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Research article

Testosterone reactivity to competition and competitive endurance in men and women☆

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ABSTRACT

Transient shifts in testosterone occur during competition and are thought to positively influence dominance behavior aimed at enhancing social status. However, individual differences in testosterone reactivity to status contests have not been well-studied in relation to real-time expressions of competitive behavior among men and women. This research tests the association between changes in endogenous testosterone levels during competition and performance in terms of competitive endurance. Participant sex, social presence, and relative status outcomes (e.g., winning vs. losing) are tested as moderators of this relationship. In two studies, men and women (total $N = 398$) competed in the competitive will task (timed weight-holding) either individually or in the presence of an opponent (Study 1) or as a team with and without the presence of a competitor team (Study 2). Results showed a positive relationship between testosterone reactivity and performance for men, particularly those who won or ranked highest among their group – with increasing testosterone predicting better performance and decreasing testosterone predicting worse performance. For women, the effect only emerged among individuals who competed in dyads and lost. In Study 2, an exploratory mediation analysis revealed that individual differences in trait dominance predicted both testosterone reactivity to competition and task performance, with testosterone reactivity (moderated by sex and status outcome) partially explaining the direct relationship between dominance-related traits and behavior. Our goal was to examine testosterone reactivity in relation to real-time competitive effort and highlight the potential role of this relationship in explaining how individual differences in trait dominance produce competitive behavior.

1. Introduction

Originally proposed in the context of territorial behavior in male birds, the challenge hypothesis (Wingfield et al., 1990) guided predictions about the kinds of social encounters that produce increases in circulating testosterone. These elevations in testosterone appear to promote aggressive behaviors that benefit reproduction by increasing competitive behavior required to gain access to receptive females. Conversely, high testosterone maintained over an extended period is hypothesized to be costly in terms of health and appears to inhibit or reduce the affiliative behavior required for parental care following successful reproduction (Muller, 2017; Wingfield et al., 2001). Thus, a key premise of the challenge hypothesis is that an increase in testosterone level in response to a social encounter should be transient and occur only within contexts in which relative social position and, correspondingly, access to a limited resource, is at stake. That is, elements of the social context should play an important role in moderating the relationship between testosterone reactivity and competitive behavior.

The challenge hypothesis has been extended to humans to generate predictions about testosterone reactivity to contests for social status observed in men and women (Archer, 2006; Casto and Edwards, 2016a; Geniole and Carré, 2018). This literature supports the notion that short-term elevations in testosterone can adaptively (for the purposes of competitive success) alter competitive and aggressive behavior and underlying neural processes in humans (e.g., Carré et al., 2009, 2013;

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Goetz et al., 2014; Hermans et al., 2008; Mehta et al., 2015a; Radke et al., 2015; van Wingen et al., 2009; Wagels et al., 2018; for review, Zilioli and Bird, 2017). Consonant with predictions from the challenge hypothesis, the relationship between the testosterone response to competition and dominance-related behavior that would facilitate competitive success appears to be dependent on aspects of the social environment (for review, Carré and Archer, 2018; Geniole and Carré, 2018).

For instance, a critical aspect of the competitive social environment that affects testosterone reactivity is the competition outcome, social status gained or lost as a result of implicit or explicit rules of the contest. According to the biosocial model of status (Mazur, 1985, for review Casto and Edwards, 2016a), testosterone should increase following a contest for status for those who experience relative social victory in order to promote subsequent dominance and decrease for those who experience relative social defeat in order to promote subsequent deference. Indeed, research has shown that this designation of a winner or loser (i.e., competition outcome) has been shown to moderate the relationship between testosterone reactivity and subsequent competitive behavior. For example, in men, change in testosterone during competition has been found to be positively related with an individual's choice to compete again afterwards (against the same opponent), but only for those who lost (Mehta and Josephs, 2006). Specifically, losers experiencing increases in testosterone were more likely to choose to compete again while losers experiencing decreases in testosterone were more likely to choose the non-competitive alternative. For winners, the direction of change in testosterone was not related to whether men chose to compete again or not. In a separate study, when men were asked to decide whether or not to compete again (against a different opponent), their testosterone reactivity to competition (increasing or decreasing) positively predicted the likelihood of making the competitive choice only for those who decisively won (Mehta et al., 2015b).

In another study of men, a positive relationship between testosterone reactivity to a competition and subsequent risk-taking behavior was found only among those who won (e.g., Welker et al., 2019), while a different study found that testosterone reactivity to competition was inversely related to subsequent risk aversion regardless of prior win or loss (Apicella et al., 2014). Carré et al. (2013) found that aggressive behavior following a competition for status was predicted by testosterone reactivity during the competition in both male winners and losers, but winners were more likely to increase in testosterone and displayed greater post-competition aggression than losers. No effects were found for women who were included in this study. In fact, in much of the research discussed above, women were either not included as participants (majority of prior studies) or, women were included, but no significant relationship between testosterone reactivity and the specific status-related behavior was found (Casto and Prasad, 2017). Nonetheless, these studies suggest that a testosterone increase during competition influences subsequent dominant, aggressive, or competitive behaviors dependent on shifts in relative status. However, these kinds of behaviors are also beneficial to status achievement during the competition period itself. Despite the importance of dominance and competitiveness in determining who will win or lose, little is known about how testosterone reactivity during competition relates to ongoing, time-matched status-related behavior such as competitive effort. Indeed, much of the prior research on the winner-loser effect in the laboratory has attempted to control for individual differences in competitive motivation or effort by rigging the competition to be demonstrably easier for those who "won" than for those who "lost" (e.g., Carré et al., 2013; van der Meij et al., 2010; Zilioli and Watson, 2012; for review, Casto and Edwards, 2016a). The present research is premised on the notion that the testosterone response to competition is meaningfully tied to, and perhaps even functions to regulate, naturally occuring individual differences in competitive performance.

Given that competition-related changes in testosterone are relatively short-lived (e.g., Casto and Edwards, 2016b; Henry et al., 2017; Oxford et al., 2010) and androgen effects on tissues including the brain can be quite rapid (Michels and Hoppe, 2008; Simoncini and Genazzani, 2003), it is likely that a testosterone increase during competition would be mechanistically capable of facilitating *ongoing* competitive effort. Although testosterone reactivity to competition has been recently linked with time-matched changes in self-reported competitiveness and observer-rated self-assuredness in men (Kordsmeyer and Penke, 2019), the extent to which testosterone reactivity to competition predicts measures of competitive *behavior* expressed during that competition has, to our knowledge, not been tested in humans. That is, despite an abundance of research on testosterone's relationship to dominant and competitive behavior, we still do not know whether testosterone reactivity promotes dominant and competitive behaviors *within the contest period* – a time when status is actively being contested and testosterone's ability to promote dominance would be most relevant to achieving the contest-related goal.

Hormone-behavior interactions are bidirectional in nature and thus, observing competition-associated testosterone change and behavior simultaneously leaves uncertainty about the direction of the relationship. Particularly in regards to rapid mechanisms of hormonal regulation interacting in coordination with sensory-cognitive and neurological processes, causal implications are particularly difficult to disentangle. Thus, the relationship is perhaps best characterized as a rapid feedback loop in which the cascade of physiological changes producing a testosterone increase flow from the awareness that one has entered a competitive contest and ongoing awareness and competitive motivation are, in-turn, affected by these hormonal changes (Casto and Edwards, 2016a, see Fig. 5 and related discussion). Causal patterns are further complicated by additional factors that modulate direct relationships within the feedback loop such as baseline individual differences in social dominance, sensitivity to status threat, the quantity of androgen receptors, and baseline levels of testosterone and cortisol (e.g., Carré and Olmstead, 2015; Eisenegger et al., 2017; Gettler et al., 2017; Vermeer et al., 2016; Zilioli and Watson, 2012).

Nonetheless, a growing body of research experimentally manipulating testosterone levels by intranasal, oral, or transdermal administration suggests that, in certain contexts, elevated testosterone causally promotes the emergence of competitive and aggressive behavior (for recent reviews; Casto and Mehta, 2019; Geniole and Carré, 2018). For example, in one study, women given supplemental testosterone were more likely to choose to compete again than women given a placebo, but only following a social victory and only if they were high in trait dominance (Mehta et al., 2015a). Exogenously administered testosterone has been shown to elevate men's perceptions of their own physical dominance (Welling et al., 2016), an effect that would likely increase competitive efforts. Additional research shows that testosterone can rapidly activate areas in the brain involved in experiences of pleasure and reward and resulting motivated behavior (Vermeer et al., 2016; Welker et al., 2015) which is consonant with reports that testosterone reactivity is associated with task enjoyment (e.g., Mehta et al., 2015b). Although the relationship between testosterone and competitive behavior is bidirectional, prior work justifies the prediction that testosterone reactivity is a driving force underlying competitive striving.

In line with previous research about the role of social context in moderating testosterone's effect on behavior (Carré and Archer, 2018), a particularly salient aspect of the competition environment is the physical presence of an opponent or opponents. While models about the dynamic relationship between testosterone and competition (e.g., the challenge hypothesis) typically assume that emergence of this relationship requires an actual social *encounter*, it is unclear whether this is indeed the case. That is, the physical presence of an opponent could motivate competitive efforts and may even be an essential eliciting condition for hormone-behavior relationships in competitive contexts (Roney, 2016). Despite this notion, many laboratory studies of testosterone reactivity to competition merely give the illusion of the physical presence of an opponent such as telling the participant that a competitor is in a nearby room or showing an avatar image of a person while the 'competitor' actions are computer generated (for review, Casto and Edwards, 2016a). It is possible that this design feature inadvertently eliminates elements of the social context provided by the physical presence of an opponent that contribute to testosterone reactivity and competitive motivation, a prediction that has not been previously tested and that we test in this research.

Another notable omission from prior research regarding social context is the intervening role of group membership and the social presence of opponent groups, a context that is likely to reflect the intergroup condition under which testosterone mechanisms for regulating competitive behavior evolved. For social species including humans and some non-human primates, contests for status often take place within the context of social groups where placement among the social hierarchy is at stake (Cummins, 2006; Hill et al., 2008; Sapolsky, 2005; Zink et al., 2008). Further, between-group dominance contests – coalitional competitions – are common among human and non-human primate species (Crofoot and Wrangham, 2010). In these instances, group membership is likely to influence testosterone reactivity to competition and competitive behavior, as members of groups must balance dominance striving with the more cooperative behavior required for within-group coalition formation and maintenance (Diekhof et al., 2014; Flinn et al., 2012; Reimers and Diekhof, 2015; Tauer and Harackiewicz, 2004). This prediction is supported by a few studies that have found that, among men, testosterone reactivity to competition is affected by whether the contest is within or between group, with attenuated responses found for the former (Wagner et al., 2002, Oxford et al., 2010, Flinn et al., 2012; see Mehta et al., 2009 for similar effects with baseline testosterone). Moreover, in between-group competitions, men who ranked the highest among their group showed a greater testosterone increase over the course of competition, but only if their group won (Oxford et al., 2010). Although never before tested in the laboratory, the physical presence of a competitor group could effectively shift focus from within-group status conflict (beating one's own groupmates) to between-group status conflict (beating members of the other group), potentially altering the ratio of dominance/cooperativeness required for success and related testosterone reactivity.

