Collective hormonal profiles predict group performance

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Prior research has shown that an individual's hormonal profile can influence the individual's social standing within a group. We introduce a different construct—a collective hormonal profile—which describes a group's hormonal make-up. We test whether a group's collective hormonal profile is related to its performance. Analysis of 370 individuals randomly assigned to work in 74 groups of three to six individuals revealed that group-level concentrations of testosterone and cortisol interact to predict a group's standing across groups. Groups with a collective hormonal profile characterized by high testosterone and low cortisol exhibited the highest performance. These collective hormonal level results remained reliable when controlling for personality traits and group-level variability in hormones. These findings support the hypothesis that groups with a biological propensity toward status pursuit (high testosterone) coupled with reduced stress-axis activity (low cortisol) engage in profit-maximizing decision-making. The current work extends the dual-hormone hypothesis to the collective level and provides a neurobiological perspective on the factors that determine who rises to the top across, not just within, social hierarchies.

testosterone | cortisol | groups | status | performance

Humans have always worked collaboratively in small groups to accomplish goals. In modern organizations, group work is increasing because of the growing competitive and technological demands placed on organizations and the belief that a greater variety of perspectives and approaches will lead to more innovative solutions (1–3). As a result, decades of research have focused on understanding the factors that can enhance group performance and allow some groups to outperform others. Not surprisingly, groups with structures, processes, and norms that facilitate collaboration and coordination tend to perform well (4, 5). Additionally, group composition can influence performance; groups composed of members that vary in diversity, skills, and intelligence outperform others when the appropriate structures, processes, and norms are in place (3, 6–10).

Past research on the effects of group composition on performance has focused primarily on the demographic and psychological characteristics of group members without taking into consideration the biological make-up of groups. This omission is particularly surprising because there is evidence that hormonal profiles can influence performance among individuals within a group. Indeed, past research has found that a hormonal profile characterized by high testosterone and low cortisol predicts an individual's performance and status attainment (11). Just as individuals have a hormonal profile that affects their individual performance and social status, we suggest that groups likewise can be characterized by a particular hormonal profile—their collective hormonal profile—which will influence group performance. We define a collective hormonal profile as the hormonal make-up of a group of individuals. Here, we test the hypothesis that groups with a collective hormonal profile characterized by high testosterone and low cortisol outperform and attain higher social standing among a collection of groups.

Across humans and various animal species, elevated testosterone, a steroid hormone released as the end product of the hypothalamic–pituitary–gonadal (HPG) axis, is positively related to social dominance and behaviors that foster the achievement or maintenance of high status (12, 13). Individuals high in testosterone tend to outcompete others (14) and rise to the top of their social hierarchies, particularly in studies of nonhuman animals (15, 16). Recently, a more nuanced perspective on the link between testosterone and status attainment in humans has begun to emerge. There is growing evidence that the HPG axis acts in concert with the hypothalamic–pituitary–adrenal (HPA) stress axis to regulate status attainment within groups (11, 17). The HPA axis secretes the steroid hormone cortisol in response to stress and anxiety; thus interactions between the HPG and HPA axes can be observed by measuring testosterone and cortisol simultaneously. Specifically, the dual-hormone hypothesis posits that testosterone has a positive impact on status-attaining behavior only among individuals with low levels of cortisol (18). This hypothesis is informed by evidence that high levels of cortisol can suppress the neurobiological pathway through which testosterone impacts behavior; thus high levels of cortisol may inhibit testosterone's positive effect on dominance and status attainment (18).

The hypothesis that testosterone and cortisol interact to predict status-related behaviors for individuals has received strong empirical support in numerous contexts. For instance, individuals high in testosterone and low in cortisol have a greater number of subordinates, a measure of attained status (17); are perceived as more dominant leaders (18); are more respected by their peers (19); are more popular within their social networks (20); and engage in more competitive behavior as well as risk-taking (18, 21), a behavioral strategy associated with the attainment of social status (22, 23).

