2 we review related literatures and develop evidence-driven hypotheses regarding overall market prices and differences in trading patterns. Section 3 describes experimental design and associated precautions associated with applying and measuring testosterone. Section 4 features traders' measured hormone levels, quantitative differences in market prices and associated individual trading decisions. Section 5 discusses various channels through which testosterone may have influenced behavior such as risk aversion, overconfidence, and cognitive impact, and section 6 concludes.

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. However, consistent evidence to the contrary has been shown, such as sensitivity to seemingly irrelevant aspects, such as evaluation periods (Gneezy and Potters 1997; Gneezy, Kapteyn, and Potters 2003) that cause behavior that defies expected utility theory. Similarly, finance theory states 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 1990's and American housing in the 2000's) can be explained by rational factors such as procyclical expansions of credit, institutional incentives with associated systemic externalities, and innovations with uncertain future cash flows (Allen and Gale 2000; Brunnermeier 2008; Bernanke 2010). However, prices have been shown to change due to reasons unrelated to intrinsic value or rational expectations thereof (Bondt and Thaler 1985; Shiller 2015), such as sentiment (Baker and Wurlger 2006; Shiller 2015), sunshine (Hirshleifer and Shumway 2003), hours of daylight (Kamstra, Kramer, and Levi 2003), columnist opinion (Dougal et al. 2012), and even professional sports outcomes (Edmans, García, and Norli 2007). Underlying many of the aggregate findings are, arguably, biological factors acting at the individual level (Smith et al. 2014; Haracz and Acland 2015; De Martino et al. 2013) and scaling to produce macroeconomic effects (Korniotis and Kumar 2011).

In addition to progressive changes in theory, new methods are now used for studying core questions in economics questions, including field (Gneezy 2009; List 2003), experimental (Smith, Suchanek, and Williams 1988), neuroscience (Frydman et al. 2014; Kuhnen 2015; Smith et al. 2014), genetics (Cesarini et al. 2010; Cronqvist and Siegel 2014), and hormonal (Cueva et al. 2015; Coates and Herbert 2008;

Kandasamy et al. 2014) studies. Together, convergent methods offer a complete and data-driven discipline.

2.2 Biological causes underlying behavioral finance findings

Experiments can test causal hypotheses and reveal underlying mechanisms of phenomena observed in naturally occurring data. For example, Kamstra, Kramer, and Levi (2003) show sunlight cycles affect asset prices mediated via 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 with an established biological connection to serotonin, a neurotransmitter demonstrably sensitive to sunlight and has been shown to affect consumer decision making (Lambert et al. 2002; Lichters et al. 2016).⁹ There is corroboration that other market-level events are caused by known, underlying biological mechanisms. For example, financial crises and periods of low returns persist due to time varying risk aversion produced by fear (Guiso, Sapienza, and Zingales 2013; Porcelli and Delgado 2009). Fear and stress are driven by hormones (Rodrigues, LeDoux, and Sapolsky 2009), and Kandasamy et al. (2014) show that chronically elevating stress hormones increases risk aversion, which affects asset allocation decisions (Shavit, Benzion, and Haruvy 2007). Similarly, Edmans, García, and Norli (2007) show stock prices change in direct relation to international sports outcomes in markets of the competing countries, with losing countries showing significant drops in asset prices without concomitant changes in fundamentals.

Evidence suggests that biological factors could underlie these results. Several studies show changes in testosterone levels among both competitors (Booth et al. 1989; Apicella et al. 2008) and spectators (Bernhardt et al. 1998) change 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 willingness to compete (Apicella, Dreber, and Mollerstrom 2014). However, other studies show little predictive power of baseline testosterone levels (Schipper 2015; Cueva et al. 2015) and thus more work is needed to clarify these relationships.

A comprehensive review by Apicella, Carré, and Dreber (2015) summarizes the multiple approaches to understanding testosterone's role in risky decisions and suggests that the hormone adaptively modulates risky behaviors.^{10, 11} Together, this literature led us to clear hypotheses and motivated testing them in a controlled environment.

⁹ Relatedly, sunshine affects vitamin D levels, which co-vary with testosterone (Wehr et al. 2010)

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, Zingales, and Maestripieri 2009; van Honk et al. 2001; van Honk et al. 2011; Williams et al. 2000), a

2.3 Experimental financial markets

Experimental financial markets provide frameworks to test foundational theories, impact of institutional design, liquidity, information, and financial options (such as shorting), and the effects of individual differences and neural decision-making processes. SSW-type experimental markets typically have four-point, positively skewed positive expected value dividend and most markets with inexperienced traders exhibit an initial underpricing followed by significant overpricing that dampens over successive rounds (Palan 2013; Dufwenberg, Lindqvist, and Moore 2005). All traders know the fundamental value of the asset, which allows for unambiguous measurement of mispricing (a table of fundamental value was provided along with trading instructions in our experiment, see section 2 of E-companion). Because traders determine market prices endogenously in their respective markets, individual buying and selling offers together with associated volume, can reveal the determinants of transaction prices and differences between experimental treatments.

The majority of studies using the SSW framework focus on institutional variables, such as dividend uncertainty and futures trading (Porter and Smith 1995b), allowing short selling (Haruvy and Noussair 2006; Ackert et al. 2006), cash to asset ratio (Caginalp and Ilieva 2008), and adding cash or changing the dividend distribution for experienced markets (Hussam, Porter, and Smith 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, Meissner, and Bosch i Domènech 2015), overconfidence (Biais et al. 2005; Michailova and Schmidt 2011), own and others' irrationality (Hargreaves and Zizzo 2012; Cheung, Hedegaard, and Palan 2014), and individual proclivity to speculate (Janssen, Weitze, and Füllbrunn 2015) on prices and trading patterns. Further, a number of recent studies manipulate states, such as emotion (Andrade, Odean, and Lin 2015; Lahav and Meer 2012) and confusion (Kirchler, Huber, and Stöckl 2012) to quantify their effects on prices and trading behavior. Similarly, this study is the first to directly manipulate a biological factor – by exogenously administering testosterone, in order to isolate and test its influence on experimental asset trading in men (See Table A.5 in section 3 of E-companion for comparison of studies).

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

¹¹ Testosterone increases dopamine—a rewarding, excitatory neurotransmitter (Rupprecht 2003) that affects neural processing and sensation seeking in men (Campbell et al. 2010)—levels, which may explain the downstream effects of the hormone on brain function and resulting behavioral effects.

2.4 Hypothesis Development

Our hypotheses regarding the effects of testosterone were informed by experimental asset trading and behavioral biology literatures discussed in previous sections. Given the challenges of establishing causality of testosterone amid conflation of cause and effect in correlational studies and because baseline levels during trading are available only for the traders given placebo ($N = 56$), we focus our analyses on the differences between the two treatment groups to quantify the causal effect of testosterone.¹²

First, because testosterone is associated with risk taking, we expected that traders with elevated testosterone would be willing to pay more for risky assets and as a result drive market prices to levels that exceed their fundamental values (i.e., cause bubbles). In a market setting, such trading behavior is especially risky because traders might be unable to profitably resell overpriced assets.