The present research was designed to explore the relationship between individual differences in testosterone reactivity to competition and competitive persistence expressed during that competition. In two studies, participants competed in the *competitive will task*, in which performance was determined by the level of endurance a participant expressed during a weight-holding contest for time. Additionally, we experimentally manipulated the social presence of one or more opponents. Although the task was 'physical' in that it involved holding a weight, there was undoubtedly a strong psychological component in that a participant had to endure substantial discomfort to outcompete others. To validate task performance as a representation of psychological motivation, we provide evidence in the present research for a positive association between performance time and self-reported individual differences in competitiveness, dominance motivation, and task-specific motivation. Additionally, we show that physical qualities associated with strength (i.e., height, weight, body mass index) do not correlate with performance and further, that the relationship between the psychological factors discussed above and performance remains after controlling for height, weight, and body mass index. Combined, these analyses suggest that trait-level characteristics related to status motivation represent underlying psychological motivations that are expressed behaviorally, at least in part, as competitive endurance above and beyond physical strength. Critically, in this task, all participants competed against an unknown set of other participants for a small monetary grand prize given to those who performed the best overall (distributed after all subjects participated). Thus, we expected that when an opponent or opponents were present, shifts in relative status as a result of having performed better (a relative win) or worse (a relative loss) would occur during the competition as relative winners would continue competing against the unknown standard of 'best overall performance among all the participants.' Thus, generally, we predicted that testosterone reactivity across the task would interact with the relative win/loss to predict competitive endurance since the status gained for winners would occur before the end of the competition.

Specifically, Study 1 was designed to test the relationship between testosterone reactivity and competitive endurance in men and women competing in dyads as well competing individually against an unseen group of individuals. For participants who competed in dyads, we also tested the moderating effects of relative social victory or defeat compared to one's opponent. We predicted that testosterone reactivity would be positively associated with competitive endurance such that greater increases in testosterone would relate to relatively longer performance times and likewise, greater decreases in testosterone would relate to relatively shorter performance times. Further, for those who competed in the presence of an opponent, we predicted that the positive relationship between testosterone reactivity and competitive endurance would emerge only for those who experienced relative social victory within that context.

Study 2 was designed to examine the relationship between testosterone reactivity and competitive endurance among men and women competing in teams, one team against another, or competing against unseen opponent teams. As in Study 1, we also tested the moderating effects of relative performance-based rank among the other participants present. We predicted that larger increases in testosterone over the course of competition would be associated with longer competitive endurance while larger decreases in testosterone would be associated with shorter competitive endurance but only for those who experienced relative social victory (ranked highest among the group). Both studies included men and women so that participant sex could be tested as moderator of the relationship between testosterone reactivity and competitive behavior. Although prior research, discussed above, would suggest that this relationship should only emerge among men (within specific contexts), with substantially less prior research on women, this prediction was made with the caveat that little is known about how these variables should relate in women (Casto and Prasad, 2017).

2. Study 1 method

2.1. Participants

A sample of 190 undergraduates (131 women and 59 men, with a mean age of 19 years, SD = 1.1, range = 18 to 25) from Emory University participated in the study. Participants were recruited from the psychology department subject pool composed of undergraduates enrolled in either of two introductory psychology courses, each of which has a research participation option as a condition for satisfactory completion of the course. To minimize potential cultural influences, only U.S. citizens whose native language was English were permitted to sign up for the study. The study was approved by the university's Institutional Review Board (IRB).

2.2. Competitive will task

A physical task was employed to determine individual differences in competitive endurance. Participants held a weight (a common dumbbell used for resistance training, 1 lb. for women, 2 lb. for men) at arm's length and shoulder height for as long as they felt they could in competition against other participants. The weight differential between men and women was decided based on pilot studies generating equivalent mean performance times for women and men with a 1:2 weight ratio. Whether competing individually or in dyads, participants were told "The competition has to do with who has the most competitive will – who can endure the discomfort of holding up their arm the longest in order to attempt to be a winner." Participants' shoulder height was marked with a line on an index card taped to the wall and each participant was instructed to hold their arm at that height, dropping it once they "no longer wished to compete or could no longer physically keep their arm above the line, whichever came first." Performance time was recorded and revealed (by showing the timer) to participants only after dropping their arm to signal the end to their competition. Participants were stopped by the experimenter if they reached the 13-minute maximum (mean performance time was 4 min, SD = 1 min and 15 s).

Participants were informed that a $20 cash prize would be offered to the one male and female participant[1] who held their arm up the longest of all the other men and women participants who participated during that semester (data was collected across two semesters). Regardless of the presence or absence of an opponent, all participants were competing against each other for the same cash prize. For those competing in dyads, relative "winners" and "losers" were determined according to who dropped his or her arm first. However, because the competition was for an overall prize, winners could continue to compete against unknown others for the best possible performance and resulting cash reward. Participants were not given any reference times for other participants' performances or any feedback about how well how their performance ranked overall. Prize winners were privately contacted at the end of the semester via email.

"Performance" in this task was operationalized as the time in seconds that a participant held up his or her arm before quitting the contest. For participants who competed in dyads, a second outcome variable, performance time over or under one's partner, was created to assess the relationship between testosterone reactivity and relative performance. This variable was calculated by subtracting the partner's time from each participants' total performance time resulting in positive values for relative winners and negative values for relative losers. This second outcome measure allowed us to test whether testosterone reactivity was particularly likely to predict post-victory competitive behavior (in line with previous research, e.g., Carré et al., 2013; Mehta et al., 2015b; Trainor et al., 2004).

2.2.1. Construct validation

We used this task because a similar physical endurance task was employed by Crust and Clough (2005) to provide criterion validity for a measure of mental toughness, a multidimensional concept from sport psychology having to do with competitive confidence, resilience, persistence, and control. Mental toughness is considered to be one of the most important psychological predictors of competitive success (Crust, 2007). In Crust and Clough (2005), total mental toughness score was positively related to "weight-holding endurance" measured in units of time ($r = 0.34$) (p. 193). To provide additional evidence of validity for the competitive will task, participants in the present study completed a series of questionnaires designed to determine individual differences in constructs related to status motivation – competitiveness (Competitiveness Index – CI, Houston et al., 2002), social power (Power and Dominance System Scales – PDSS, Murphy, 2016), social achievement goal orientation (Social Achievement Goal Orientation Survey, revised – SAGOS, Horst et al., 2007), and academic achievement motivation (Academic Motivation Scale – AMS, Vallerand et al., 1992) – which we correlated with task performance.

Among the 190 participants in this study who completed these measures and participated in the competitive will task, performance was significantly and positively related to subscales for CI enjoys competition ($r = 0.22$, $p = .002$), PDSS dominance motivation ($r = 0.21$, $p = .004$), and AMS intrinsic motivation ($r = 0.23$, $p = .002$) demonstrating good convergent validity (full correlation matrix shown in supplementary data). Task performance was not significantly related to CI contentiousness, PDSS felt power, PDSS attention to power cues, AMS extrinsic motivation, AMS amotivation, or any of the SAGOS scales (performance and mastery approach and avoidance in social goals). Additional competitiveness questions administered alongside these scales, "I do not give up easily in competition" ($r = 0.23$, $p = .001$) and "I am a competitive person" ($r = 0.19$, $p = .009$) also demonstrated a significant positive correlation with performance. Finally, task performance also significantly and positively correlated with responses to the task-specific pre-competition question "How motivated are you to win?" ($r = 0.25$, $p = .001$) and post-competition questions "I tried really hard to win the competition" ($r = 0.45$, $p < .001$) and "I really wanted to win the competition" ($r = 0.32$, $p < .001$). When separating by sex, observed relationships were generally the same across men and women, but correlation coefficients were consistently larger among women participants. All p-values for each correlation were considered significant after adjusting the "statistical significance" set point for alpha based on false detection rate from conducting multiple tests (Benjamini and Hochberg, 1995).

Given the potentially confounding nature of competitive endurance and physical strength in the competitive will task, we tested the relationship between task performance and physical qualities associated with strength (height, weight, and body mass index). Additionally, we tested the relationship between the psychological characteristics associated with status motivation (discussed above) and performance after controlling for height, weight, and body mass index (BMI). Overall, and separately in men and women, physical qualities associated with strength were not related to performance in the competitive will task ($r = -.07–.005$, n.s.) and did not explain the positive associations between performance and the psychological factors previously discussed (full results shown in supplemental data).

2.3. Procedure

Men and women were randomly assigned to either be the only participant in the room or one of two tested at the same time. Dyads were randomly assigned so that there was a combination of same- and mixed-sex pairs.[2] Upon arrival, participants read and signed a consent form and received a brief introduction to the study (i.e., that the study was about the relationships among hormones, competition, and social context). The same female experimenter walked each participant through the study. After consent, they completed questionnaires for approximately 15 min, then provided their first (baseline) saliva sample. Next, the experimenter gave specific instructions about the competitive will task and potential for prize money (see description above). Participants then competed in the task. After the competition, participants provided their immediate post-competition saliva sample (the time elapsed from the baseline sample to the immediate post-competition sample was different for each participant, depending on their performance time in the task). They then completed an unrelated questionnaire designed to serve as filler task (indicating behaviors that

[1] Separate cash prizes were given to men and women in Study #1 in an attempt to reduce performance effects due to socialized factors (e.g., perceptions of physical inferiority and backlash for competitive behavior) in mixed-sex dyads. "Opponent" in this research is someone else competing at the same time, a person who the participant can reference when making relative judgements about status position, i.e., relative winner vs. loser. In Study #2, discussed below, cash prizes were not separate for men and women because of the larger number of participants competing at the same time.

[2] Although samples sizes of experimental groups were not large enough for adequately powered analyses based on sex of one's competitor for dyads (Men who competed against a woman $N = 26$; Men who competed against a man $N = 16$; Women who competed against a man $N = 26$; Women who competed against a woman $N = 58$), exploratory analyses revealed no significant differences in testosterone reactivity, task performance, or their relationship based on whether one's opponent was of the same or opposite sex (supplemental data).

the participant has ever engaged in and which they typically express themselves during interactions with others) for 15 min between the end of competition and the final saliva sample (delayed post-competition sample).

2.4. Saliva samples and hormone assay

Participants were instructed not to eat, exercise, smoke, or consume caffeinated beverages or food within the hour prior to arriving at the laboratory for the study. Saliva samples were obtained prior to, immediately after, and 15 min after competing in the competitive will task. Immediately before providing a saliva sample, each participant rinsed his/her mouth with water. Approximately 1.5–1.8 ml of saliva was collected for each sample via passive drool into 2 ml plastic vials using plastic saliva collection aids (Salimetrics). Collection time varied according to the individual, but typically took between 3 and 5 min. Samples were stored at −20 °C initially and then transferred to a −80 °C freezer within several hours. Samples were assayed in duplicate for testosterone[3] on a single thaw by the Emory Clinical Translational Research Laboratory (Atlanta, Georgia) using competitive enzyme immunoassay kits from Salimetrics (State College, PA). Inter-assay coefficients of variation for low and high controls were 18.0 and 6.2%. All participants were tested in the afternoon between 2 and 4 PM to standardize collection time with reference to normal diurnal fluctuation in testosterone levels.

2.5. Testosterone reactivity

Testosterone concentrations for two women participants were not obtained due to insufficient saliva provided during the collection periods leaving a total sample size for analyses involving testosterone reactivity of 188 (men $N = 59$; women $N = 129$). In men, testosterone levels were normally distributed. In women, testosterone levels at all three collection points were positively skewed. Outlier participants, i.e., individuals whose testosterone levels were more than three standard deviations higher or lower than the mean for their sex, were identified (a common SD benchmark for identifying outliers in hormone analyses, Pollet and van der Meij, 2017). Testosterone levels for these individuals (three women and one man) were replaced with the mean plus or minus three standard deviations, effectively replacing outlier values with high and low values that maintain relative position among other data points while reducing skewness (Erceg-Hurn and Mirosevich, 2008).