The current work explores whether the hormonal profile of a group predicts its standing among groups. We test whether the hormonal profile of high testosterone and low cortisol at the

Significance

Past research has focused primarily on demographic and psychological characteristics of group members without taking into consideration the biological make-up of groups. Here we introduce a different construct—a group's collective hormonal profile—and find that a group's biological profile predicts its standing across groups and that the particular profile supports a dual-hormone hypothesis. Groups with a collective hormonal profile characterized by high testosterone and low cortisol exhibit the highest performance. The current work provides a neurobiological perspective on factors determining group behavior and performance that are ripe for further exploration.

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Table 1. Correlations among study variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Group performance												
2. Cortisol, mean	0.10											
3. Testosterone, mean	0.21	0.72*										
4. Dominance, mean	−0.07	0.19	0.06									
5. Anxiety, mean	0.10	−0.19	0.04	−0.12								
6. Cortisol, SD	−0.05	0.21	0.16	0.00	−0.01							
7. Testosterone, SD	0.01	0.02	−0.18	−0.05	0.11	0.02						
8. Dominance, SD	0.29*	0.05	0.12	−0.13	−0.03	0.04	−0.04					
9. Anxiety, SD	0.11	0.06	0.18	−0.14	0.59*	0.09	0.21	0.12				
10. Time of day	0.08	−0.49*	−0.41*	0.14	−0.23*	−0.22	−0.11	0.18	−0.17			
11. No. of females	−0.18	0.00	−0.30*	−0.14	0.19	0.04	0.21	−0.23*	0.12	−0.46*		
12. Group size	0.22	0.19	0.30*	0.15	0.13	0.06	0.12	−0.18	0.20	−0.22	0.17	
Minimum	−3.08	−2.63	3.90	3.34	1.33	0.07	0.15	0.19	0.25	9.00	0.00	3.00
Maximum	1.11	−0.67	4.95	5.22	2.83	1.01	1.22	2.04	1.61	16.00	2.00	6.00
Mean	0.00	−1.77	4.52	4.43	2.04	0.51	0.60	1.16	0.78	11.67	1.78	4.93
SD	0.84	0.47	0.22	0.38	0.34	0.22	0.21	0.38	0.31	2.41	0.45	0.69

Group performance is a composite of standardized group performance measures and therefore has a negative minimum value. Testosterone and cortisol data represent the log-transformed values. $n = 74$ groups.
*$P < 0.05$.

collective level predicts which groups rise to the top. We propose that the dual-hormone hypothesis can explain behavior and performance not only at the individual level but also at the group level.

To test this prediction regarding collective hormonal profiles and performance, we collected saliva samples from 370 Master in Business Administration (MBA) students, randomly assigned the students into 74 groups ranging in size from three to six members, and monitored the groups' performance in a week-long group decision-making task. Saliva samples were collected approximately 1 wk before the group decision-making task and were assayed for testosterone and cortisol. Unbiased mean levels of each hormone were calculated for each group using a multilevel modeling approach, and the interaction of group-level testosterone and cortisol served as our key predictor variable.

The group decision-making task was a computerized exercise (Littlefield Labs, Responsive Learning Technologies) simulating the supply-chain process of a series of laboratories providing blood testing to customers. Each group was responsible for managing one laboratory outside of class time for 7 d, with the goal of maximizing the laboratory's profitability through effective inventory management. Groups were told that they would compete with the other groups in the class in managing several aspects of the laboratory (e.g., buying and selling capacity, adjusting lead-time quotes, changing lot sizes and inventory-ordering parameters, and selecting scheduling rules). The task was interdependent, because groups were encouraged to involve all group members in developing and executing a strategy that would maximize performance. The exercise lasted 7 d but simulated 315 d of laboratory operations. Group-level performance, which was an aggregated score of all performance metrics including profitability, number of contracts received, number of customer reorders, and the group ranking relative to other groups in the class, served as our key outcome variable. It is important to note that there was no normative solution or decision-making model in the decision-making exercise. Groups could use a variety of strategies to optimize financial performance. We examined whether the collective hormonal profile of high testosterone and low cortisol, reflecting the dual-hormone hypothesis, predicted group performance on day 7 of the exercise (simulating 315 d of laboratory operations). We also examined the stability of this effect by analyzing interim performance data on day 5 of the exercise (simulating 170 days of laboratory operations) for 52 of the 74 groups for which we had data on interim performance (*Supporting Information* and Table S1). In all analyses, testosterone and cortisol were log-transformed to account for skewness (see Table 1 for descriptive statistics and correlations among all study variables). We controlled for time of day of saliva collection, for the number of females on each team because of the known relationships between these variables and the HPA and HPG axes, and for group size to account for the number of observations that were used to create the collective profiles (Table 2, model 2). We also ran the analyses without any covariates (Table 2, model 1).