Second, the recent evidence that exogenous testosterone increases optimism regarding future prices shown by Cueva et al. (2015) suggests that traders in the testosterone sessions will bid higher prices due to the belief in higher future prices and subsequent capital gains through resale. Given recent evidence that testosterone increases preference for high-volatility assets via optimism, traders may expect that prices will be higher and will therefore bid higher. Given recent evidence of exogenous testosterone promoting intuitive decision making with a decrease in deliberate thinking, we expect changes in fundamental value to be incorporated less accurately among testosterone markets. Finally, Haruvy, Lahav, and Noussair (2007) show that expectations of future prices are predictive of future prices, so we integrated retroactive survey questions regarding price expectations to test differences between treatment groups. The preceding lead to the following hypotheses:

Market prices and volume

H1: Markets with traders given testosterone will produce larger bubbles in aggregate as measured by *amplitude* and *market value amplitude* (defined below) (Section 4.2).

H2: Markets with traders given testosterone will produce longer lasting bubbles in aggregate as measured by *duration* (Section 4.2).

H3: Markets with traders given testosterone will trade at higher volume as measured by *turnover* (Section 4.2).

¹² In unreported analyses, we tested whether baseline levels are predictive of behavior in both the placebo and testosterone groups and verify that they are not.

Bidding

H4: Individual traders given testosterone will bid higher prices relative to traders given placebo as measured by bid prices (Section 4.3).

H5: Individual traders given testosterone will post higher ask prices when selling shares relative to traders given placebo (Section 4.3).

H6: Individual traders given 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).

H7: Individual traders given testosterone will post sell offers at higher volume relative to traders given placebo as measured by number of offers to sell called *selling turnover* (Section 4.3).

Expectations of prices

H8: Individual traders given testosterone will incorporate changes in fundamental value less accurately relative to traders given placebo (Section 4.4).

H9: Individual traders given testosterone will have expectations of higher prices relative to traders given placebo as measured by the inter-round survey (Section 5).

Our results show strong evidence for our primary hypotheses that testosterone administration causes higher market prices and for greater durations as well as higher bid prices relative to markets with traders given a placebo.¹³ Individual trader analysis reveals the process by which this occurred: traders' persistently higher bids and asks drive higher transaction prices and maintain high prices despite the declining fundamental value of the asset. We find testosterone induces above-fundamental value bidding (i.e., momentum) strategies that dissociate transaction prices from asset value. Further, higher levels of DHT increase earnings from trading among testosterone-treated cohorts, and testosterone treatment increases traders' confidence in their own trading skill and upwardly biases price sentiment.

3. The Experiment

There were 17 *sessions* of continuous double-auction markets, each consisting of 3 *rounds* of 12 trading *periods* each lasting 1.5 minutes during which traders buy, sell, bid, and ask for shares of a financial asset.

¹³ As in other studies, including SSW, there are several definitions of bubbles yet we limit our discussion to *amplitude* and *market value amplitude* to measure prices relative to fundamental value. Our results are similar for the additional measures proposed by Stöckl, Huber, and Kirchler (2010) (such as *relative deviation*) and summarized in Table A.1 in the E-companion.

Only one asset type was traded throughout the session (described below). Ten *cohorts* (traders in a particular session) were given testosterone gel (84 traders), and 7 cohorts (56 traders) received gel containing no testosterone (placebo); cohorts ranged in size between 5 and 14 due to variation in recruiting responses and show-up rates. The distributions of traders between treatment groups (number of individual traders in testosterone cohorts: 6, 7, 9, 12, 5, 11, 10, 8, 7, 9; placebo cohorts: 7, 14, 6, 6, 7, 6, 10) are similar as judged by t-test (p -value = 0.76, t -statistic (15) = 0.32; non-parametric test Mann-Whitney p -value = 0.49) and comparable in range to other studies (Lei, Noussair, and Plott 2001). A Kolmogorov-Smirnov test suggests that there is no significant difference in the distributions of group sizes (exact p -value = 0.69). All prices were denominated in experimental currency units (abbreviated ECUs) that was converted to USD at the end of the session and paid in cash according to trading performance. Participants were informed of the exchange rate of 1 ECU for 1 cent.

3.1 Experimental setting and design

We created a market for trading securities with a single asset with simple and predictable fundamental value structure. Each share of the asset paid a dividend of 0 or 18 at the conclusion of each period with equal probability (i.e., expected value of 9 per share for each of 12 periods) and followed a random process (see section 1 of E-companion). Traders were endowed with either 6 stocks and 216 ECUs, or 2 stocks and 648 ECUs at the start of every round by random assignment (both worth 864 ECUs). The fundamental value of the asset begins at 108 ECUs at the start of each round, decreasing by 9 each period and reaching zero at the end of each round. Participants were provided a complete table of the asset's expected value and average dividend over the course of an entire round (See section 1 of E-companion). Surveys were conducted after each trading round to assess mood, perception of prices, self-evaluation and rating of trading performance, as well as beliefs and associated certainty about which treatment was received using unincentivized seven-point Likert scales.

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, 2011 and November 11, 2011. We used a between-group design where all traders in a cohort were assigned to either the testosterone or placebo treatment group allowing for comparison between them to quantify the effects of testosterone. Each trader participated only once. Trader characteristics were evenly distributed between treatment groups, such as age (two-tailed t -test between treatment groups p = 0.14, t -stat (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 according to published pharmacokinetics (Swerdloff et al. 2000) (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 with a uniform schedule and clear operational protocols (such as male-only research assistants) to minimize changes in testosterone.