Competition-related testosterone reactivity was calculated as the percent change in hormone level from pre-competition baseline (ΔT%). Values for this variable are represented in magnitude, absolute percent change, and direction of change resulting in both negative and positive values. Because hormones were sampled three times (immediately before competition, immediately after, and 15 min after competition), there are two time references for expressing change associated with the competition – from before to immediately after and from before to 15 min after. Laboratory studies of hormones and competition typically derive hormone-behavior relationships from saliva samples obtained 10–15 min following competition (e.g., Mehta and Josephs, 2006; Schultheiss et al., 2005) on the assumption that a hormone value for a saliva sample obtained 15 min after the end of competition reflects the blood level of hormone during competition. Consonant with this precedent, all results presented in this study regarding testosterone change refer to the relative change from baseline to 15 min after competition. However, there is some evidence for more rapid steroid hormone diffusion from blood into saliva (for review, Casto and Edwards, 2016a). Change values for saliva samples obtained immediately after the end of competition are presented in the supplemental results. For ΔT% used in subsequent analyses (calculated from before competition to 15 min after), two additional outlier participants (both women) whose testosterone *change* score was more than three standard deviations higher or lower than the mean were identified. Testosterone levels for these individuals were replaced with the mean plus or minus three standard deviations depending on the direction of change for the original value. As a robustness check, hypotheses were also tested in relation to two other common ways of expressing testosterone change in the literature: the unstandardized residual change in testosterone from pre-to-post competition (Tres) and area under the curve with respect to increase (AUCi, an indicator of the intensity of hormone change over time, Pruessner et al., 2003). For both of these additional metrics of change, values are represented in terms of magnitude and direction of change meaning there will be a range of negative to positive values. For AUCi, when a participant's testosterone levels decrease over time, the resulting value “must be regarded as an ‘index of decrease’ rather than an area (Pruessner et al., 2003, p.921)”.

2.6. Hormonal contraceptive use

Following consent, each female participant provided information regarding contraceptive use. Specifically, women were asked to circle “yes” or “no” to four questions: “Are you currently using an oral contraceptive?”; “Are you currently using an injected or patch-delivered hormone-based contraceptive?”; “Are you currently using an intrauterine device (IUD)?”; and “Are you currently using a Nuvaring?” Of the 131 women participating in this study, 66 reported that they were not using any form of contraception, 55 reported using an oral contraceptive, three a hormone-based injection or patch, six an IUD, and one reported using a Nuvaring.

Women using oral contraceptives typically have lower basal levels of testosterone than non-users (e.g. Edwards and O'Neal, 2009; Wiegratz et al., 1995; Zimmerman et al., 2014), but do not appear different from non-users in competition-related testosterone reactivity (Casto and Edwards, 2016a; Edwards and O'Neal, 2009). Although not the main purpose of the study, among women participants, hormonal contraceptive use (HC use; yes/no) was tested as an additional moderator of the relationship between testosterone reactivity and performance. For the purposes of analysis, oral contraceptive and patch users were combined into a single category of hormonal contraception users ($N = 58$) for comparison to women not using any form of hormone contraception ($N = 66$). IUD ($N = 6$) and Nuvaring ($N = 1$) users were excluded from analyses by HC use due to an incomplete understanding of the peripheral hormone exposure from these contraception methods and the small sample size of these groups.[4] These seven participants were not excluded from main analyses.

3. Study 1 results

Descriptive statistics and correlations for the principal variables of the study are shown separately for men and women in Table 1 as are between-sex statistical comparisons and comparisons between women hormonal contraceptive users and non-users. As expected, men had significantly higher testosterone levels than women. Men and women did not significantly differ in testosterone reactivity to competition whether measured as ΔT%, unstandardized residual, or AUCi. Women using hormonal contraceptives had significantly lower salivary testosterone levels relative to women not using any form of hormonal contraception, but users and non-users did not significantly differ in testosterone reactivity to competition (ΔT%, unstandardized residual, or

[3] This research was a part of a larger study that also included measurement of cortisol levels. Only testosterone levels are included for analysis in the present study.

[4] Because testosterone levels for two women participants are missing, the final sample size for analyses involving HC use and testosterone reactivity is 122.

Table 1
Study 1 main variable descriptive statistics, correlations, and mean comparisons.

	M(SD)	CI LB	CI UB	T2	Metrics of T reactivity			Performance
					ΔT%	Tres	AUCi	
Women (N = 129)								
T1 (pg/ml)	29.82 (15.68)	27.09	32.55	0.88**	−0.14	−0.06	−0.30**	0.21*
T2 (pg/ml)	26.77 (15.57)	24.06	29.48	–	0.30**	0.43**	0.14	0.25**
ΔT%	−8.62 (26.85)	−13.30	−3.95		–	0.88**	0.74**	0.14
Tres	−1.19 (7.48)	−2.50	0.11			–	0.85**	0.12
AUCi	−58.44 (119.38)	−79.24	−37.64				–	0.06
Performance	238.0 (80.32)	224.0	252.0					–
Men (N = 59)								
T1 (pg/ml)	92.87 (32.84)	84.31	101.4	0.83**	−0.34**	−0.27*	−0.40**	0.04
T2 (pg/ml)	87.28 (30.06)	79.44	95.11	–	0.19	0.32*	0.09	0.16
ΔT%	−3.41 (22.03)	−9.15	2.33		–	0.91**	0.77**	0.20
Tres	2.61 (17.45)	−1.94	7.15			–	0.82**	0.20
AUCi	−69.72 (297.6)	−147.3	7.85				–	0.16
Performance	251.5 (62.08)	235.3	267.7					–

	$Mean_{diff}$	CI_{diff} LB	CI_{diff} UB	t	df	p	d
Difference between men and women							
T1 (pg/ml)	63.05	54.09	72.00	14.03	186	< .001	2.06
T2 (pg/ml)	60.51	52.24	68.78	14.59	186	< .001	2.14
ΔT%	5.22	−2.67	13.11	1.30	186	.194	0.19
Tres	3.80	−0.921	8.52	1.61	186	.113	0.24
AUCi	−11.28	−91.43	68.86	−0.281	186	.780	0.04
Performance	14.35	−6.80	35.51	1.34	188	.182	0.20
Difference between HC users and non-users							
T1 (pg/ml)	16.03	11.21	20.84	6.60	120	< .001	1.20
T2 (pg/ml)	14.90	10.00	19.03	6.03	120	< .001	1.10
ΔT%	−0.06	−9.79	9.67	−0.012	120	.990	< 0.00
Tres	0.485	−2.25	3.22	0.351	120	.726	0.06
AUCi	−36.74	−79.74	5.49	−1.69	120	.093	0.31
Performance	29.09	1.07	57.12	2.06	122	.042	0.37

T1 = baseline sample, T2 = 15 min post-competition sample, ΔT% = % change in testosterone, Tres = unstandardized residual testosterone change, AUCi = area under the curve increasing, M = mean, SD = standard deviation, CI = confidence interval, LB = lower bound, UB = upper bound, d = Cohen's d effect size.

* $p < .05$.

** $p < .01$

AUCi). ΔT%, Tres, and AUCi were highly positively correlated. Absolute testosterone levels before and after competition were highly conserved across individuals (T1 to T2 correlation in Table 1).

There were no significant differences in task performance between those who competed individually (M = 242.5, SD = 79.2) and those who competed in the presence of an opponent (M = 241.1, SD = 73.5), $t(188) = 0.12$, $p = .905$. Among women, hormonal contraceptive users showed significantly lower performance on average (see magnitude of difference and Cohen's d in Table 1). For those who competed in dyads, performance was significantly and positively correlated with the performance of the other member of the dyad ($r = 0.42$, $p < .001$). When separating men and women, this relationship was weaker and non-significant among men, while remaining quite strong among women (men: $r = 0.27$, $p = .083$; women: $r = 0.46$, $p < .001$), although the difference between the correlation coefficients was not significant ($z = -1.15$, $p = .25$). As shown in Table 1, testosterone levels and metrics of reactivity were positively correlated with performance among men and women, but only the relationship between absolute testosterone levels and performance in women was significant, whether at baseline or after competition.

3.1. Testosterone reactivity and task performance

On average, across conditions (i.e., competing individually or with an opponent) testosterone levels decreased slightly in men and women from before to after competition, although there were large individual differences in both the magnitude and direction of testosterone change (Table 1). There were no significant differences in testosterone reactivity by condition (overall or by sex). Further, for dyads (i.e., participants competing with an opponent present), there was no significant difference in testosterone reactivity for those who won compared to those who lost (overall or by sex). For more detail, see the supplemental results.

A hierarchical regression analysis was conducted to test the relationship between testosterone reactivity and performance. Step 1 included condition, sex, and ΔT%, step 2 included the interaction of condition by ΔT% and sex by ΔT%, and step 3 included the three-way interaction between condition, sex, and ΔT%. Results revealed a significant main effect (in Step 1) for ΔT% in predicting performance ($N = 188$, $b = 0.46$, $SE = 0.22$, $t = 2.12$, $p = .035$, $95\%CI = 0.03–0.88$, $R^2_{partial} = 0.02$), but no other significant main effects or interactions. This main finding was in the same direction when using the unstandardized residual for testosterone and when testosterone change was represented as AUCi, although the magnitude of the relationship was reduced (supplemental results).

In women participants, a follow-up hierarchical regression analysis was conducted in which step 1 included condition, HC use, and ΔT%, step 2 included the interaction of condition by ΔT% and HC use by ΔT%, and step 3 included the three-way interaction between condition, HC use, and ΔT%. Results showed that the relationship between ΔT% and performance previously demonstrated among the combined sample of women and men was supported among this sample of just women ($N = 122$, $b = 0.47$, $SE = 0.26$, $t = 1.80$, $p = .075$, $95\%CI = -0.05–0.99$, $R^2_{partial} = 0.03$), although no longer statistically significant. Results also revealed a significant main effect (in step 1) for contraceptive use on performance ($N = 122$, $b = -34.61$, $SE = 14.61$,

$t = -2.37$, $p = .019$, 95%$CI = -63.54–5.68$, $r^2_{partial} = 0.05$), such that HC users had lower performance times than non-users, but no other significant main effects or interactions. Despite the absence of an interaction between ΔT% and HC use, the simple correlation between ΔT% and performance was stronger in users compared to non-users ($R^2 = 0.07$ vs. $R^2 < 0.01$). These results were supported when using the unstandardized residual for testosterone and when testosterone change was represented as AUCi (supplemental results).

3.1.1. *Testing relative win/loss as a moderator*

Winning and losing in the task was determined by the total amount of time spent competing– winners endured longer than their losing counterpart. However, because winning and losing was only in reference to the other person's performance who was present at the time of testing, winning was not always associated with better absolute performance overall and losing was not always associated with a worse absolute performance overall. As a result, winning/losing was significantly, but not strongly correlated with absolute performance ($r = 0.39$, $p < .001$). Thus, although relative win/loss and performance are overlapping variables, the relative status shift during competition is a feature of the competitive environment that is functionally different than absolute performance. Among the men and women participants who competed in the presence of an opponent ($N = 126$), a hierarchical regression analysis was conducted in which step 1 included relative win/loss, sex, and ΔT%, step 2 included the interaction of win/loss by ΔT% and sex by ΔT%, and step 3 included the three-way interaction between win/loss, sex, and ΔT%. Results revealed a significant 3-way interaction (in step 3) between win/loss, sex, and ΔT% ($F_{change}(1,119) = 6.80$, $p = .010$, $R^2_{change} = 0.04$; $b = -2.99$, $SE = 1.15$, $t = -2.61$, $p = .010$, 95%$CI = -5.25–0.72$). As shown in Fig. 1, ΔT% was positively correlated with performance only for men who won ($b = 1.24$, $SE = 0.58$, $t = 2.13$, $p = .035$, 95%$CI = 0.09–2.39$) and women who lost ($b = 0.79$, $SE = 0.34$, $t = 2.29$, $p = .024$, 95%$CI = 0.11–1.47$). This three-way interaction was supported when using the unstandardized residual for testosterone and when testosterone change was represented as AUCi (supplemental data). Additionally, although samples sizes were uneven across groups and too small for adequately powered tests by the sex of the competitor (see Footnote 2 for further information), exploratory analysis of this interaction revealed that the fairly strong positive association between testosterone reactivity and performance among women who lost was apparent regardless of whether she lost to a man or woman (competed against a woman, $N = 29$: $R^2 = 0.14$; competed against a man: $N = 16$: $R^2 = 0.13$). Likewise, the fairly strong positive association between testosterone reactivity and performance among men who won was apparent regardless of whether he defeated a man or woman (competed against a woman, $N = 16$: $R^2 = 0.36$; competed against a man: $N = 8$: $R^2 = 0.49$).