Results

In support of the dual-hormone hypothesis, the interaction between group-level testosterone and cortisol significantly predicted

Table 2. Multilevel models predicting group performance

	Model 1					Model 2				
Variable	Slope	SE	*df*	*t*	*P*	Slope	SE	*df*	*t*	*P*
Intercept	0.18	0.11	70	1.66	0.10	0.18	0.11	67	1.55	0.13
Cortisol, mean	−0.08	0.36	70	−0.23	0.82	0.04	0.34	67	0.13	0.90
Testosterone, mean	1.15	0.92	70	1.25	0.22	0.71	0.84	67	0.85	0.40
Cortisol × testosterone, mean	−3.35	1.42	70	−2.36	0.02	−2.68	1.18	67	−2.27	0.03
Time of day						0.04	0.05	67	0.85	0.40
No. of females						−0.07	0.27	67	−0.26	0.79
Group size						0.13	0.13	67	0.94	0.35

$n = 74$ groups.

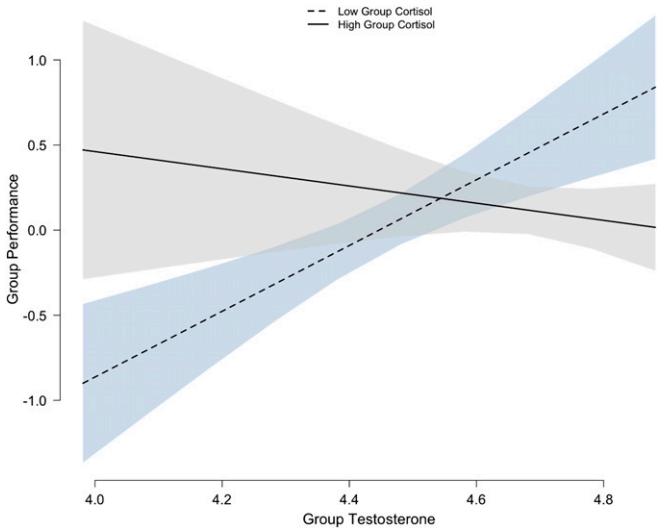

Fig. 1. Group performance as a function of group-level testosterone and group-level cortisol.

group performance ($b = -2.68$, SE = 1.18, $r = -0.27$, $P = 0.03$) (Fig. 1; see Table 2, model 2 for full statistics). When group cortisol was relatively low, group testosterone was significantly predictive of performance ($b = 1.93$, SE = 0.93, $r = 0.25$, $P = 0.04$) (dashed line in Fig. 1). However, group testosterone was unrelated to performance when group cortisol was high ($b = -0.51$, SE = 1.06, $r = -0.06$, $P = 0.64$) (solid line in Fig. 1). A robustness check excluding the covariates in the model indicated that the interaction between group-level testosterone and cortisol remained significant ($b = -3.35$, SE = 1.42, $r = -0.27$, $P = 0.02$) (Table 2, model 1). The positive simple slope between group testosterone and performance among groups collectively low in cortisol also remained significant ($b = 2.64$, SE = 1.14, $r = 0.27$, $P = 0.02$). Furthermore, group testosterone remained unrelated to performance when group cortisol was high ($b = -0.33$, SE = 1.09, $r = -0.04$, $P = 0.76$). The interaction between group-level testosterone and cortisol was seen not only in our aggregated measure of group performance but also in the component metrics of group performance, with the strongest of these metrics being profitability and group ranking: profitability ($b = -1027247.81$, SE = 403289.37, $r = -0.30$, $P = 0.01$); contracts ($b = -1.26$, SE = 0.82, $r = -0.18$, $P = 0.13$); reorders ($b = -39.32$, SE = 28.85, $r = -0.16$, $P = 0.18$); and group ranking ($b = 9.01$, SE = 3.57, $r = 0.29$, $P = 0.01$). In other words, all component measures of group performance showed a trend in which group performance was highest when collective testosterone was high and collective cortisol was low. These findings demonstrate that the HPA and HPG axes play a dual role across groups, just as they do within groups.