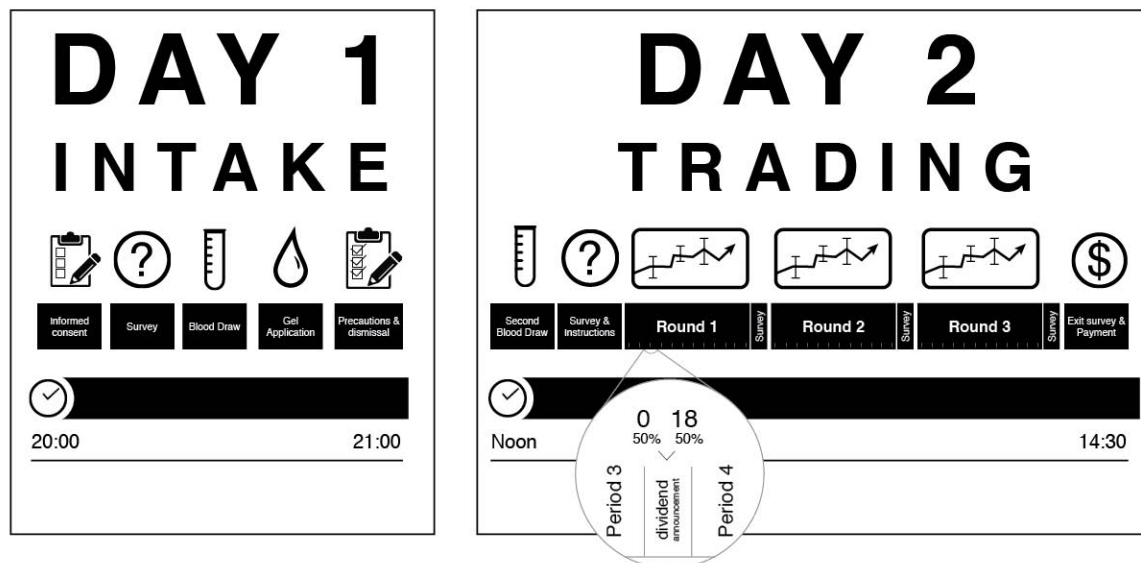
The first day of a session consisted of a medical screening, blood draw by a licensed phlebotomist, double-blind gel application, and demographic survey at 8:00pm. Traders were informed that they were receiving either testosterone or an inert placebo with equal probability. Trading took place immediately after the second blood draw at noon the second day. Testosterone has been shown to vary naturally over the short term, decreasing as low as 60% (Kreuz, Rose, and Jennings 1972) among officers in training to increasing as much 72% after sex (Escasa, Casey, and Gray 2011) from baseline. The experimental dose of 10mg (2 packets of 50g of 1% Androgel®) increased traders' blood testosterone levels to "high normal" comparable to the normal range of variation for men in their respective age group (Salameh et al. 2010).¹⁶ The clinical dosage, double blind randomized experimental design, temporally proximal trading sessions, and multiple blood measures, rule out the possibility of group-specific influence of random exogenous factors, and support the claim that differences in trading are caused by a single dose of testosterone. In addition to completing Protecting Human Research Participants training and receiving corresponding certification by the National Institute of Health (NIH), all research assistants participated in several mandatory training sessions and ran multiple pilot studies at the lab prior to starting the study. The phlebotomist was strictly in charge of all blood acquisitions, and a licensed psychiatrist conducted medical intakes. The institutional review board approved this study and extensive safety, sterility, and participant protection measures were maintained throughout. No adverse events occurred in the study.

¹⁴ We find slightly higher Body Mass Index among the testosterone group (23.7 relative to 25.1 in placebo group, $p=0.03$), yet there is no immediate theoretical ramification on analysis or interpretation of results for measures in our range (Gunstad et al. 2007).

¹⁵ There is an extensive clinical literature on testosterone and its manipulation as well as 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 well as the time-course of levels in the body after administration.

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

Figure 1
Structure of intake and drug administration and trading sessions



Participants arrived the evening prior to their trading session to sign informed consent forms and take pre-trading surveys prior to their blood draws and gel administration (Day 1). Trading took place in three rounds of twelve periods each in each session the following day (Day 2). After each period a dividend of either 0 or 18 is issued to every share of the asset (i.e., every share in the entire market receives the same dividend). After each round a survey was given to assess participant market perceptions and attribution of performance. It includes questions such as, “What do you think determined your performance?” where traders rate on a 1-7 scale how specific factors such as luck, talent, and their calculations. In addition, traders were asked about whether prices were higher or lower than expected and whether price fluctuation was higher/lower than expected.

3.3 Trading

The double-auction format allows participants to simultaneously bid for and sell assets, as well as immediately buy and sell them. Traders can buy or sell assets using a standard electronic limit order book where outstanding orders can be fulfilled by selecting the desired price. Traders can see all transacted prices in the current period, standing sell and buy orders, and their current cash and stock holdings (see Section 2 of E-companion). Posted offers can be retracted with a “Remove” button, allowing traders to rescind offers as market conditions change. Limit orders must be integers between 0 and 500 ECUs and are 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 in comparison to placebo gel. Transaction data suggest traders used the trading platform correctly by posting

bids to buy that were lower than offers to sell and thus poised to profit from transactions. We test for differences in prices then proceed to analyze individual trading patterns between testosterone-treated relative to placebo-treated markets.

4.1 Testosterone results

We measured testosterone and DHT twice to obtain baseline and post-treatment levels. Baseline testosterone levels were similar between groups, with the testosterone group's average testosterone level at 473 nanograms per deciliter (ng/dl)¹⁷ (SD = 17.8) and the placebo group average was 439 ng/dl (SD = 24.5) (two-tailed p-value = 0.36, t-statistic (138) = 0.98)¹⁸; baseline DHT levels were similar as well, with the testosterone group's average DHT level at 47.3 ng/dl (SD = 16.2) and the placebo group average was 44.5 (SD = 18.9) (two-tailed p-value = 0.35, t-statistic (138) = 0.93). Post administration testosterone and DHT were significantly higher in the testosterone group compared to placebo, with the testosterone group's average increase of 63% (t-test relative to baseline: p = 0.000, t-statistic (138) = 14.4), placing many traders near the upper end of the natural male range (known as "high normal") with only 5 traders who exceeded this range and only slightly so. The placebo group was statistically similar to their initial levels and experienced an expected small increase due to typical daily variation (p = 0.13, t-statistic (110) = 1.51).¹⁹ The testosterone group had significantly higher androgen levels on day 2 (p-value = 0.000, t-statistic (167) = 8.3). Due to natural heterogeneity in baseline testosterone levels (146 to 1,125 ng/dl in the total sample) and range of change in testosterone (-76 to 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 E-companion). Similar to testosterone levels, DHT levels increased 180% from 47 to 132 ng/dl in the testosterone-treated group (p = 0.00, t-statistic = 13.1, df = 83), 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-statistic (55) = 1.99) (see Figure 2).

In terms of traders' beliefs in which gel they received (testosterone or placebo), both treatment groups had statistically similar proportions of traders who believed that they received testosterone (test of equality in proportions of subjects believing in receiving testosterone: testosterone group mean = 0.70, placebo group mean = 0.73; p-value = 0.70, t-statistic (120) = 0.38). Traders were systematically incorrect about whether they 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).

¹⁷ This is a standard measure of testosterone in blood.

¹⁸ These levels are within normal range of 250 to 1200 ng/dl for this age group (Salameh et al. 2010)

¹⁹ Testosterone follows a diurnal cycle and 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 vary between 20 and 61% (Brambilla et al. 2009; Diver et al. 2003).

The placebo group was weakly more certain of their beliefs at the 10% level (on a Likert scale of 7 with 7 being the most certain: testosterone group mean = 2.8, placebo group mean = 3.4; p-value = 0.06, t-statistic (105) = 1.9).²⁰

Figure 2

Manipulation check: testosterone levels at baseline and post-treatment

2.a.

2.b.