Due to the previously discussed positive correlation between an individual's performance and the performance of the opponent who was present during competition, the above analysis was repeated with the opponent's performance time included as a covariate. The same three-way interaction between win/loss, sex, and ΔT% was found after controlling for the opponent's performance (supplemental results).

3.1.2. *Testing "time over opponent" as a special case dependent variable*

For winners in the dyad condition, the shift in relative social status occurred while they were still competing (i.e., they were aware of when the loser dropped his or her arm and could continue on as long after as possible). Thus, for these individuals, testosterone change during the competition could have, over the absolute performance time, uniquely predicted the amount of time they endured after knowing that they were a relative winner. There were individual differences in how long a winner continued to compete after relative status was determined ($N = 63$, in seconds: $M = 60$; $SD = 62$; min = 2, max = 320). As an exploratory analysis, testosterone reactivity for winners was regressed on "time over opponent" (performance time minus their opponent's performance time). No significant effects emerged using any of the measures of testosterone reactivity (supplemental results).

4. Study 1 discussion

Overall, results of Study 1 demonstrate a positive but weak relationship between testosterone reactivity and task performance in men and women, independent of whether one was competing alone or in the physical presence of an opponent. Specifically, because testosterone reactivity essentially centered around zero, those who increased in testosterone endured longer relative to those whose testosterone decreased. For those who competed in the physical presence of an opponent, and thus, were exposed to shifts in relative social status, this positive association emerged only among men who won and women who lost relative to their opponent.

The presence or absence of an opponent had no clear effect on testosterone reactivity, performance, or the relationship between

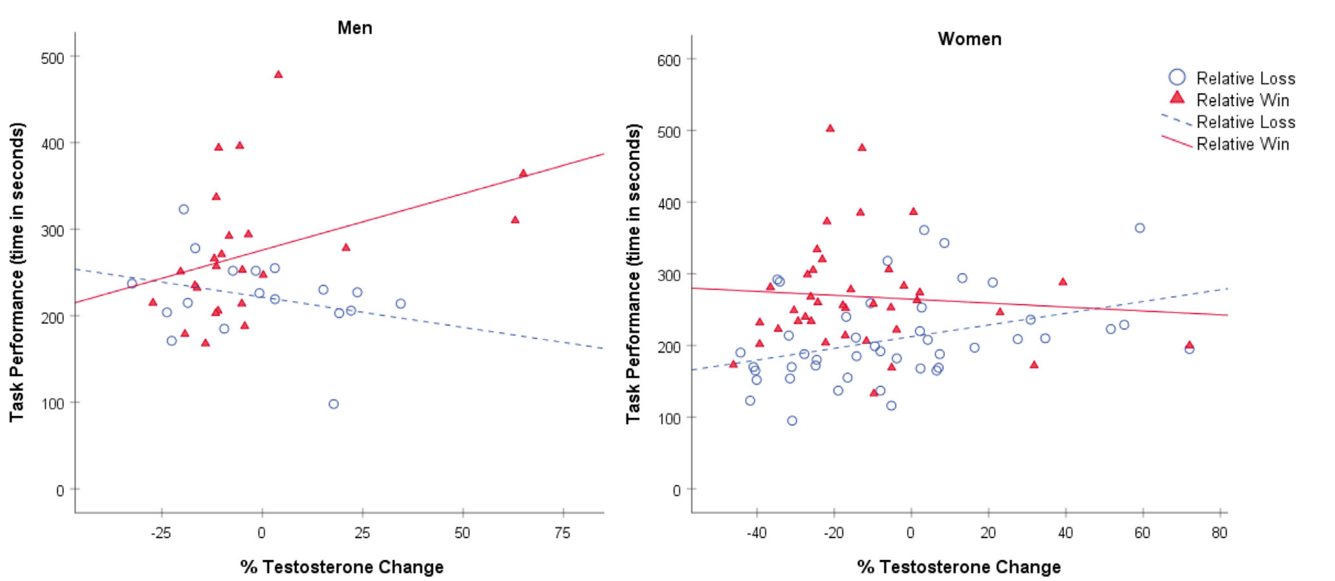

Fig. 1. Correlation between testosterone reactivity and performance. Separate graphs for men (win: $R^2 = 0.15$, loss: $R^2 = 0.08$) and women (win: $R^2 < 0.01$, loss: $R^2 = 0.14$).

testosterone reactivity and performance. Although the presence of an opponent did afford the opportunity for shifts in relative status outcomes that produced differences in the direction and strength of the relationship between testosterone reactivity and performance (as discussed above), physical presence of a competitor alone does not appear to be an essential environmental condition for stimulating greater competitive effort, testosterone reactivity, or their coupling. Indeed, men and women who competed individually, in the absence of an opponent, also showed a positive testosterone reactivity-performance relationship.

Real-world competitions for status, resources, and mates occur within the context of relevant social groups. Although the presence of a single opponent was not sufficient to alter testosterone reactivity, performance, or the relationship between these two variables, the presence of a group and relevant competitor group may be a more ecologically valid test of social presence effects (Wagner et al., 2002; Oxford et al., 2010; Flinn et al., 2012; Mehta et al., 2009). Competition among groups provides an opportunity for individuals to gain status both within and across groups and reflects a more realistic coalitional nature of competition. Thus, in a follow-up study, we test the relationship between testosterone reactivity and performance among men and women participants competing in teams, with and without the presence of a competitor team, a context in which status *rank* is established among those present based on relative performance in the competitive will task.

5. Study 2 method

5.1. Participants

A sample of 208 undergraduates (with a mean age of 20 years, $SD = 3.0$, range = 18–42) from the University of Oregon participated in the study. Seventy-nine participants identified themselves as assigned male at birth. Three of the 129 participants identifying themselves as assigned female at birth reported their current gender identity as transgender and reported using hormonal therapy. These three individuals were excluded from all analyses. Two individuals assigned female at birth reported their current gender identity as genderqueer, but had testosterone levels typical of females and were not taking hormonal therapy – these participants were combined with the women for analyses by "sex". This gives a sample size of 205 participants (79 men and 126 women). Ethnicity was predominantly European/European-American (58%) with relatively large subsets of Hispanic/Latino (17%) and Asian/Asian-American (14%). Participants were recruited from the psychology department subject pool composed of undergraduates enrolled in introductory psychology and linguistics courses, each of which has a research participation option as a condition for the satisfactory completion of the course. The study was approved by the university's Research Compliances Services.

5.2. Competitive will task

The same competitive task from Study 1 was employed in Study 2; participants held a weight (a common dumbbell used for resistance training, 1 lb. for women, 2 lb. for men) at arm's length and shoulder height for as long as they felt they could in competition against other participants. The incentive scheme was altered for the group setting to promote task investment at both the individual and group level. The top five individuals of all participants from each academic semester would receive a cash prize based on place: 1st = $50, 2nd = $40, 3rd = $30, 4th = $20, 5th = $10. Additionally, individuals were assigned to teams (details below) to facilitate our operationalization of competing in the presence or absence of others. Each team was in competition against all other teams for an overall grand prize, 1st = $200, 2nd = $150, 3rd = $100, given to the top three teams whose average score of all its members was the longest of all other teams competing in the same academic semester (and split evenly among team members). Importantly, regardless of the number of competitors and teams present at any one testing session, all participants were competing against each other for the same prize (to the five individuals and three teams who performed the best overall) and respective winners were not contacted until the end of the academic term to collect their prize. Data collection took place over the course of two semesters, so there were two batches of prize money winners. This incentive scheme was necessary to standardize the competition across conditions. That is, even if a participant held their arm up longer than others within their testing session, they continued to compete against the unknown others for the best possible performance to count towards the overall rankings.

As in Study 1, relative status rank among the participants present during each testing session (resulting from performance in the competitive will task) was an available social context factor. "Group rank" was determined for all participants who shared the same testing session by categorical separation into subgroups: those who finished in the top 25%, middle 25–75%, and the bottom 25% of the participants who were present.

5.2.1. Additional construct validation

To provide additional evidence of validity for the competitive will task, participants completed a series of questionnaires designed to determine individual differences in constructs related to status motivation – competitiveness (Competitiveness Orientation Measure – COM, Newby and Klein, 2014), social power (Power and Dominance System Scales – PDSS, Murphy, 2016), dominance and prestige (Cheng et al., 2010), grit (Duckworth and Quinn, 2009), and academic achievement motivation (Academic Motivation Scale – AMS, Vallerand et al., 1992). Task performance was significantly and positively related to all subscales for competitiveness orientation (general: $r = 0.31$, $p < .001$; dominant: $r = 0.22$, $p = .002$; competitive affectivity: $r = 0.24$, $p = .002$; personal enhancement: $r = 0.32$, $p < .001$), prestige ($r = 0.16$, $p = .024$), grit ($r = 0.20$, $p = .005$), PDSS dominance motivation ($r = 0.25$, $p < .001$), and AMS intrinsic motivation ($r = 0.17$, $p = .015$) demonstrating good convergent validity (full correlation matrix shown in supplementary data). Performance was not significantly correlated to dominance (as measured by Cheng et al., 2010), PDSS felt power, PDSS attention to power cues, AMS extrinsic motivation, or AMS amotivation. Additionally, participants completed task-specific items related to motivation following competition ("I tried really hard to win the competition," and "I really wanted to win the competition"). Task performance was significantly and positively correlated with responses to both items ($r = 0.52$, $p < .001$ and $r = 0.51$, $p < .001$, respectively). Correlations were generally the same among both men and women. All p-values for each correlation were considered significant after adjusting the "statistical significance" set point for alpha based on false detection rate from conducting multiple tests (Benjamini and Hochberg, 1995). Consonant with analyses from Study 1, physical qualities associated with strength (i.e., height, weight, BMI) were not related to performance in the competitive will task and, did not explain the positive associations between performance and the psychological factors previously discussed (results shown in supplemental data).

5.3. Procedure

Participants arrived to the laboratory in mixed-sex groups of three to eight people. Two experimenters, one male and one female, were present for all testing sessions. Upon arrival, participants read and signed a consent form and received a brief explanation of the study (i.e., that the study was about the relationships among personality, social context, competition, and hormones). After consent, participants completed questionnaires in private testing rooms for approximately 25 min and then, afterward, provided their first saliva sample. For groups of three to five individuals, the experimenter told them they would be competing as a team in subsequent tasks (specific instructions to follow) and then asked them to come up with a team name for recording purposes. If more than six participants were present, the groups were randomly split into two teams and asked to stand on opposite sides of the room. The experimenter then told each group that they would be competing as a team in the following tasks and asked them to come up with a team name for recording purposes. There were no testing sessions held with fewer than three participants. Next, the experimenter gave specific instructions about the competition and the prize money structure (discussed above). Participants were reminded that they were competing for an overall individual and team prize and told that they were free to talk and interact during the competition. On the "Begin" command each participant raised their arm to initiate the competitive will task. Once participants dropped their arms to signal end to their competition, their individual timer was stopped and they were instructed to return to their individual testing rooms to complete a post-competition survey. Participants were retrieved from their private room 10 min later to give the second saliva sample. Because participants finished the task at different times, beginning the second saliva sample was tapered based on finish place to ensure that each participant had approximately 10 min between the end of their competition and the start of the saliva sample (i.e., the time elapsed from the baseline sample to the post-competition sample was different for each participant, depending on their performance time in the task). For purposes beyond the scope of the present study, participants next completed a team-based cooperative task, followed by a third saliva sample, and a set of questionnaires regarding group identification.