Next we tested whether this dual-hormone interaction still predicted group performance when controlling for two personality characteristics conceptually linked to testosterone and cortisol—trait dominance and trait anxiety, respectively. An effect of collective hormonal profiles on performance in this analysis would rule out the alternative explanation that collective hormonal profiles simply reflect self-reported dispositional factors. Both dominance and anxiety were assessed via self-report several weeks before the group performance task, and unbiased group-level means of both personality traits were calculated. Neither dominance nor anxiety was correlated respectively with testosterone or cortisol (Table 1), as is consistent with prior research highlighting the relative independence of responses across nonbiological and biological systems (24–26). Furthermore, when we added group-level trait dominance, trait anxiety, and their interaction to our main regression model, the interaction between group testosterone and group cortisol remained a significant predictor of group performance ($b = -2.38$, SE = 0.92, $r = -0.31$, $P = 0.01$) (Table 3, model 1). This robust effect of the collective hormonal profile on group performance, when controlling for self-reported personality traits, is aligned with research suggesting that the motives captured by hormonal measures may not be easily detected by self-report measures that are meant to assess typical trait-like behavior and can apply to a variety of contexts (27). In contrast, hormonal measures may be more situational and linked to behavior in very specific contexts, which in the case of the present research are contexts that evoke status attainment. Our findings also align with theories proposing that the HPG and HPA axes influence motivation and behaviors primarily outside conscious awareness (28, 29).

The analyses thus far reveal that group-level concentrations of testosterone and cortisol predicted group performance. However, past research has found that groups with low within-group variability in a marker of prenatal androgen exposure (second-to-fourth digit ratio), which is conceptually related to social dominance and status, are less productive because of heightened intragroup conflict (30). This finding is consistent with research demonstrating that the presence of too many high-status individuals on a team can have a negative effect on group performance

Table 3. Multilevel models including trait anxiety, trait dominance, and cortisol and testosterone SDs as predictors of group performance

	Model 1					Model 2				
Variable	Slope	SE	*df*	*t*	*P*	Slope	SE	*df*	*t*	*P*
Intercept	0.18	0.10	64	1.76	0.08	0.19	0.11	64	1.68	0.10
Cortisol, mean	0.50	0.32	64	1.56	0.12	0.02	0.39	64	0.06	0.95
Testosterone, mean	0.00	0.66	64	0.00	1.00	0.92	1.09	64	0.84	0.40
Cortisol × testosterone, mean	−2.38	0.92	64	−2.59	0.01	−2.84	1.17	64	−2.44	0.02
Anxiety, mean	0.31	0.33	64	0.95	0.35					
Dominance, mean	−0.46	0.33	64	−1.42	0.16					
Anxiety × dominance, mean	0.44	1.01	64	0.44	0.66					
Cortisol, SD						−0.15	0.52	64	−0.29	0.77
Testosterone, SD						0.48	0.55	64	0.88	0.38
Cortisol × testosterone, SD						−0.75	1.67	64	−0.45	0.65
Time of day	0.08	0.06	64	1.26	0.21	0.05	0.05	64	0.89	0.38
No. of females	−0.19	0.28	64	−0.68	0.50	−0.03	0.28	64	−0.11	0.91
Group size	0.22	0.15	64	1.42	0.16	0.08	0.15	64	0.51	0.61

$n = 74$ groups.