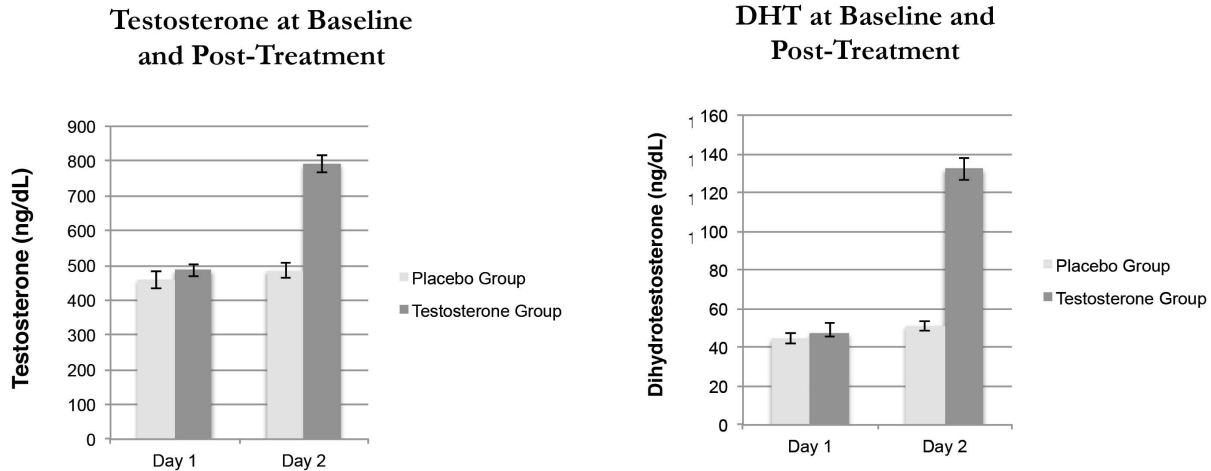


Figure 2.a. shows testosterone and figure 2.b. shows DHT levels for all cohorts by treatment condition (testosterone n = 84; placebo n = 56). Both testosterone and DHT baseline levels are comparable between the two cohorts (Day 1). Post-administration levels on day 2 show the treatment groups' testosterone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

4.2 Testosterone effect on prices

Sessions with traders who received placebo exhibited price bubble size comparable to sessions with similar parameters, such as Sutter, Huber, and Kirchler (2012) (see Figure A.2 and Table A.5 in E-companion). Consistent with other papers using the SSW paradigm, we anticipated bubbles would monotonically decrease and differences between testosterone and placebo groups diminish as traders

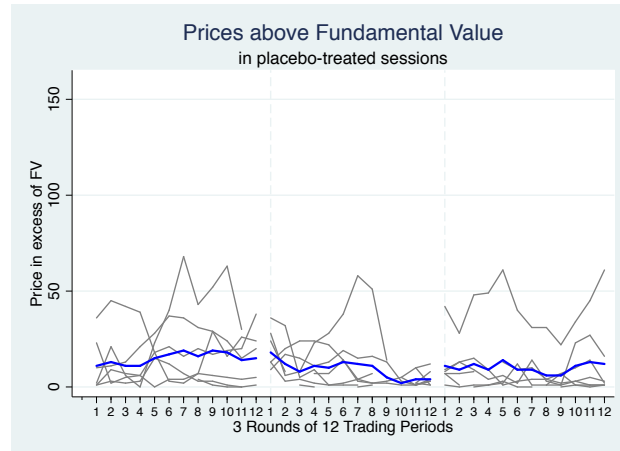
²⁰ Multiple elements would need to coincide in order for beliefs in treatment received to have an effect. First, in order for beliefs per se to have an effect on trading, traders must have an a priori notion about what testosterone is supposed to cause them to do differently. Traders are trading for the very first time in this paradigm and have never taken exogenous testosterone and therefore have no foundation upon which to base an expectation about how they would be affected by an exogenous hormone. Second, their belief about treatment would affect their expectations of others' behavior yet for similar reasons they cannot form reliable predictions of others behavior 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.

gained experience in the market.²¹ We find evidence of higher prices in the testosterone-treated groups relative to placebo, affirming our primary hypothesis. Figure 3 shows price deviation from fundamental value by treatment condition and that it was greater in testosterone relative to placebo sessions.

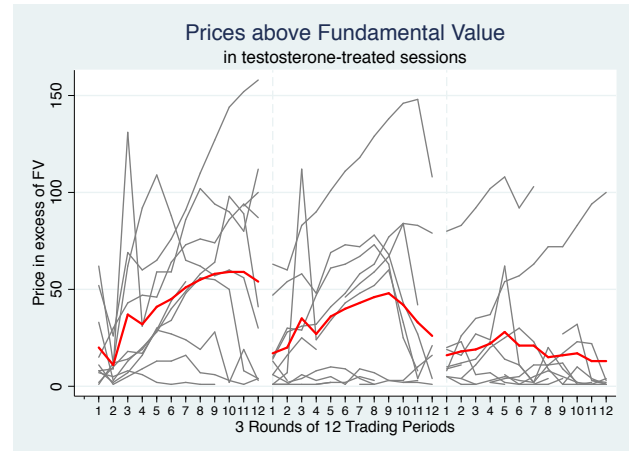
Figure 3

Price bubbles: Prices in excess of fundamental value in all three trading rounds

3.a



3.b



Figures 3.a. and 3.b. depict overpricing by showing price minus fundamental value for the entire experiment by treatment condition. Grey lines show prices in excess of their fundamental value for a particular cohort across three rounds of each session, and the average of all placebo cohorts is in blue in panel “a” and red in panel “b” for testosterone. Consistent with virtually all other asset trading experiments, bubbles decrease in size with each round and approach fundamental value in the third round. The diminutive size of the bubble in the placebo condition is due to the low uncertainty about the asset fundamental value in our design, as dividends could only be 0 or 18, creating a narrow range of expected values similar to Porter and Smith (1995a). These graphs show that increasing testosterone causes higher prices without any indication of high future prices and despite knowledge of future decreasing fundamental values.

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 placebo.²² Bubble size was measured by amplitude, the maximum normalized difference between average prices and fundamental value during a trading period (Porter and Smith 1995a), and MVA, volume-weighted average price above fundamental value (Hussam, Porter, and Smith 2008). *Duration* measures the number of consecutive periods the difference between average price and fundamental value grew. *Turnover*, similar to volume in large exchanges such as the NYSE, captures

²¹ Mispricing among placebo groups is lower relative to similar markets. See Figure A.2 E-companion for comparison to prices in Sutter, Huber, and Kirchler (Sutter, Huber, and Kirchler 2012).

²² We test differences in bubble size using every published measure and obtain the same pattern in results and report them in Table A.1 in E-companion (see Table A.2 in E-companion for definitions and formulae of all measures used).

relative trading activity and is measured by the number of trades divided by the number of shares in the market (Porter and Smith 1995a) (All measures defined in Table A.1 in E-companion).