The participants did not know each other. They were requested not to sign up to participate with anyone they knew and this was confirmed upon arrival to the laboratory. The ecological validity of status among groups of people who do not interact outside of the laboratory is a concern for this kind of research. However, this paradigm is consistent with psychological research that employs a "minimal groups design" (Tajfel et al., 1971; Otten, 2016) which is effective for altering perceptions of in-group identity and belonging.

5.4. Saliva samples and hormone assay

Saliva samples were collected using the same procedure as Study 1 at two time points, immediately before and 10 min after competition. Samples were stored at −20 °C initially and then transferred to a −80 °C freezer. Samples were assayed for testosterone[5] by Dresden Lab Service using IBL chemiluminescence immunoassay kits with 20% of samples tested in duplicate. CV% for low and high controls were 4.86% and 4.29%, respectively and intra-assay CV was 4.5%.

5.5. Testosterone reactivity

Testosterone concentrations for five women participants and two men participants were not obtained due to insufficient or contaminated saliva provided during the collection periods leaving a total sample size for analyses involving testosterone of 198 (men $N = 77$; women $N = 121$). In men and women, testosterone levels at both points were positively skewed. Following the same procedure for correcting outliers discussed in Study 1, five individuals (three women and two men) were identified as outliers and testosterone levels for these individuals were replaced with the mean plus or minus three standard deviations, effectively reducing skewness. As in Study 1, testosterone reactivity was calculated as the percent change from before to 10 min after. Four additional outlier participants' (2 women, 2 men) testosterone levels were replaced with the mean plus or minus three standard deviations depending on the direction of change for the original value. As in Study 1, hypotheses were also tested as a robustness check using two additional metrics of testosterone reactivity, Tres and AUCi.

5.6. Hormonal contraceptive use

Following consent, each participant provided information regarding contraceptive use. Specifically, participants were asked to respond "yes" or "no" to the question "Are you taking any form of hormonal contraceptive/birth control (e.g., pill, patch, injection)?" No men answered yes to this question. Among women, 54% of participants said "Yes" and were then asked to indicate "What kind of hormonal contraception are you taking?" with options for oral contraceptive pill, hormonal patch, hormonal injection, IUD, and hormonal implant. Of the 126 females participating in this study, 58 reported that they were not using any form of contraception, 44 reported using a pill, 12 an IUD, 8 a hormonal-based implant, and 4 a hormone-based injection or patch.

As in Study 1, among women, hormonal contraceptive use (HC use; yes/no) was tested as a moderator of the relationship between testosterone reactivity and performance. For the purposes of analysis, oral contraceptive pill and hormonal patch, injection, and implant users were combined into a single category of hormonal contraception users ($N = 56$) for comparison to women not using any form of hormone contraception ($N = 58$). The twelve IUD users were excluded from analyses involving HC use as an experimental variable due to incomplete understanding of the peripheral hormone exposure from these contraception methods and the small sample size of this group.[6] These participants were not excluded from main analyses.

6. Study 2 results

Descriptive statistics and correlations for the main study variables for men and women are shown in Table 2. As with Study 1, salivary testosterone levels before and after competition were significantly higher for men compared to women. Men and women did not significantly differ in testosterone reactivity to competition (ΔT%, unstandardized residual, or AUCi). Women using hormonal contraceptives had significantly lower testosterone levels relative to women not using any form of hormonal contraception, although effects were small (Table 2). Users and non-users did not significantly differ in testosterone reactivity to competition (ΔT%, unstandardized residual, or AUCi). ΔT%, Tres, and AUCi were highly positively correlated.

Individuals who competed in the condition where another competitor team was present had significantly higher performance than those who competed without a competitor team present ($Mean_{diff} = 57.67$, $t(203) = -3.59$, $p < .001$, $d = 0.50$). As shown in Table 2, men had significantly higher performance on average than women (even with a 1 lb. higher weight differential). Among women, hormonal contraceptive users showed lower performance on average, but this effect was not significant. Task performance was significantly and positively correlated with the mean performance of the other competitors present for each testing session ($r = 0.210$, $p = .002$). When separating men and women, the relationship was weaker and not significant among men ($r = 0.11$, $p = .331$), but remained strong among women ($r = 0.32$, $p < .001$), although the difference between the correlation coefficients was not significant ($z = -1.48$, $p = .14$). As shown in Table 2, post-competition testosterone levels and metrics of reactivity were generally positively correlated with performance among men, but not women.

[5] This research was a part of a larger study that also included measurement of cortisol and DHEA-S levels. Only testosterone levels are included for analysis in the present study.

[6] Because testosterone levels for five women participants are missing, the final sample size for analyses involving HC use and testosterone reactivity is 109.

Table 2
Study 2 main variable descriptive statistics, correlations, and mean comparisons.

	M(SD)	CI LB	CI UB	T2	Metrics of T Reactivity			Performance
					ΔT%	Tres	AUCi	
Women (N = 121)								
T1 (pg/ml)	19.81 (14.70)	17.16	22.45	0.81**	−0.23**	−0.38**	−0.02	−0.13
T2 (pg/ml)	17.22 (13.23)	14.84	19.60	–	0.23*	0.23**	0.46**	−0.09
ΔT%	−6.91 (36.29)	−13.44	−0.377		–	0.75**	0.43**	0.07
Tres	−1.38 (8.43)	−2.90	0.139			–	0.76**	0.08
AUCi	−.781 (9.89)	−2.56	0.999				–	−0.01
Performance	269.7 (91.95)	253.2	286.3					–
Men (N = 77)								
T1 (pg/ml)	90.90 (39.41)	81.95	99.84	0.87**	−0.19	−0.13	−0.30**	0.04
T2 (pg/ml)	88.13 (40.68)	78.90	97.36	–	0.28*	0.35**	0.19	0.28*
ΔT%	−2.01 (21.20)	−6.92	2.71		–	0.93**	0.85**	0.44**
Tres	1.11 (15.70)	−2.45	4.68			–	0.88**	0.52**
AUCi	−1.74 (10.98)	−4.23	0.749				–	0.46**
Performance	302.9 (137.7)	271.7	334.2					–

	$Mean_{diff}$	CI_{diff} LB	CI_{diff} UB	t	df	p	d
Difference between men and women							
T1 (pg/ml)	71.09	61.78	80.40	15.17	196	< .001	2.17
T2 (pg/ml)	70.97	61.46	80.49	14.83	198	< .001	2.11
ΔT%	4.80	−3.26	12.87	1.18	196	.242	0.17
Tres	2.49	−1.37	6.35	1.28	196	.203	0.18
AUCi	−0.961	−4.01	2.08	−0.624	196	.534	0.09
Performance	30.48	−4.12	65.07	1.75	203	.084	0.25
Difference between HC users and non-users							
T1 (pg/ml)	7.23	1.59	12.87	2.54	107	.012	0.49
T2 (pg/ml)	6.31	1.33	11.29	2.51	109	.013	0.48
ΔT%	8.54	−5.22	22.29	1.23	107	.221	0.24
Tres	−0.514	−3.78	2.75	−0.312	107	.756	0.06
AUCi	−2.04	−5.98	1.89	−1.03	107	.305	0.20
Performance	29.89	−3.79	63.57	1.76	112	.081	0.33

T1 = baseline sample, T2 = 15 min post-competition sample, ΔT% = % change in testosterone, Tres = unstandardized residual testosterone change, AUCi = area under the curve increasing, M = mean, SD = standard deviation, CI = confidence interval, LB = lower bound, UB = upper bound, d = Cohen's d.
* p < .05.
** p < .01.

6.1. Testosterone reactivity and task performance

As in Study 1, in both men and women and across experimental condition, testosterone levels decreased on average from before to after competition, although the magnitude of this decrease was small and there were large individual differences in both the magnitude and direction of testosterone reactivity (Table 2). There were no significant differences in mean testosterone reactivity by experimental condition (whether analyzed overall or separately by sex) or by group rank category (overall or by sex). For more detail, see the supplemental results.

A hierarchical regression analysis was conducted to test the relationship between testosterone reactivity and performance. Step 1 included condition (presence or absence of a competitor team), sex, and ΔT%, step 2 included the interaction of condition by ΔT% and sex by ΔT%, and step 3 included the three-way interaction between condition, sex, and ΔT%. Results revealed a significant interaction (in step 2) for sex by ΔT% in predicting performance above and beyond sex, condition, and ΔT% alone ($N = 198$, $F_{change}(2,192) = 9.93$, $p < .001$, $R^2_{change} = 0.09$; $b = -2.94$, $SE = 0.66$, $t = -4.45$, $p < .001$, $CI = -4.24$–1.63). Simple slopes analysis revealed a significant positive relationship between testosterone reactivity and performance in men ($N = 77$, $b = 2.84$, $SE = 0.68$, $t = 4.21$, $p < .001$, $CI = 1.50$–4.18, $r^2_{\mathrm{partial}} = 0.19$), while there is no significant relationship in women ($N = 121$, $b = 0.19$, $SE = 0.23$, $t = 0.82$, $p = .417$, $CI = -0.27$–0.65, $r^2_{\mathrm{partial}} < 0.01$). This main finding was supported when using the unstandardized residual for testosterone, however, the interaction was weaker and the main effect for testosterone reactivity independent of sex explained the most variance in performance. Similarly, when testosterone change was represented as AUCi, the main effect for AUCi significantly predicted performance independent of participant sex (supplemental results). In summary, both men and women showed a positive linear relationship between testosterone reactivity and performance, but the effect was stronger in men across all three metrics of testosterone reactivity. Specifically, because testosterone change ranged from negative to positive, a larger testosterone increase was related to relatively better performance in the competitive will task, while a larger testosterone decrease was related to relatively worse performance.

In women participants, a follow-up hierarchical regression analysis was conducted in which step 1 included condition, HC use, and ΔT%, step 2 included the interaction of condition by ΔT% and HC use by ΔT%, and step 3 included the three-way interaction between condition, HC use, and ΔT%. Results revealed a significant main effect (in step 1) for HC use ($N = 109$, $b = -37.07$, $SE = 17.05$, $t = -2.17$, $p = .032$, $CI = -70.87$–3.26, $r^2_{partial} = 0.21$), such that HC users had lower performance than non-users. Additionally, there was also a significant main effect for group condition ($N = 109$, $b = 52.38$, $SE = 17.46$, $t = 3.00$, $p = .003$, $CI = 17.76$–87.00, $r^2_{partial} = 0.28$), such that women competing in the presence of a competitor group had higher performance than in the absence of a competitor group. There were no other statistically significant main effects or interactions. Robustness analysis using the unstandardized residual for testosterone and AUCi produced the same overall results in terms of the direction and magnitude of effects (supplemental results).