(31–34). To rule out the possibility that within-group hormonal variability was a key driver of our performance effects, we calculated each group's SD in testosterone and cortisol and tested whether within-group variability in testosterone, cortisol, or their interaction was related to group performance. When included in the main regression model, there were no significant effects of within-group variability in either hormone or their interaction on group performance. Further, the interaction between mean levels of testosterone and cortisol on group performance remained significant when within-group hormone levels were included in the model ($b = -2.84$, SE = 1.17, $r = -0.29$, $P = 0.02$) (Table 3, model 2). We also conducted exploratory analysis to test whether testosterone and cortisol unbiased means and SDs interacted to predict group performance and found no significant effects (*Supporting Information*). Additionally, we examined each group's concentration of individuals with the high-testosterone and low-cortisol profile to test whether greater concentrations of this collective hormonal profile predicted performance. We found no reliable effects of group concentration on group performance (*Supporting Information*), suggesting that the relationship between collective hormonal profiles and group performance is an emergent process that is not simply a reflection of individuals' hormonal profiles (Table S2).

The results demonstrate that groups collectively high in testosterone and low in cortisol outperform others, attaining higher standing. This finding is consistent with the dual-hormone hypothesis: Groups collectively high in testosterone may have a heightened status drive, but this status drive results in optimal decision-making only when coupled with low cortisol, a potential indicator of reduced stress and attenuated behavioral inhibition. Indeed, recent evidence suggests that increased testosterone combined with reduced cortisol may elevate an individual's status by promoting rational decision-making focused on maximizing financial profits (35). Our findings extend this research to the group level and suggest that groups with a propensity for status attainment, but without inhibition, engage in profit-maximizing decision-making strategies.

Our findings offer several avenues for future research. For instance, future studies should try to capture the emergent process through which an individual's neurobiology is transformed in an adaptively synergistic way to affect group performance. It is also critical to consider other neurobiological profiles that might influence group performance. Because anabolic hormones, such as dehydroepiandrosterone (DHEA), can counterregulate catabolic hormones (e.g., cortisol) and are indicative of an adaptive, thriving response during acute stress (36), we may expect to find that the interaction of group-level DHEA and cortisol predicts group performance under acute stress. This example, combined with our findings, highlights the importance of examining both the linear and interactive effects of collective hormones on group outcomes to capture the context-dependent nature of hormones (18), particularly as they relate to HPA and HPG axis activation. Additionally, although here we focus on resting hormone levels, examining hormonal reactivity and hormonal covariation among group members is another important direction for future research.

Our theorizing focuses on status attainment motivation as the key mechanism underlying our group performance effect; however, future studies should examine group-process measures to advance our knowledge of how status attainment motivations manifest themselves in group dynamics. There is evidence that the combination of elevated testosterone and reduced cortisol produces greater social rapport in interdependent decision-making tasks (35). This past finding suggests that groups in the present study with a collective hormonal profile of high testosterone and low cortisol may have experienced greater intragroup cohesion. Because intragroup cohesion is a critical determinant of group performance (37–40), we suspect that high testosterone/low cortisol groups produced more favorable performance outcomes partly because they were more cohesive.

The current research goes beyond past work that has focused on observable behaviors of the group or on psychological characteristics of individuals within the group as predictors of group performance without paying attention to biological factors at the collective level. By showing that groups collectively high in testosterone and low in cortisol outperform other groups, we provide a broader perspective on the processes at play in determining which groups rise to the top across and not just within social hierarchies. In doing so, we both establish evidence in support of the dual-hormone hypothesis at the collective level and open up additional questions regarding the neurobiology of group behavior and performance.

Materials and Methods

Participants. Participants were 370 Master in Business Administration (MBA) students (63.8% male; 36.2% female) enrolled in an introductory organizational behavior course and an operations management course at a business school in the northeastern United States. The average age of the sample was 27.44 y (SD = 1.93 y); 157 participants (42.4%) were born outside the United States. The ethnic composition of our sample was diverse: 54.9% white, 16.5% Asian, 10.8% Hispanic, 9.4% South Asian, 4.6% black, 1.4% Southeast Asian, and 2.4% other. Participants provided informed consent, and the Institutional Review Board of Columbia University approved all materials and procedures in our study.