We observe 120% larger amplitude—the primary measure of bubble size—between testosterone and placebo sessions and associated Cohen’s d of 1.10, which is considered large (Cohen 1992). To contextualize our results with other papers in the first round of trading, our treatment effect lies between Janssen, Weitze, and Füllbrunn (2015) who observe 130% larger amplitude between low and high speculators, and Lahav and Meer (2012) who find 100% larger amplitude caused by positive relative to neutral emotional induction (See Table A.5 in E-companion).

By estimating a linear regression controlling for trading group size and round fixed effects, we find that testosterone treatment increased amplitude, MVA, and duration but not turnover, and that effects were largest in round 1 (See Table 1 for regression results and Table A.2 in E-companion for summary statistics and non-parametric t-tests).²³

In addition to treatment effects, we also test *post hoc* whether testosterone levels in markets affected the degree of mispricing and find cohorts’ average testosterone levels positively correlated with amplitude ($r = 0.27$, $p = 0.05$, t-statistic (49) = 1.96) and market value amplitude ($r = 0.33$, $p = 0.02$, t-statistic (49) = 2.45) (See Figure A.3 in E-companion).²⁴ In summary, results confirm H1, H2, and disconfirm H3.

²³ 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. The results still hold (Table A.3 in E-companion).

²⁴ We found similar positive correlations between DHT levels and amplitude ($r=0.36$, $p=0.01$, t-statistic (49) = 2.70), and market value amplitude ($r = 0.38$, $p = 0.007$, t-statistic (49) = 2.79). Figure A.3 in the E-companion exhibits the correlations between amplitude and market value amplitude and DHT for all participants.

Table 1**Market level regressions**

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

Note: Regression of market measures as dependent variables and a binary variable ("Treatment") for testosterone (1) and placebo (0), dummy variables for rounds (Round = 1 omitted), and number of traders in cohort (Size) included. Each session produced three observations, one for each round of trading (N = 51). Results show testosterone-treated groups had larger and longer periods of prices exceeding fundamental value while controlling for cohort size.

Robust standard errors reported in parentheses

*** Significant at 1 % level, ** 5 % level, * 10 % level

4.3 Testosterone effect on bids and asks

Buying and selling prices

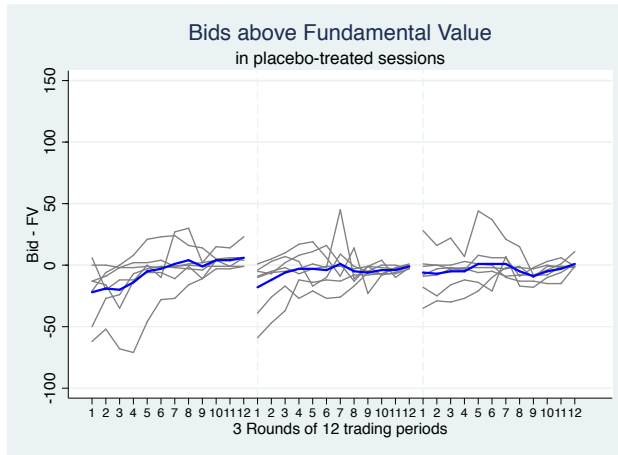
We find significantly higher average bidding prices among traders in the testosterone group in round 1 and 2 and greater but insignificant in round 3, which is consistent with H4. This empirical result explains why prices were higher among testosterone-treated markets: markets in which buyers are willing to pay more will trade at higher transaction prices.²⁵ Similarly, asks were higher among testosterone compared to placebo groups in all three rounds (see Table 2), confirming H5.

²⁵ The correlation between bid prices and transacted prices aggregated at the session level is greater than 0.94 for all periods for both testosterone and placebo for each round ($p < 0.000$, $t\text{-stat}(70) < 23$).

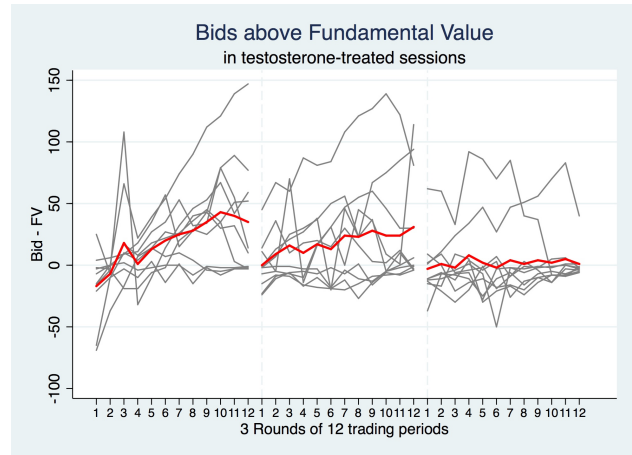
Figure 4

Bidding above fundamental value

4.a



4.b



Figures 4.a. and 4.b.: Average bids minus 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 the average in red in panel “a” for placebo and blue in panel “b” for testosterone. 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 overprices shares and continue to bid despite obvious upward deviations from asset fundamental value.

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, disconfirming H6. Selling turnover is significantly higher among testosterone-treated traders, confirming H7. Also, we find spreads (difference between buying and selling prices) were significantly higher among testosterone markets in all three rounds as traders in this group attempted to ‘buy high’ and to ‘sell higher’, as seen in high asking prices. Spread in round 3 drastically widened in the testosterone sessions, which was likely due to traders attempting to recapture losses sustained in earlier rounds with efforts to sell assets above their fundamental values (as high asking prices carry no risk of loss) in the final round of trading. Higher spread is associated with lower trading volume, which, coupled with lower bid prices, may have precipitated bursting of bubbles in later periods (see Table 2).

Table 2**Summary of bids, asks, and spread between placebo (P) and testosterone (T)**

		Round 1		Round 2		Round 3	
<i>Variable</i>		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	0.00		0.00		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		0.00	
	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	0.00		0.00		0.00	
	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	0.00		0.00		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		0.00	
	t-statistic	2.5		2.2		2.9	

Complementing Figure 3, we see traders in testosterone (T) groups bid and ask higher prices in most rounds of trading relative to placebo (P). T-test results are one-tailed (null hypothesis being that testosterone is greater than placebo) tests due to directional hypothesis of testosterone bid and ask prices expected to exceed 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 market with higher bids and offers as observed in testosterone-treated markets. Standard deviations shown below in parentheses. DF = 202.

Influence of testosterone on bidder type

Haruvy and Noussair (2006) and Caginalp and Illeva (2008) uniquely categorize traders by type to depict evolution of prices, cash holdings, and trading strategies among traders within trading sessions. Adapting a similar framework, we identify traders as *momentum* or *fundamental* bidders by isolating periods in which prices exceeded fundamental value, and assign a positive point for every fundamental bid (i.e.,

below fundamental value) and a negative point for every momentum bid (i.e., above fundamental value) for each trader. A trader is categorized as a fundamental bidder in a period if the summed points in that period are positive, and momentum if the points are less than zero (and neutral if zero). The rationale for using bids to establish a type, is that bids bind buyers to a contract, indicate expectations of future prices, and carry risk of capital losses through inability to resell. We use an event window of 5 periods prior to the peak price and two periods afterwards and depict period-by-period proportions of momentum and fundamental traders similar to Caginalp and Illeva (2008). Corroborating findings that testosterone traders do not ‘track’ fundamental value, we find testosterone-treated markets are constituted primarily by momentum bidders in every period relative to placebo, and the opposite for the proportion of fundamental bidders (see Figures 5).