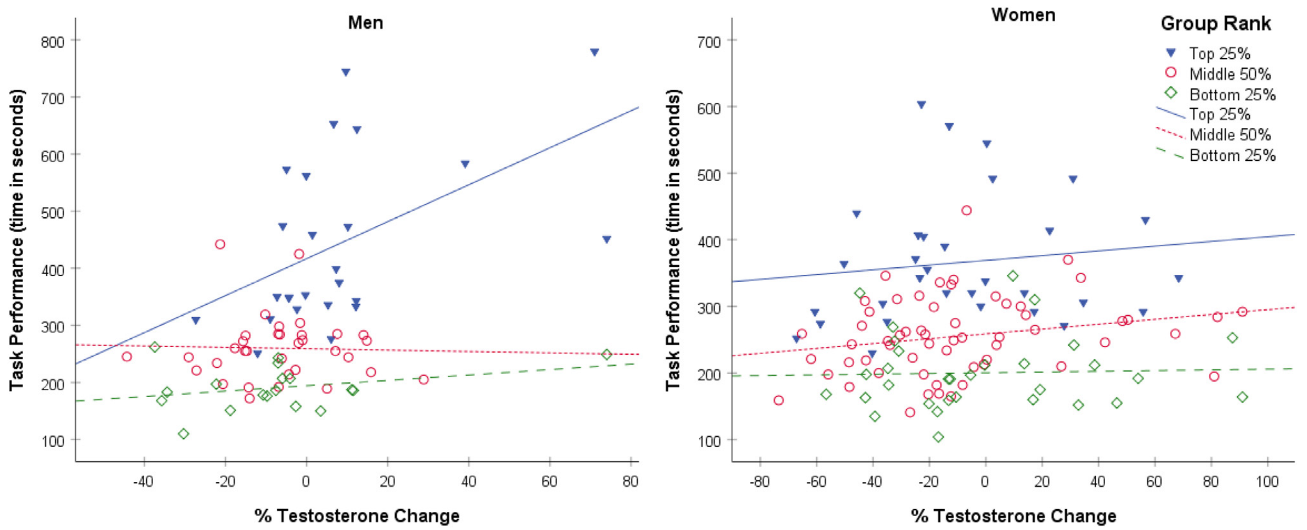

Fig. 2. Correlation between testosterone reactivity and task performance by group rank. Separate graphs for men (top 25%: R^2 = 0.25, middle 50%: $R^2 \leq 0.01$, bottom 25%: R^2 = 0.09) and women (top 25%: R^2 = 0.02, middle 50%: R^2 = 0.05, bottom 25%: $R^2 < 0.01$).

6.1.1. *Testing group rank as a moderator*

As in Study 1, relative status was determined among participants competing at the same time. Group rank is a categorical variable that relates to absolute performance (r = 0.67, p < .001), but is also conceptually independent from it. To test the moderating effect of relative status outcome (group rank), a hierarchical regression analysis was conducted in which step 1 included group rank, sex, and ΔT%, step 2 included the interaction of group rank by ΔT% and sex by ΔT%, and step 3 included the three-way interaction between group rank, sex, and ΔT%. Results revealed a significant 3-way interaction (in step 3) between group, sex, and ΔT% (N = 198, $F_{change}(1,191) = 6.37$, p = .012, R^2_{change} = 0.016; b = 1.45, SE = 0.57, t = 2.52, p = .012, CI = 0.32–2.59). As shown in Fig. 2, only men who ranked within the top 25% of their group showed a significant positive relationship between ΔT% and performance (N = 25, b = 3.24, SE = 1.18, t = 2.75, p = .011, CI = 0.80–5.68, r^2_{partial} = 0.25). Although simple slopes were in the positive direction for men ranking in the bottom 25% and women above the bottom 25%, these trends were non-significant (supplemental results). In summary, men who increased in testosterone during competition endured relatively longer in the task (performed better overall), but only if they also placed relatively high among the other participants who competed at the same time. Likewise, only among high-ranking men were decreasing or relatively unchanged testosterone levels associated with reduced competitive endurance relative to other participants' performances.

Due to the previously discussed positive correlation between an individual's performance and the performance of all others present during testing, the above analysis was repeated with the mean performance time of others present included as a covariate. This analysis produced the same results as above, a three-way interaction between group rank, sex, and ΔT%, after controlling for the mean performance of the others present (supplemental results). Additionally, although robustness analysis using the unstandardized residual for testosterone and AUCi produced slightly larger effect sizes for the relationship between testosterone reactivity and performance among women participants, the same overall results were observed in terms of the direction and magnitude of the positive relationship between testosterone reactivity and performance among top-ranking individuals, particularly among men (supplemental results).

6.1.2. *Testing "time over the group mean" as a special case dependent variable*

For those who outperformed the majority of the group (top 25%), the shift in relative social status occurred while they were still competing (i.e., they were aware of when the others dropped their arm and could continue on as long after as possible). That is, for these individuals, testosterone change during the competition could have, over the absolute performance time, uniquely predicted the amount of time they endured after knowing that they were relatively high-ranking within their group. On average, these participants (N = 58) continued to compete for 133 s over the group mean of others present during testing (SD = 104; min = 1, max = 526). As an exploratory analysis, testosterone reactivity for individuals in the top 25% of their group was regressed on "time over group mean" (absolute performance time minus the mean performance time of all others in the group). Sex and the interaction of sex and testosterone reactivity were included in the analysis. Results revealed an interaction for testosterone reactivity and sex (N = 56, $F_{change}(1,52)$ = 11.49, p = .001, R^2_{change} = 0.143; b = −3.05, SE = 0.90, t = −3.39, p = .001, CI = −4.86–1.25). For men, but not women, who ranked fairly high and thus, received feedback about their high status while competing, testosterone reactivity significantly positively predicted the amount of time they endured past the group mean performance time (men: N = 25, R^2 = 0.33, b = 3.16, SE = 0.95, t = 3.33, p = .003, CI = 1.20–5.12; women: N = 31, R^2 < 0.01, b = 0.11, SE = 0.36, t = 0.30, p = .765, CI = −0.62–0.83). However, after controlling for the absolute performance (which is highly correlated, r = 0.90, with "time over group mean"), this effect was the same direction, but no longer significant and was substantially reduced in magnitude (men: b = 0.78, SE = 0.45, t = 1.72, p = .100, CI = −0.16–1.71; women: b = −0.09, SE = 0.22, t = −0.42, p = .675, CI = −0.55–0.36). Testosterone reactivity among the top-ranked individuals measured as the unstandardized residual (b = 3.57, SE = 0.94, t = 3.80, p < .001, CI = 1.69–5.46, r^2_{partial} = 0.21) and AUCi (b = 3.71, SE = 1.31, t = 2.84, p = .006, CI = 1.09–6.34, r^2_{partial} = 0.13) significantly predicted endurance time over the group mean. Although the interaction of sex was not significant in these robustness analyses, the effects of both unstandardized residual change in testosterone and AUCi were substantially larger in men (Men: R^2 = 0.32 and 0.18, respectively; Women: R^2 = 0.01 and 0.01). As with percent change in testosterone, the effect was the same direction, but no longer significant and substantially reduced in magnitude after controlling for absolute performance (supplemental results).

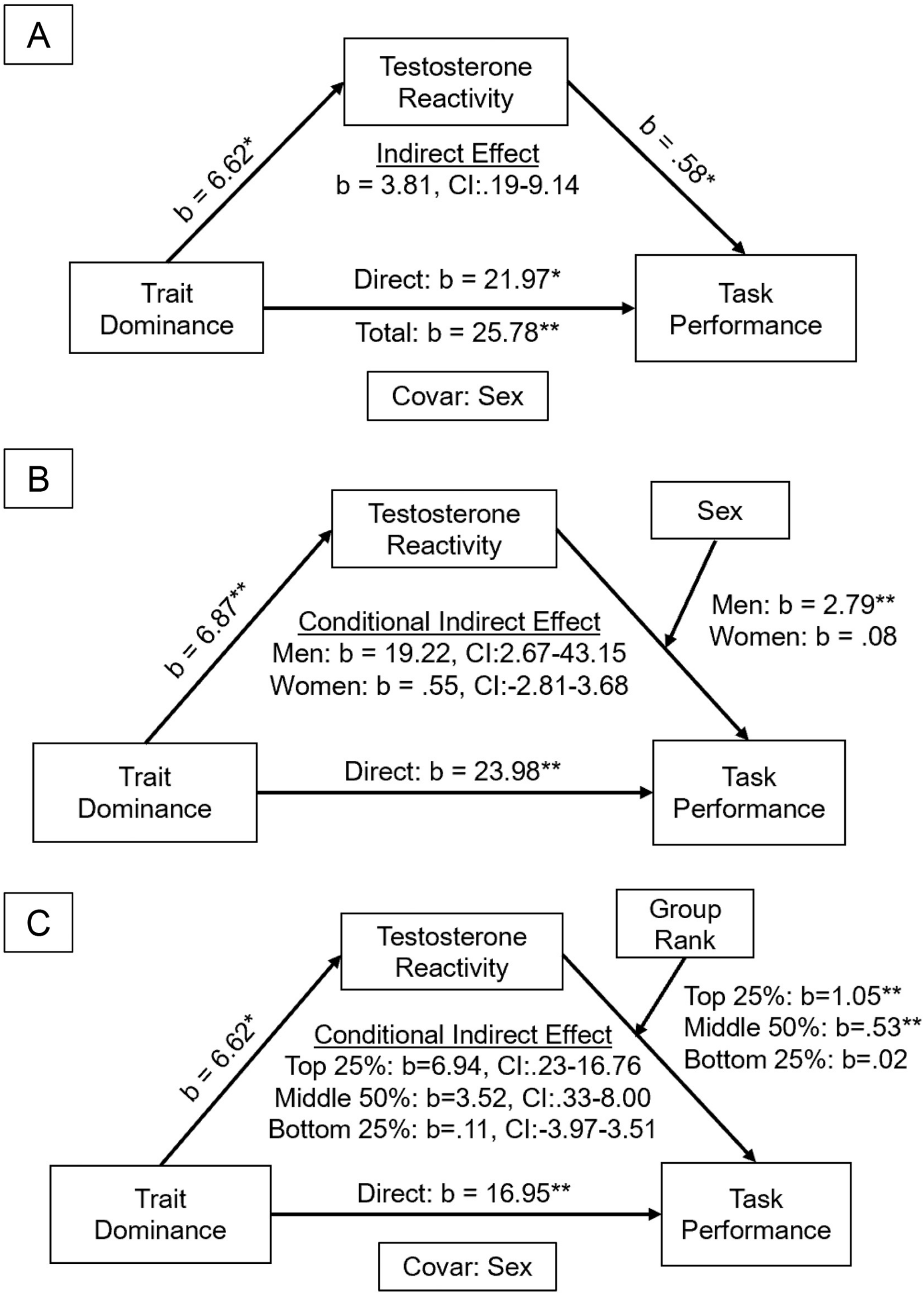

Fig. 3. Exploratory mediation analysis of the relationships between trait dominance, testosterone reactivity, and task performance ($N = 197$). A) Simple mediation; B) moderated-mediation with sex; C) moderated-mediation with group rank. $*p < .05$, $**p < .01$. Indirect effects are bootstrapped.

6.2. *Exploratory analysis of the role of trait dominance*

When conducting construct validation for the competitive will task, two self-report personality traits representing dominance motivation were positively related to both performance *and* testosterone reactivity: *dominant competitiveness* from the competitiveness orientation measure (Newby and Klein, 2014, this subscale contains 13 items rated on a 5-point Likert scale, e.g., "I like to be better than others at almost everything.") and social power-based *dominance motivation* from the power and dominance systems measure (Murphy, 2016, this subscale contains 6 items rated on a 7-point Likert scale, e.g., "I like to have power over other people."). Thus, the three-way positive relationship between trait dominance, testosterone reactivity, and performance raises the possibility of mediation. Using PROCESS version 3.0 software (Hayes, 2017), a simple mediation analysis (model 4, shown in Fig. 3A) was tested first with X = Trait Dominance, M = Testosterone reactivity, Y = Performance and, with Sex as a covariate. Next, given the interaction of sex and testosterone reactivity in predicting performance in the main analyses, a moderated mediation (model 14, shown in Fig. 3B) with Sex moderating the path between M and Y (path b) was conducted. Lastly, given the role of relevant social status in moderating the testosterone reactivity-performance relationship in men and women, a second moderated mediation analysis (model 14, shown in Fig. 3C) was conducted with Group Rank moderating the path between M and Y and Sex included as a covariate.