Procedure. Participants were randomly assigned to 74 groups ranging in size from three to six people. These groups met regularly during the semester (6 wk) and were required to work on a variety of tasks together outside of class. There were no formally assigned positions or roles within the groups, allowing groups to develop roles and form status hierarchies naturally over time (41). Additionally, there was little variance across groups in gender composition, because the MBA sample was predominantly male. Specifically, 1.4% of the groups had no women, 18.9% of the groups had one woman, and the remaining 79.7% had two women. Furthermore, gender composition did not moderate our observed effects [$b = 0.15$, SE = 4.47, $t(64) = 0.03$, $r < 0.01$, $P = 0.85$]. The lower-level interaction between mean levels of testosterone and cortisol was still a significant predictor of group performance when gender was considered as a moderator instead of as a covariate [$b = -2.74$, SE = 1.28, $t(64) = -2.14$, $r = -0.26$, $P = 0.04$].

At the start of the semester, during their organizational behavior course, participants completed a survey assessing trait dominance. Two weeks later, they provided a saliva sample and completed a survey assessing trait anxiety. One week after providing the saliva sample, participants engaged in a competitive group decision-making task in their operations management course in which their performance was measured relative to other groups in the class at two time points.

Measures.

Testosterone and cortisol. Participants provided one saliva sample at the start of class during their assigned class time of 9:00 AM (early morning session), 10:45 AM (late morning session), 2:15 PM (early afternoon session), or 4:00 PM (late afternoon session). Participants first completed informed consent and biological questionnaires and then, after a 15-min rest period, provided a saliva sample that was later assayed for testosterone and cortisol. Saliva samples were frozen until the study was completed and then were shipped overnight on dry ice to a laboratory in College Park, PA. Saliva samples were assayed for testosterone and cortisol using a highly sensitive enzyme immunoassay (Salimetrics). Average intra- and interassay coefficients of variation were 2.5% and 5.6%, respectively, for testosterone and 3.5% and 5.1%, respectively, for cortisol. Before analysis, both hormone measures were log-transformed to account for significant positive skew, and mean levels were centered around their grand means (see *Supporting Information* and Table S3 for raw hormone values). Finally, group-level testosterone and cortisol profiles were calculated from the best linear unbiased predictors of testosterone and cortisol levels within each group (see *Data Analysis Strategy*), because groups varied in size from three to six members. We also calculated group-level SDs in testosterone and cortisol for each group.

Group performance. The group decision-making task was a computerized exercise (Littlefield Labs, Responsive Learning Technologies) simulating the supply-chain process of a series of laboratories providing blood testing to its

customers. Groups were told that they were employees at the blood-testing laboratory and that they would compete with the other groups in the class in managing several aspects of the laboratory (e.g., buying and selling capacity, adjusting lead-time quotes, changing lot sizes and inventory-ordering parameters, and selecting scheduling rules). Specific instructions were as follows:

> The lab has been running for 50 days, and management has hired a high-powered operations team (you) to manage the capacity, scheduling, purchasing, and contract quotations to maximize the cash generated by the lab over its lifetime. You will have control of the lab from day 50 to day 218. At 1 hour per simulated day, this translates to 7 real days. At day 218, you lose control of the lab, and the simulation will quickly run another 97 days of simulation. When you lose control of the lab, management expects you to leave the lab parameters set to maximize the lab's cash position when the lab shuts down later on day 315.

Groups were required to make decisions in response to historical records of inventory levels, queues, utilization, lead times, cash flows, and the group's standing relative to the other competing groups. Each group simultaneously received the same information through the computer interface. For example, new orders arrived at each group's fictional factory at exactly the same time. Our key dependent variable was a composite of the key group performance measures produced by the Littlefield Labs simulation: profitability in millions of dollars, number of contracts secured, number of reorders on existing contracts, and group rank relative to other groups in the class. Because these measures had different scales, they were first standardized and then averaged to create the aggregated group performance metric ($\alpha = 0.86$). Performance was assessed at two time points: 5 d into the simulation (simulating 170 d of laboratory operations) and 7 d into the simulation (simulating 315 d of laboratory operations). It is important to note that there was no normative solution or decision-making model in the decision-making exercise. Groups could use a variety of strategies to optimize financial performance.