Figure 5
Composition of traders by treatment condition

Fig. 5a

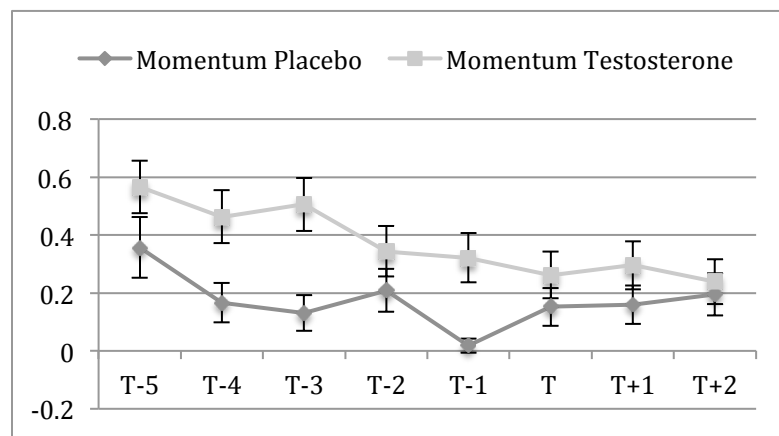
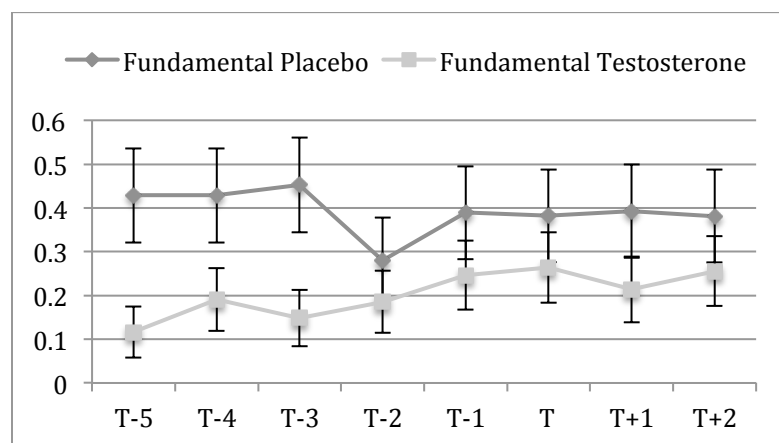


Fig. 5b



Figures 5.a. and 5.b. show proportion of traders by type for testosterone and placebo treatment groups in the 5 periods preceding

and 2 proceeding peak price during a trading round (with SE bars). We see a consistently high proportion of momentum traders and correspondingly low proportion of fundamental traders among testosterone-treated cohorts, and the opposite for placebo sessions. *Note:* Proportions do not add to 1 due to a quantity of traders who classify as neither momentum nor fundamental (neutral).

We quantified the effects of being in the testosterone group on the likelihood of bidding above fundamental value using a logistic regression for each round, controlling for lagged deviations from fundamental value ($\text{Price} - \text{FV}$), change in price from $t-2$ to $t-1$ (ΔPrice), and number of periods prior to and after that particular rounds' price peak. We find that the marginal effect of being in the testosterone group, versus the placebo group, is an increase in the odds of bidding above fundamental value by about a factor of 1.65 in rounds 1 and 2, corroborating other results (Table A.6 in E-companion).²⁶

Next we estimate how traders' bidding responded to rising prices and dividend payments. We identify periods of rising average prices with 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 *no pay* indicates number of consecutive periods of zero dividend payouts, as traders' perception of asset fundamental value affects prices (Noussair, Robin, and Ruffieux 2001). The results show traders who received placebo did not increase buying prices as prices increased. Conversely, high testosterone traders posted higher buying prices as market prices increased in round 1 by an average of 22 ECU ($p = 0.013$), in round 2 by an average of 40 ECU ($p = 0.009$) and in round 3 by an average of 19 ECU ($p = 0.015$). 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 the placebo group decreased bidding prices in response to 'streaks' of zero dividends, but the testosterone group did not (see Table 3).²⁷

²⁶ Eisenegger et al. (2010) suggest 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 6 with controlling for belief in treatment and find that beliefs have no significant explanatory power.

²⁷ We test for effects of price changes on volume of bidding during periods of serial price increases and do not find significant results for either treatment group.

Table 3**Bidding in response to price changes in placebo and testosterone markets**

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

Note: This table reports OLS regression results using the bidding prices as the dependent variable, 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 price increased in the previous period; Pay (NoPay) is equal to the number of consecutive periods with dividend payment (no dividend payment).

Standard errors clustered at the session level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4.4 Rational expectations

We show 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 propose that the mean price change between periods can be decomposed into (a maximum of) three components: decline in fundamental value, adjustment for risk²⁸, and revealed excess demand for shares arising from capital gains expectations. They postulate that excess demand is correlated with excess bids with endogenously expected capital gains, thus a “surrogate” for excess demand and use the following “rational expectations” equation:

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

where $\bar{P}_t - \bar{P}_{t-1}$ is the change in mean price from period $t-1$ to period t and $B_{t-1} - O_{t-1}$ 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 average expected differences in fundamental value between periods as well as risk aversion on the part of traders. An alpha of 9 ECUs is the expected change in

²⁸ This 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 our trading data.

fundamental value between periods, while an alpha less (more) than 9 reflects risk aversion (seeking) in regards to dividends.²⁹ We hypothesized that the intercept term would be significant and approximate the change in fundamental value of 9 ECUs per period among placebo sessions due to the tight tracking of prices with fundamental values and poorly track fundamental value for testosterone sessions.³⁰ Due to 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 run separate regressions for testosterone and placebo treatment groups with price adjustment between periods as the dependent variable and lagged excess bids as the sole explanatory variable, and find that the constant term is significantly negative for the placebo group in all three rounds at magnitudes notably close to the decline in fundamental value of 9 ECUs per period as found in some stable price markets in SSW. Following SSW's interpretation of this term, this result suggests traders in the placebo sessions systematically incorporated the declining fundamental value into their trading decisions and did not expect capital gains in future rounds evidenced by being unable to reject the hypothesis that $\beta = 0$. In testosterone markets we find non-significant intercept (cannot reject the hypothesis $\alpha = 0$) in round 1, confirming H8, and intercepts in rounds 2 and 3 that more poorly estimate declining fundamental value relative to placebo markets. Lagged excessive bids significantly positively correlate with price changes in round 2, and a weaker such correlation in round 3 (see Table 4) in testosterone markets only.