Path analyses and results for all models are shown in Fig. 3 (all output for both measures of trait dominance is provided in the supplemental results). Effects were the essentially identical whether using trait competitive or social-power based dominance motivation (results in Fig. 3 are for *dominant competitiveness*). Generally, results supported the main analyses in all respects: 1) testosterone reactivity positively predicts task performance (total model: $R^2 = 0.08$), but this effect is moderated by sex ($R^2_{change} = 0.08$, significant in men but not women) and 2) regardless of participant sex, group rank also moderated this relationship ($R^2_{change} = 0.01$, the positive relationship is strongest for men and women who ranked in the top 25% of their group). As expected, trait dominance was a significant predictor of performance. All paths were significant and the bootstrapped confidence intervals for the indirect effects did not cross zero (Fig. 3). While all three variables are inter-related, testosterone reactivity to competition only minimally (statistically) *explains* the relationship between trait dominance and subsequent dominance-related behavior. This suggests that testosterone reactivity is likely one of several possible mechanisms for translating competitive motivation into competitive behavior.

Due to precedent for the role of trait dominance in *moderating* testosterone's effect on competitive behavior, we also tested "dominant competitiveness" and "dominance motivation" as a moderator of the effect of testosterone reactivity on performance. Although the independent effects of both testosterone reactivity and trait dominance on performance remained, the interaction was not significant in either case ($R^2_{change} = 0.002$ and 0.004, respectively; full analysis in supplemental results).

7. Study 2 discussion

Study 2 was designed to extend evidence on the relationship between testosterone reactivity and task performance within the group context. With groups of 3–8 participants assigned to teams, the social presence of a competitor team was manipulated and the incentive structure of the competitive will task was altered to motivate both individual and team-based competitive effort. In addition to physical presence of a competitor team, the moderating effects of participant sex and social status in the form of relative rank among the competitors present in each testing session were tested. Generally, testosterone reactivity positively predicted performance, the amount of endurance expressed in competition, but this effect was significant only among men. Specifically, because testosterone reactivity centered around zero, greater increases related to better performance and greater decreases related to worse performance. In both men and women, those who attained higher status relative to the others present (performed relatively better) showed the strongest positive relationship between testosterone reactivity and performance, but again, effects were most pronounced among men. Although participants performed better on average with increasing number of people present, the presence or absence of a competitor team did not affect testosterone reactivity or its relationship with performance.

An exploratory mediation analysis was conducted to test the role of trait dominance as an individual difference factor that drives both testosterone reactivity to competition and the expression of competitive behavior. We provide initial evidence that testosterone reactivity at least partially mediates the strong relationship between trait dominance and task performance. The main effects regarding sex and group rank as moderators of the direct relationship between testosterone reactivity and performance were supported with moderated-mediation. Overall, Study 2 provides novel evidence for a positive association between changing testosterone over the course of competition and performance on an endurance-based task, with greater increases (or fewer decreases) associated with greater endurance especially among men and those who performed better than their group-mates. This finding was robust across different measures of testosterone reactivity and analytic approach. Additionally, Study 2 provides initial evidence for the potential role of trait dominance in driving both testosterone changes associated with competition and the expression of competitive efforts.

8. General discussion

Performance in the competitive will task was defined as the amount of time a participant endures in a weight-holding contest for time. Endurance requires a combination of physical and mental components that interact to aid in the expression of competitive "effort" in nearly all contests for time. Indeed, holding a weight for time and has been previously and independently validated as a measure of mental toughness, a psychological construct in which competitive persistence is a core feature (Crust and Clough, 2005). Generally, in the absence of obvious differences in skill or knowledge, those who succeed in social contests must display superior energy, effort, mental or physical strength, willpower, and endurance over their opponent. Competitive endurance is just one of the ways in which motivation to dominate or attain social status over others is materialized behaviorally. The weight holding task used in this research is a relatively simple and face valid application for revealing individual differences in the propensity for exerting competitive effort. In support of this notion, we present data from two studies of nearly 400 participants total that demonstrate a significant positive correlation between performance in the competitive will task and individual differences in traits having to do with competitiveness and dominance motivation as well as task-specific desire to win and perceived effort. Furthermore, physical qualities associated with strength – height, weight, and BMI – were unrelated to task performance and did not explain variance in the relationship between performance and psychological traits. Combined, this evidence provides a strong initial case that performance in the competitive will task is a behavioral measure of underlying psychological motives associated with status-seeking.

Increasing testosterone during a competitive social encounter is thought to promote psychological states and behaviors that would aid in dominating an opponent (Wingfield et al., 1990; Archer, 2006). However, individuals differ with respect to the direction and magnitude of their hormonal response to competition. The present study is premised on the idea that these individual differences in testosterone reactivity should correlate with individual differences in the degree of competitive behavior expressed during that competition. Across both studies, testosterone reactivity over the course of the competitive will task ranged from around a 60% decrease to a 75% increase with the average response centering just below zero, i.e., no change. Concordant with predictions, increasing testosterone was associated with relatively better performance in the competitive will task and decreasing testosterone was associated with relatively worse performance. Further, in line with previous research and predictions, there were several important moderators of this relationship: participant sex and status outcome relevant to other physically present competitors (Study 1, win/loss; Study 2, group rank). For men in both studies, the correlation between testosterone reactivity and performance was strongest for those who won or ranked highest among their group. For women, the effect was less generalized, appearing only among those who lost to a single competitor (Study 1). In Study 2, among high-ranking men participants, individual differences in testosterone reactivity positively predicted the time one endured over the group mean (time that they continued to compete while knowing they were relatively high in status), but controlling for absolute performance virtually eliminated the effect. Overall, the mere presence or absence of a competitor or competitor group did not affect the relationship between testosterone reactivity and performance.

The direction of causality of the hormone-behavior relationship found in the two studies is not known. Although we propose that testosterone reactivity predicts the time-matched expression of competitive behavior, it is also likely that this behavior in the context of competition drives the testosterone response. Indeed, attaining social status through competition is thought to produce elevated testosterone as a means to maintain dominance (for review, Casto and Mehta, 2019). Although the design of this research cannot parse direction of causality from the results, trait dominance, which is a stable and pre-existing characteristic of individuals and therefore present before engaging in the competitive task, predicted both performance and testosterone reactivity. Further, initial evidence from the present research shows that testosterone mediates the effect of trait dominance on task performance. This suggests that the testosterone response to competition may act as an underlying mechanism by which individual differences in motivation for dominance are translated into behaviors to achieve this end within particular adaptive contexts. Alternatively, given that performance is confounded with time spent engaging in the task, testosterone change could be a manifestation of time independent of psychological motivation. This limitation could be addressed in future research by including a control group that did not compete while testosterone levels were assessed at different time intervals or by using a task in which persistence is not synonymous with time (e.g. number of questions or components of a task completed within a fixed time interval).

Nevertheless, discussions about causality are complicated by the rapid and intertwined nature of hormone-behavior feedback loops, one in which hormones influence behavior and behavior subsequently provides ongoing perceptual information that regulates hormonal responding in real-time to meet the demands of the evolving competitive context.

8.1. Moderating role of relative status

Findings from both studies regarding the importance of status-related outcomes in influencing the hormone-behavior relationship of interest are consonant with prior research. According to the biosocial model of status, shifts in status gained or lost through competition should impact the direction of testosterone change during a competitive encounter, increasing for those who experience social victory and decreasing for those who experience social defeat (Mazur, 1985; Mazur and Booth, 1998). Increases and decreases in testosterone levels are thought to respectively promote or discourage future competitive or aggressive behaviors. Meta-analytic evidence (Geniole et al., 2017) generally supports the ‘winner-loser effect’ on testosterone change, but the effects are small overall and significant only for male participants. In the research presented, contrary to the winner-loser effect, there were no significant differences in the testosterone change across competition between relative winners and losers, in men or women. Rather, relative status moderated the relationship between testosterone reactivity and task performance such that a positive association emerged only among men who experienced relative social victory. This finding is in-line with previous studies showing that, among men, competition outcome moderates the relationship between competition-related changes in testosterone level and psychological variables such as power motivation and competitive decision-making as well as, in the reverse direction, the relationship between competitive effort and post-competition testosterone levels (Carré and McCormick, 2008; Mehta and Josephs, 2006; Mehta et al., 2015b; Oxford et al., 2010; Schultheiss and Rohde, 2002; Schultheiss et al., 2005).

The status-relevant outcomes seen in the competitive will task are, by the very nature of the contest rules, highly related to absolute performance time. That is, people who endured longer were more likely to win or finish in the top tier of their group. Still, there were many who would have lost or won and placed lower or higher had they competed against a different opponent (Study 1) or within a different group (Study 2). Importantly, participants were not given any information about average performance times or overall placement; the only information participants had with which to assess their own performance was the performance of others whom they shared that particular space and time. Thus, for participants who competed individually (Study 1), there was no way to assess their relative position. For those who won or finished in the top tier of their group, some portion of their performance continued after they achieved relative victory – participants were all competing for an overall cash prize that would not be determined until a later date based on how their absolute performance compared the much broader body of participants. As a result, status outcome in the present research was absent of a direct monetary outcome and represented a somewhat unique condition of social status achieved based on context-specific criteria – the other participants in the room.

The overlapping nature of task performance and relative status outcome (Study 1: $r = 0.39$, Study 2: $r = 0.67$) was an intentional component of the present research, one that accurately reflects how status is often determined in real-world contests. While previous studies of the winner-loser effect in the laboratory often “fix” the competition outcome (random assignment to win or loss condition) in an attempt to reduce the influence of competitive effort (e.g., van der Meij et al., 2010; Zilioli and Watson, 2012; for review, Casto and Edwards, 2016a), the set of studies presented here provide evidence that testosterone reactivity may actually map onto those efforts in real-time and, as in naturalistic competition, play a major role in determining relative status gained or lost. Alternatively, competitive effort, which still functions to increase the probability of attaining status in the ongoing contest, produces elevated testosterone after the task in order to serve the purpose of future status attainment and maintenance. The implication that testosterone fluctuations coordinate or facilitate real-time competitive effort is corroborated by some prior evidence that testosterone reactivity to competition is linked with time-matched competitiveness and dominance signaling in men (Gonzalez-Bono et al., 1999; Kordsmeyer and Penke, 2019). Furthermore, the present research provides additional evidence that the positive relationship between testosterone reactivity and competitive behavior emerges only among relative winners and high-ranking individuals, a result that demonstrates the compounding nature of effort and status achievement. More so, among the high-ranking participants, the strong positive relationship between testosterone reactivity and individual differences in competitive endurance after achieving relative status (time over group mean) was explained by their absolute performance time across the contest. Thus, an individual's overall effort, perhaps facilitated by rising testosterone, increased the likelihood of achieving status in terms of both high absolute performance and relative social position among others. Future work with the competitive will task should identify a marker for performance time after the onset of discomfort, a variable that could better capture differences in status motivation over absolute performance.

8.2. Sex effects, the inclusion of women, and hormonal contraceptive use

Findings regarding the positive relationship between the testosterone change associated with competition and competitive endurance expressed during that competition, discussed above, were largely specific to men who participated in the present research. Women participants also showed similar directional trends, but the effect sizes were significantly reduced. Results from this research are consonant with prior research that has found smaller effect sizes or no effects for the relationship between testosterone reactivity and competitive choice in women compared to men (e.g., Carré et al., 2013; Geniole et al., 2013; Geniole and Carré, 2018). However, studies administering exogenous testosterone have found that, in certain contexts, supplemental treatment with testosterone increased competitive decision-making for trait dominant women (Mehta et al., 2015a). However, given the lower number of men compared to women in this study, interpretations about the replicability of the observed sex difference should be made cautiously.