Self-report measures. Participants completed an online survey assessing trait dominance using the Revised Interpersonal Adjective Scales (IAS-R) (42). Three items—dominant, assertive, and forceful—were rated on a scale ranging from 1 (does not describe me at all) to 7 (describes me very well) to assess dominance. These three items have demonstrated high correlations with the full eight-item Dominance Scale (43) and thus are considered suitable measures of trait dominance. The three items were intercorrelated ($\alpha = 0.79$) and therefore were combined into one overall index of trait dominance. Two weeks later, participants completed the Positive and Negative Affect Schedule (PANAS) (44) and rated their feelings on 20 emotional states (10 positive and 10 negative) using five-point scales ranging from 1 (not at all) to 5 (a great deal). We were particularly interested in the anxiety subscale of the PANAS (nervous, afraid, scared; $\alpha = 0.84$), given that cortisol increases in situations that evoke psychological stress and anxiety (45).

Data Analysis Strategy. The primary analyses reported in the main text examine the final results (i.e., day 7 of the exercise) using a multilevel model (46). Specifically, our dependent variable, group performance, was collected at the group level, but we wanted to predict this group-level outcome from the hormones that were collected at the individual level. Therefore, we conducted a multilevel model that accounted for the nesting of individuals (level 1) within groups (level 2) by estimating the collective group hormones from the best linear unbiased predictor for all group aggregates of variables measured at the individual level. This approach is known to be superior to simply using group means as predictors, and the multilevel model corrects the slope SEs to account for heteroscedasticity caused by unequal group sizes. In the *Supporting Information* we also modeled group performance as a function of time of performance (day 5 or day 7, which simulated days 170 and 315 of laboratory operations, respectively); group unbiased means and group SDs for testosterone and cortisol; the three-way interaction between time of performance, group testosterone, and group cortisol; and all three possible two-way interactions between time of performance, group testosterone, and group cortisol using a multilevel model controlling for time of day, gender composition, and group size. All predictors were mean centered before analysis. All analyses were conducted using R 3.2.2 (47). The full data and analysis script that reproduces the numbers reported in the main text and in *Supporting Information* are provided on the Open Science Framework (https://osf.io/jg5z4).

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Supporting Information

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SI Materials and Methods

In addition to assessing each group's final performance (day 7), we collected an interim (day 5) measurement of performance for a subset of the groups ($n = 52$), because we wanted to explore whether collective hormonal profiles predicted performance consistently throughout the simulation or had a stronger effect over time. To test this additional hypothesis, we accounted for the repeated measurements by estimating a two-level multilevel model in which the interim performance (day 5) and final performance (day 7) measurements were nested within groups. We estimated a random intercept for each group to allow for group differences in overall performance and a random slope of time of performance to allow groups to show different trajectories for performance over the week. For this growth curve model, time of performance was effect coded so that −1 represented performance on day 5 and 1 represented performance on day 7.

We also tested an exploratory hypothesis suggested by an anonymous reviewer as to whether the concentration of the collective hormonal profile of high testosterone and low cortisol within groups predicted performance. Because the dual-hormone hypothesis is traditionally considered as the interaction between continuous variables, we needed a robust way to classify individuals into hormonal profiles in 2D space. We conducted this classification with a *K*-means cluster analysis (48) with the MacQueen algorithm to identify four hormonal profiles, using ± 1 SD as the a priori centers for the clusters. This method is preferable to using a median split to create the groups, because the continuous nature of the hormone measurements is negated in a median split, and each variable is assumed to play an independent role in a median split. The cluster analysis fully uses the dimensionality of the hormones and classifies participants into hormonal profiles by considering both hormones simultaneously. The cluster analysis also converged on a stable solution in seven iterations, creating four profiles that varied by low and high combinations of testosterone and cortisol. After participants were classified into each hormonal profile by the cluster analysis, we summed the number of participants within each group that followed the ideal high testosterone/low cortisol profile and the opposing high testosterone/high cortisol profile and used these variables to predict group performance.

Finally, we conducted exploratory analyses to examine and rule out the possibility that (*i*) group-level testosterone exerts its effect on group performance when there is variability in group-level cortisol, and (*ii*) variability in group-level testosterone predicts group performance when group-level cortisol is low.