²⁹ SSW hypothesize that under rational expectations in the case of Muth (labeled REM), the change in prices is a combination of expected fundamental value change and an adjustment for risk aversion (which can be disentangled using traders' price forecasts, which we not measured in our experiment). REM is rational expectations as depicted by Muth (1961), meaning that outcomes support predictions of a particular theory. In this case, the theory is that traders will have forward-looking expectations of future prices that rationally reflect fundamental value over time.

³⁰ SSW explicitly solicited expectations of future prices and formally tested the two components of the intercept while we do not and thus can only quantify the significance of the intercept and not its constituent elements.

Table 4**Rational expectations regressions**

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

Note: 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 (difference between buying offer turnover and selling offer turnover in period t-1) as the independent variable, with standard error clustered at the session level.

Standard errors clustered at the session level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4.5 Testosterone's effect on trading behavior pre- and post-peak

We have shown testosterone caused traders to bid higher for assets and this led to higher transaction prices relative to markets composed of traders given placebo. Because most price paths rise, then fall, within trading rounds we analyze differences between treatment conditions in relation to price peaks. We find that placebo treated traders post more buying offers and on average below fundamental value relative to testosterone traders, suggesting 'buy low to sell high' prior to as well as after peak price in each round. Conversely, testosterone-treated traders bid in excess of fundamental value to 'buy high to sell higher' both before and after price peaks. The notable differences between buying and selling prices are measured as significantly larger spreads in testosterone sessions both before and after price peak. We find more selling offers among testosterone traders after prices peaked and at higher prices relative to placebo, likely because traders were attempting to sell assets for which they overpaid during the run up to peak price (see Table 5).

Table 5**Differences in trading behavior relative to peak prices**

	Pre-peak			Post-peak		
	P	T		P	T	<i>p</i> -value
Buying turnover	0.47 (0.26)	0.36 (0.25)	<i>p</i> -value = 0.00 t-statistic = 3.84 DF = 357	0.47 (0.31)	0.36 (0.29)	<i>p</i> -value = 0.02 t-statistic = 2.71 DF = 251
Average buying price	66.3 (28.0)	88.8 (33.2)	<i>p</i> -value = 0.00 t-statistic = 6.82 DF = 357	33.0 (22.4)	50.0 (37.7)	<i>p</i> -value = 0.00 t-statistic = 3.99 DF = 251
Selling turnover	0.51 (0.26)	0.53 (0.28)	<i>p</i> -value = 0.60 t-statistic = 0.51 DF = 357	0.45 (0.23)	0.71 (0.35)	<i>p</i> -value = 0.00 t-statistic = 6.32 DF = 251
Average selling price	102.3 (85.7)	176.2 (236.1)	<i>p</i> -value = 0.00 t-statistic = 3.73 DF = 357	82.0 (149.4)	174.2 (297.8)	<i>p</i> -value = 0.01 t-statistic = 2.79 DF = 251
Average spread	35.9 (81.9)	87.4 (236.3)	<i>p</i> -value = 0.01 t-statistic = 2.61 DF = 357	48.1 (147.1)	124.2 (297.9)	<i>p</i> -value = 0.02 t-statistic = 2.32 DF = 251

Differences in buying and selling offers before and after peak prices using two-sample t-test between testosterone-treated (T) and placebo-treated (P) traders. Standard deviation below in parentheses. Two-tailed *p*-values shown.

Note: Standard deviation reported in parentheses

Further, we test the influence of buying and selling volume on overpricing (measured by price minus fundamental value) before and after price peaks by regressing price minus fundamental value on bid and ask volume, bid and ask prices, while controlling for rounds, and cohort size and find testosterone and placebo markets are distinct. We find bidding volume pushes prices in opposite directions between treatment groups, causing downward pressure in placebo markets due to coupling with below-fundamental value bidding (despite higher volume) and upwards pressure in testosterone markets due to above-fundamental value bidding. We find bid price significantly predicts overpricing for both placebo and testosterone markets, yet the amplitude of the latter is much higher. However, selling (i.e., ask) volume does not significantly influence overpricing before price peak in placebo- or testosterone-treated

sessions. Post-peak, we find no effect of bids or offers on mispricing and strong prediction of bid price for both groups yet a much higher coefficient for testosterone (see Table 6).

Table 6
Influence on overpricing in relation to price peak

	Pre-peak		Post-peak	
	Placebo	Testosterone	Placebo	Testosterone
Ask Volume	-6.005 (5.074)	6.631 (8.134)	-7.494 (8.323)	9.797 (6.427)
Bid Volume	-9.912* (5.100)	20.74** (8.568)	-23.11*** (7.264)	8.618 (7.891)
Average Ask Price	0.0225 (0.0152)	-0.00392 (0.00916)	-0.00458 (0.0130)	0.0112 (0.00740)
Average Bid Price	0.137*** (0.0477)	0.698*** (0.0675)	0.369*** (0.0864)	0.645*** (0.0619)
Round = 1	-7.757** (3.289)	9.660* (5.405)	12.46** (4.834)	25.56*** (5.813)
Round = 2	-3.817 (3.048)	2.847 (5.298)	6.829 (4.571)	14.37** (5.681)
Size	0.176 (0.461)	1.039 (0.967)	-3.150*** (0.767)	-1.396 (1.023)
Constant	4.017 (6.507)	-56.16*** (10.89)	37.20*** (10.42)	-17.01 (10.92)
Observations	157	200	94	158
R ²	0.150	0.446	0.381	0.542

This regression shows differences in effect of bid and ask prices and volume on asset price before and after peak price while controlling for round, number of traders in the market, and bid and sell prices.

OLS Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

5. Discussion

We show that testosterone increases prices of financial assets in an experimental setting, and now discuss potential channels underlying the effect

Risk Aversion

An obvious candidate for why testosterone-treated men bought overpriced assets is decreased risk aversion. Men generally show lower risk aversion than women (Eckel and Grossman 2002) and produce larger price bubbles in experimental markets (Eckel and Füllbrunn 2015). Because testosterone is the essential causal agent for primary and secondary sexual characteristics that distinguish gender 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), elevated levels may induce higher risk taking. Testosterone is associated with various types of risk taking (Apicella, Carré, and Dreber 2015) including evidence that endogenous changes predict subsequent risk-taking (Apicella, Dreber, and Mollerstrom 2014), as well as exogenous application increasing willingness to invest in high variance stocks (Cueva et al. 2015). This paper contributes to the testosterone and risk taking literature by demonstrating that higher levels of testosterone increasing bid prices for financial assets, a pattern which places traders at risk of capital losses in a dynamic trading environment.