There are several possible explanations for the observed sex difference. First, it is possible that women have a different or intervening hormonal mechanism for regulating competitive behavior that was not accounted for in the present research. For example, some research has shown that fluctuating levels of estradiol and progesterone associated with the menstrual cycle influence intra-sexual competition in mating domains (e.g. Cobey et al., 2013; Durante et al., 2008; Puts, 2005, but see Hahn et al., 2016) as well as competitive decision-making in economic tasks (e.g., Buser, 2012; Eisenbruch and Roney, 2016; Pearson and Schipper, 2013). Future research should explore these potential mechanisms among women competing for social status. Second, due to the large differences in how competitive behavior is socialized in western women (punished) compared to men (reinforced) (e.g., Andersen et al., 2013; Carpenter et al., 2018; Williams and Tiedens, 2016), women face different social pressures in competitive contexts that are not accounted for in study designs (for review, Casto and Prasad, 2017). In the present research, women who lost when competing against a single opponent showed a fairly strong positive association between testosterone reactivity and performance. Although this effect did not replicate among low-ranking women in the group setting, it suggests a possible avenue for future research that addresses the nuance of social status tradeoffs for women in competitive contexts. This research should consider how society and culture shape and have shaped women's competitive and dominance motivated behavior, which evolved and currently exists within a structure in which these behaviors incur risk (social and physical) and require greater tact, strategy, and concealment (Campbell, 2004; Prentice and Carranza, 2002; Rudman and Phelan, 2008). A third, and perhaps more parsimonious explanation, could be that there is greater measurement error when determining testosterone concentrations for women (e.g. Welker et al., 2016; Prasad et al., 2019; Schultheiss et al., 2019) making it more difficult to detect what are fairly small to moderate effects. Advancement in techniques for assaying testosterone more precisely even at low concentrations, such as mass spectrometry, will improve understanding of hormonal mechanisms that influence competitive behavior in women. Finally, effects by sex in the present research are limited by the fact that the weight held was twice as much for men as for women. Although this was a deliberate feature of the competitive will task that was designed to reduce sex differences in task difficulty (perhaps owing to differences in body size), the task was nonetheless different for men and women. Future research exploring sex as a moderator of the relationship between testosterone reactivity and competitive effort should consider using a task that is independent of sex when all aspects of the task are held constant.

Importantly, the moderating effects of sex in the present research highlights the importance of including women in study designs and testing for the interaction of participant sex; it both provides a relevant reference group for effects observed in men and, adds to larger understanding of the contexts, tasks, and conditions under which women's testosterone reactivity does and does not predict behavior. Importantly, men and women did not differ overall in the direction or magnitude of the testosterone change associated with participating in the competitive will task. The challenge for future research is to uncover what these individual differences mean for women's competitive and status-related behavior.

Approximately half of the women who participated in the present research were taking some form of hormonal contraception (pill, patch, or injection-based methods). Although these women had significantly lower testosterone levels, their testosterone reactivity to competition was not significantly different than women not using any form of hormonal contraception, in agreement with what has been reported in other studies (Edwards and O'Neal, 2009; Casto and Edwards, 2016b; Wiegratz et al., 1995; Zimmerman et al., 2014). Further, hormonal contraceptive use did not moderate the relationship between testosterone reactivity and task performance. That said, hormonal contraceptive users across both studies demonstrated, on average, lower performance than women not using hormonal contraception, raising the possibility that the use of hormone contraceptives may negatively affect competitive endurance. This finding is supported by a limited number of previous studies that have found women using hormonal contraception, compared to non-users, make less advantageous competitive bidding decisions (Pearson and Schipper, 2013), self-report lower intrasexual competitiveness (Cobey et al., 2013), demonstrate less perseverance on tasks requiring cognitive control (Bradshaw et al., 2020), and are less likely to self-select into a competitive than noncompetitive tournament scheme (Buser, 2012). Further, there is increasing evidence that hormonal contraceptive users display altered social-emotional processing such as reduced fear extinction, dysregulated social reward mechanisms, and increased emotional reactivity to aversive stimuli (Montoya and Bos, 2017). Whether or not hormonal contraceptive use influences women's motivation for status, competitiveness, and ability to achieve and maintain high status positions is a critical question for future research.

8.3. Individual differences in trait dominance

Although the drive for social status is considered a core psychological motive (Anderson et al., 2015), individuals differ in the intensity with which they desire status and the behavioral effort they are willing to give in attempts to attain and maintain it (Fiske, 2009). In some, this drive is sufficiently strong to prompt efforts to seek out, engage in, and succeed in situations where relative judgments about performance are made (Festinger, 1954; Garcia et al., 2013). Because comparison to others through competition is how relative social status is determined, individual differences in competitiveness – the "desire to win in interpersonal situations" (Smither and Houston, 1992, p.408) – can be seen as reflecting individual differences in the motivation to acquire social status. As a trait, competitiveness or dominance should be manifest in the level of exertion or persistence expressed towards the goal of winning i.e., competitive effort. Thus, it is no surprise that trait dominance appears to play an important moderating role in the relationship between testosterone and aggression, dominance, and competitiveness under certain contexts (Carré et al., 2009; Geniole et al., 2013; Carré et al., 2017; Mehta et al., 2015a). In the present research, individual differences in trait competitive-dominance positively predicted both performance and testosterone reactivity to competition, and testosterone reactivity partially explained, statistically, the direct relationship between the competitive trait and behavior. Thus, we propose that individual differences in dominance motivation produce variations in testosterone responses to a competitive social encounter, increasing for those high in dominance and decreasing for those low in dominance. Further, increasing testosterone may function to promote competitive persistence, i.e., the likelihood of success, for those who desire it. As also demonstrated in this exploratory analysis, the path between testosterone reactivity and performance was moderated by sex (apparent in men) and relative status outcome in the form of group rank (apparent among those who ranked highest). The present research provides novel evidence for the importance of accounting for hormonal reactivity and social context in understanding how motives and traits translate into behavior – hormone change perhaps serving as one physiological activator of goal-directed motivation within relevant social contexts.

8.4. Social presence

As both the challenge hypothesis and biosocial model of status are founded on the notion that competitive social encounters drive testosterone reactivity, we aimed to test the role of the physical presence of an opponent, an actual social encounter, in affecting the relationship between testosterone change during competition and performance. In Study 1, we manipulated the physical presence of an opponent so that participants competed either individually or in the presence of a singular opponent. In Study 2, we placed participants in teams of 3–5 individuals and then manipulated the physical presence of an opponent team. In both studies, the physical presence or absence of an opponent or opponent team was independent of reward anticipation because the competition rules for determining prize winners were the same in both conditions. However, the two conditions were necessarily confounded by the number of participants present, a fact that is particularly relevant for the group competition where effects could be driven by inter-group vs. intragroup dynamics or simply, the smaller vs. larger number of competitors present.

Results from both studies showed that the physical presence of an opponent or opponent team did not significantly affect testosterone reactivity or the relationship between testosterone reactivity and performance. Additionally, in Study 1, the mean performance time for individuals competing individually (in seconds, M = 243; SD = 79) was scarcely different from the mean for individuals competing in the physical presence of a single opponent (in seconds, M = 241; SD = 73). Although not directly compared, participants who competed as a team, but in the absence of a competitor team in Study 2, showed a similar mean performance time (M = 244; SD = 74) to individuals and dyads from Study 1. However, Study 2 participants who competed in the presence of a competitor team, and thus competed among at least four other people, had significantly higher mean performance time (M = 302; SD = 123) than other Study 2 participants who did not compete in the presence of a competitor team. Thus, perhaps larger social groups and/or the element of coalitional competition (between group competitive focus) are necessary conditions for producing social facilitation effects on performance.

Testing the influence of social presence on competitive behavior and hormonal relationships with competitive behavior is important because it is likely that these behaviors and related mechanisms evolved within the context of complex social groups (Crofoot and Wrangham, 2010; Flinn et al., 2012). Further, previous research has found that increased testosterone in response to competition is specific to between-group, but not within-group contests (Wagner et al., 2002; Oxford et al., 2010; Flinn et al., 2012), suggesting that testosterone reactivity to competition is attenuated in contexts in which within-group status dynamics are at play – where prosocial and cooperative behavior, in contrast to overt dominance, may also be required to simultaneously maintain within-group status (Diekhof et al., 2014; Reimers and Diekhof, 2015). In the present research, manipulating the physical presence of a competitor group was intended to shift competitive focus towards or away from the out-group by providing a relative reference for out-group when a competitor group was present. When a competitor group was not present, participants' only reference for social comparison would be their own teammates. However, this manipulation did not moderate the relationship between testosterone reactivity and performance. First, it is possible that this manipulation did not effectively alter in-group vs. out-group competitive focus or that the group assignment, via minimal groups design (Tajfel et al., 1971; Otten, 2016), did not substantively alter perceptions of group membership. Second, and perhaps more likely, it is possible that the non-zero-sum competitive scheme was unsuccessful in creating a trade-off between group cooperation and individual competitive motivation. That is, because there were separate individual and team prizes, but individual performance also figured into the team mean performance, outperforming one's teammates improved both one's own rank for the individual prize and also raised the group average (rank among other teams). Interestingly, it was not uncommon for participants who dropped their arm earlier to 'cheer on' their persisting teammate(s) as they exited the testing room or for persisting participants to claim that they were 'doing it for the team.' It is perhaps no surprise then that these high-ranking individuals showed the strongest positive correlation between testosterone reactivity and performance – these individuals increased their personal chances of winning money *and* gained prestige among their group. Future research should test the presence or absence of opponent social groups where individual performance comes at a cost to team performance outcomes (e.g., Cárdenas and Mantilla, 2015; Ronay et al., 2012).

One final element of social presence in the context of competition worth discussing is the presence of members of the opposite sex. Recent reviews and meta-analysis of the challenge hypothesis across taxa have found that testosterone does reliably increase during a competitive challenge from another male in fish and insects, but that in other taxa, including mammals, this effect was more variable and perhaps specific to contexts in which there is direct access to a mating opportunity, e.g., male-female interactions (Goymann et al., 2019; Moore et al., 2019; Tibbetts et al., 2019). In the present research, all male participants competed in the presence of a female; many female participants competed in the presence of a male. Although mating opportunities were not part of the formal incentive structure, the degree with which men and women believed their performance influenced their likelihood of garnering sexual interest from others, and differences in this belief, is a potentially interesting and important factor to account for in future research (e.g., Kordsmeyer and Penke, 2019).

9. Conclusion

In the present research, we introduced a novel competitive task designed to determine individual differences in competitive endurance. Performance in the competitive will task reflects personal characteristics that would be advantageous for success in dominance contests in both early (primitive) and modern human social contexts. Across two studies and a relatively large sample, the present research provides original evidence of a positive relationship, in men, between testosterone reactivity to a competitive social challenge and task performance under conditions of elevated relative social status. That is, among men who won against an opponent or performed well relative to a group, increased testosterone over the course of competition predicted relatively better performances. Initial exploratory evidence showed that individuals who reported higher dominance motivation endured longer in the competitive will task, and this relationship is partially mediated by testosterone reactivity. This three-way relationship demonstrates the importance of accounting for hormonal reactivity in understanding how status-seeking motives and traits translate into competitive behavior – with hormones perhaps serving as activators of goal-directed activity within relevant social contexts.

The notion that "when challenged by another male, testosterone increases to allow the defender to confront the challenge (Oxford et al., 2010, p.202)" is well-espoused and central to the application of the challenge hypothesis to human behavior. Despite this, the relationship between testosterone reactivity to competition and real-time competitive behavior that would aid in success within that competition has heretofore remained relatively unknown. Furthermore, we demonstrate the moderating effects of status shifts on this relationship when status position is not fixed by the experimenters, but rather, is determined by the participant's own competitive drive relative to others.

Transparency and open science practices

All supplementary results, analysis code, and data are available on the open science framework (https://osf.io/6r7da/).

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