SI Results

Time of performance did not moderate the group-level hormone effects ($b = -0.001$, SE = 0.39, $r = -0.001$, $P = 0.99$) (Table S1). However, the interaction between testosterone and cortisol reliably predicted both interim-simulation and final group performance ($b = -2.70$, SE = 0.93, $r = -0.33$, $P = 0.01$). This result suggests that the group's dual-hormone profile was already predictive of performance relatively early in the simulation and that this profile continued to predict which group would ultimately perform the best at the end of the simulation.

We repeated our primary analysis depicted in Table 2 of the main text with concentrations of collective hormonal profiles instead of allowing group levels of testosterone and cortisol to vary continuously. Specifically, we modeled group performance as a function of the count of the number of group members with the high testosterone/low cortisol and the high testosterone/high cortisol profiles, controlling for time of day, number of females in the group, and group size. This analysis of collective hormonal profile concentrations revealed no reliable effects of group concentration on group performance (Table S2). The number of group members with the high testosterone/low cortisol profile was unrelated to group performance ($b = 0.001$, SE = 0.04, $r = 0.002$, $P = 0.99$), as was the number of group members with the high testosterone/high cortisol profile ($b = 0.005$, SE = 0.05, $r = 0.01$, $P = 0.93$). This analysis suggests that the relationship between collective hormonal profiles and group performance is not necessarily driven by a few key individuals with the target hormonal profile but rather reflects an emergent process that arises from the combination of all group members together.

Finally, the interaction between group-level testosterone and group-level variability in cortisol was not significant [$b = 0.92$, SE = 2.32, $r = 0.05$, $t(67) = 0.40$, $P = 0.69$], nor was the interaction between group-level variability in testosterone and group-level cortisol [$b = 1.26$, SE = 1.38, $r = 0.11$, $t(67) = 0.92$, $P = 0.36$]. Thus, it seems that group performance is best predicted by the collective hormonal profiles built from unbiased group means of testosterone and cortisol, not from their variability.

Table S1. Multilevel model predicting group performance

Variable	Slope	SE	*df*	*t*	*P*
Intercept	0.22	0.10	67	2.10	0.04
Time of performance	−0.04	0.05	48	−0.86	0.40
Cortisol, mean	0.14	0.33	67	0.41	0.68
Testosterone, mean	0.14	1.04	67	0.14	0.89
Time of performance × cortisol, mean	−0.10	0.15	48	−0.65	0.52
Time of performance × testosterone, mean	0.56	0.39	48	1.43	0.16
Cortisol, mean × testosterone, mean	−2.70	0.93	67	−2.90	0.01
Time of performance × cortisol, mean × testosterone, mean	0.00	0.39	48	−0.01	0.99
Time of day	0.04	0.06	67	0.66	0.51
No. of females	−0.08	0.34	67	−0.23	0.82
Group size	0.12	0.16	67	0.73	0.47

$n = 74$ groups for final performance measured on day 7, and $n = 52$ groups for interim performance measured on day 5. Time of performance refers to whether group performance was assessed in the interim (day 5) or at the end of the simulation (day 7).

Table S2. Exploratory model predicting group performance from group concentrations of testosterone and cortisol

	Model 1					Model 2				
Variable	Slope	SE	*df*	*t*	*P*	Slope	SE	*df*	*t*	*P*
Intercept	−0.01	0.17	71	−0.04	0.97	−0.01	0.17	68	−0.04	0.97
High testosterone/low cortisol	0.00	0.05	71	−0.01	0.99	0.00	0.04	68	0.01	0.99
High testosterone/high cortisol	0.01	0.06	71	0.13	0.89	0.00	0.05	68	0.09	0.93
Time of day						0.02	0.05	68	0.34	0.74
No. of females						−0.39	0.25	68	−1.60	0.11
Group size						0.33	0.14	68	2.26	0.03

$n = 74$ groups.

Table S3. Descriptive statistics for raw hormone measures

	Males				Females			
Testosterone/cortisol	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Testosterone, pg/μL	141.43	58.45	52.74	541.23	55.77	25.63	15.28	155.53
Cortisol, mg/dL	0.21	0.16	0.04	0.95	0.23	0.24	0.03	2.18

$n = 370$ participants.