Overconfidence

We observed testosterone-treated traders attributed their performance more to their skill and less to luck than their placebo-treated counterparts, which is the definition of attribution bias presented by Gervais and Odean (2001). The rise in confidence may have led to differential trading behavior, which caused the pronounced overpricing as predicted by the model. Barber and Odean (2001) argue overconfidence is a cause of excessive trading (and find that men overtrade relative to women), however we find similar trading volume between treatment conditions, likely due to paucity of crossing of supply and demand evidenced by larger spreads among testosterone-treated sessions. Also, traders' elicited expected ranking show no systematic differences from their actual ranking between groups, meaning that testosterone did not cause traders to overpredict their own performance. Together, we find that testosterone increased confidence in one's trading skills during trading yet did not increase confidence in expectations of trading performance. Despite stereotypes of testosterone and overconfidence among men, there is no evidence testosterone causally affects overconfidence *per se* and our data present context-dependent evidence towards this open question.

Beliefs

Higher prices in testosterone-treated markets might have been initiated by belief in higher future prices (i.e., optimism) and subsequently increased due to endogenous increases in probability of capital gains caused by high bids and transaction prices in a self-fulfilling manner. This is consistent with a recent study showing exogenous testosterone increases optimism about future prices (Cueva et al. 2015) and may be one of the key behavioral drivers. Together, testosterone may have altered beliefs about future prices and motivated bidding above fundamental values (in order to capitalize on future capital gains), leading to overpricing observed in this experiment.³¹ Survey data support this claim, as we observed significant differences in expectations about future prices between treatment groups, with testosterone traders expecting higher prices than their placebo counterparts as discussed above (and in Table A.9 in E-companion), confirming H9. Future research using SSW's inter-round price forecasts can further test this channel of influence and quantify the effects of testosterone on beliefs.

Cognition

Trading financial assets in a dynamic market is a complex cognitive task. It requires simultaneously and rapidly estimating, planning, learning, responding and re-optimizing in an unpredictable setting. Therefore, financial cognition is a broad skill set that likely correlated with other types of intelligence underlying trading behavior, and this aptitude presumably affects performance. Indeed, Bosch-Rosa, Meissner, and Bosch-Domènech (2015) show larger bubbles in markets composed exclusively of traders with low cognitive sophistication as measured by a battery of tests including the Cognitive Reflection Test (abbreviated CRT) scores (Frederick 2005).

Nave, Nadler, and Camerer (2016) show that the same exogenous testosterone treatment used in our trading experiment also reduces CRT scores in a similar population. 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 processes ('system 2') (Kahneman 2003). Also, similar to Biais et al. (2005), testosterone might have influenced cognitive type, leading to changes in bidder type (as shown in section 2.5). In the same paper, Nave, Nadler and Camerer show that testosterone had no effect on mathematical abilities, suggesting that overpricing might not be driven by impairment in the capacity of performing simple calculations, but rather in the probability of using such calculation as a cognitive strategy. Further, Hermans et al. (2010) show testosterone increases impulsivity, a trait central to rapid financial decision making. Therefore, testosterone is likely to affect decisions by biasing towards intuitive and rapid processes that exclude

³¹ Future work will test this hypothesis by surveying traders' opinion of future prices prior to each round of trading.

complex and relevant information in various contexts and may have contributed to higher earnings among testosterone-treated traders within their cohorts.

In addition to reflective cognition, active trading requires forecasting others' behavior. Thus, social cognition and theory of mind may play a role in this experiment as shown in De Martino et al. (2013) in that traders engaging theory of mind are likely paying less attention to fundamental value and may consequently under-perform. Aside from differences in expectations of prices and bidding, our survey data show differences in the role of others' strategies in traders' success and this can be further explored in future research.

Status Seeking

Obtaining high social status is universal human desire and testosterone has been shown to correlate with status seeking behavior (Kenrick et al. 2010; Mazur and Booth 1998). Testosterone has bi-directional social and hierarchical relationship, as testosterone drives status seeking and status *per se* affects testosterone levels (Sapolsky 2004). The crucial elements of (non-aggressive) status is that it can be signaled to others reliably and can be easily identified by competitors and potential mates (Zahavi 1975). However, as this experiment was anonymous, rankings were not known by traders, and trading stations private, which eliminate the display of status earned through earnings in the group, and reduce the probability status seeking as a chief channel. The same trading paradigm can easily be modified to include a salient ranking component to ascertain sensitivity to group status in future research.

Mood

Andrade, Odean, and Lin (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 affect 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 regimes (Anderson, Bancroft, and Wu 1992; O'Connor et al. 2001). Concordantly, we find no significant differences between treatment groups' affect which strongly suggests mood is not the channel through which trading behaviors differed between testosterone and placebo markets (See Table A.9.f. in E-companion).

6. Concluding Remarks

In this paper, we show that exogenously increasing testosterone in men increases bidding prices and causes price increases for an asset with a universally known fundamental value, leading to bubbles and

crashes. These results show us the effects of a specific hormone on men's trading of financial assets and presents attendant market implications. Much like sentiment, which causes entire asset classes to move in the same direction, endogenous changes in testosterone can cause synergistic co-movements in financial markets: traders winning in bull markets likely experience increase in endogenous production of testosterone. The resulting increase of testosterone in response to wins can fuel overpricing and bubble formation as shown in this experiment. Possibly exacerbating such scenarios is the associated biased self-attribution that accompanies high-testosterone states. Even more troubling is the easy access of testosterone supplementation and proliferation of use among financial professionals and concomitant lack of public knowledge of the behavioral effects of the drug.

This research suggests hormonal influences on decision making ought to be considered in professional settings, such as intelligently integrating biological aspects into proactive trading systems in financial firms and considering the impact of impulsive corporate decisions. Human biological factors can exacerbate capital risk and therefore firms may benefit from detecting where hormones assert influence, such as positive feedback cycles unsupported by fundamentals or technical indicators, and provide appropriate decision support where feasible.³² These findings are likely applicable also to non-users of exogenous testosterone as endogenous levels affect behavior, yet users ought to be aware of the cognitive effects of the drug shown in the literature. It is unknown if these results generalize to women and closer examination of gender differences in financial trading—an area difficult to study empirically due to paucity of female traders in the field—would improve our understanding.

The chief objective was to test for a causal relationship between testosterone and trading, yet future projects may conclusively identify specific changes in economic primitives such as discounting and more distinctly disentangle beliefs and preferences. Further, in order to better control for market influences and improve identification, future experiments will have both testosterone- and placebo-treated traders in the same session to test whether the androgen causes separation between treatments and increases heterogeneity in trading strategies and performance within rounds. Also, future work could measure post-trading testosterone levels to test the 'winner/loser hypothesis' of testosterone to approximate the hormonal response caused by engaging in competitive markets as well as the resulting effect of performance on testosterone levels.

Alfred Marshall 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. Our results harmonize previous findings and provide compelling evidence of hormones affecting financial decision

³² One of them is John, a forty-year-old venture capitalist, is quoted in an Financial Times article saying 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).

making. These results stand to inform retail and professional asset trading and given these results and their impacts on financial cognition it is likely testosterone significantly affects decisions that meaningfully impact the economy.

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