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Neural, Mood, and Endocrine Responses in Elite Athletes Relative to Successful and Failed Performance Videos

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In this follow-up study, self-referential videos of success and failure were used for mood provocation to investigate mood, neural, and endocrine activity among 26 internationally competitive athletes using functional Magnetic Resonance Imaging (fMRI) and salivary hormone measures. The initial sample of 14 athletes who had experienced career-threatening failure was contrasted to 12 athletes with exceptional success. Endocrine data were added to the preliminary report to round

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out a psychoneuroendocrinology perspective on success and failure. On-line and prepost mood ratings confirmed successful mood provocation. fMRI BOLD signals revealed significantly greater activation in right premotor cortex and left sensorimotor cortices following self-reference video for successful athletes than (previously reported) failed athletes. Percentage gains in the ratio of testosterone to cortisol from Time 1 to Time 2 among success athletes positively correlated with right premotor cortex BOLD activity. Overall, the results suggest that affect associated with self-reference corresponds to an integrated neural and endocrine response to competitive challenge.

Keywords: cortisol, testosterone, self-reference, fMRI, athlete, mood

In a previous fMRI study, we had monitored elite swimmers who had failed competitively to make the Canadian Olympic team (Davis et al., 2008). That study used a unique sample of former Olympians and persons who had earned high international performance rankings. The study was the first to report significant motor and sensorimotor compromises related to negative affect, but it was limited to an analysis of the effectiveness of a cognitive-behavioral mood intervention on the neural areas linked to self-reference among failed competitive athletes only. Moreover, to show the relationship of mood to neural activity, the design required two sessions of fMRI, one as a baseline and one following the intervention. This first report did not address endocrine activity related to competitive outcome (although endocrine data had been collected), and it did not include winning athletes. In the present article, using only one fMRI session (and no intervention), we provide a brief follow-up to the initial fMRI findings and (a) assess interactions between the neural and endocrine activity to viewing personal-successful or personal-failed competitive challenge response and (b) frame this follow-up within the *challenge hypothesis.*

Among humans, the challenge hypothesis (Hau, Wikelski, Soma, & Wingfield, 2000; Logan & Wingfield, 1990; Wingfield, 2005) posits that androgens should be high around times of social challenge. Research has investigated the effects of competition on testosterone (T; Archer, 2006; van Anders & Watson, 2007) and cortisol (C), which sometimes acts in an inverse relation to testosterone and augments a dominance assertion (Edwards & Kurlander, 2010; Edwards, Wetzel, & Wyner, 2006; Fry, Schilling, Fleck, & Kraemer, 2011; Wirth, Welsh, & Schultheiss, 2006). In addition, studies addressing whether differential competition outcomes relate to changes in testosterone and cortisol have focused on wins vs. losses relative to attitudes toward challenge, dominance, and social status (Edwards et al., 2006; Mehta & Josephs, 2010; Salvador & Costa, 2009).

The endocrine work utilizing athletic competitions has yielded an overall set of mixed findings. In women, competition readiness appears to increase testosterone reliably (Edwards & Kurlander, 2010; Oliveira, Gouveia, & Oliveira, 2009), but not unidirectionally (Wirth et al., 2006), while cortisol does not always shift predictably with either a win or a lose outcome (Oliveira et al.). Moreover, competition outcomes appear generally related to increased testosterone in men (Fry et al., 2011), but even these data are mixed with null results (Oliveira et al., 2009) and inconsistencies attributable to mediators such as prior learning (Salvador & Costa, 2009; Wirth et al., 2006).

The lack of clear effect for competition on endocrine outcomes has led researchers to explore additional dimensions of successes and failures. One body of work has focused on mood and cortisol as potential moderators in the ratio of testosterone to cortisol (T/C) response. For example, data suggest that increases in testosterone postcompetition may be a function of reward valence (Carre, 2009; Mehta & Josephs, 2010) and related to positive mood changes (Mehta & Josephs, 2006; Salvador, Suay, Gonzalez-Bono, & Serrano, 2003). Other findings suggest that confidence, competitiveness, and a motivation to win are associated with increases in both cortisol and testosterone (Suay et al., 1999). Further, it appears that cortisol and testosterone may moderate each others' response to competition and status threats (e.g., Czoty, Gould, & Nader, 2009; Mehta & Josephs, 2010), highlighting the potential importance of the ratio of testosterone to cortisol. In addition, T/C ratios have been argued to be an important indicator of overtraining stress (Armstrong & VanHeest, 2002; Goodyer, Herbert, & Altham, 1998; Salvador et al., 2003).

We view competition as a form of evaluative stress and, regardless of outcome, consider both testosterone and cortisol to be important correlates of self-reference processing following stress: cortisol may affect not only testosterone but the balance of T/C (Iellamo et al., 2003; Salvador et al., 2003; Suay et al., 1999), though, in the end, both testosterone and cortisol are central to understanding the endocrine response. Competition resulting in disappointment and failure can yield relative increases in cortisol (Mehta, Jones, & Josephs, 2008; Tang et al., 2007), perhaps due to the accompanying negative affect, status threat, and limbic involvement that failure may entail (Tang et al., 2007; Young, 2004). Changes to testosterone occur following competition for similar reasons (e.g., Hermans, Ramsey, & van Honk, 2008; van Wingen et al., 2009).

Given our initial findings, which highlight the role of motor cortices in self-reference processing of failure, we elected to expand the neural exploration of competitive challenge to a success-failure paradigm and to examine, at the same time, whether expected neural differences in success-failure processing are reflected in parallel endocrine activity.

Method

Participants

Twenty-six elite athletes (15 female, 11 male), ages 18–31 years, participated in the study on the basis of having won a medal at a major international competition or having had career-threatening failure (mean age = 23.5, *SD* = 4.13 years). For each athlete, the fMRI session occurred within roughly eight months of the international competition.

The failure condition consisted of 14 athletes (10 female, 4 male); 11 had missed qualification for the Olympic Games, and 3 had failed at the Olympic Games. All held lower world rankings following failure than they had at the time of entry to the Olympic trials or Olympic Games (the fMRI results relative to this fail group were published elsewhere, but without hormonal data [Davis et al., 2008]; where the first study had two fMRI blocks with an intervention between blocks, the present experiment contrasted success and fail athletes on only one fMRI block).

The success condition consisted of 12 athletes (7 male, 5 female). Two athletes had won an Olympic gold medal, 1 had won silver at the Olympic Games, and 9

had medaled at a World Championship competition. In total, the success group participants had medaled 49 times at the Olympics and at World Championships.

Among the fail athletes, none reported a history of having used medication for a mood disorder. Means on the Beck Depression Inventory-II (Beck, Steer, & Brown, 1996) before fMRI were 9.86 (SD = 6.89) for fail athletes and 2.25 (SD = 3.33) for success athletes, $F(1,24) = 8.48$, $p < .01$.

All athletes had undergone regular testing for drug abuse under World Anti-Doping Protocols, and none had ever tested positive for using banned substances at a major event or out of competition. None of the athletes reported a history of a substance abuse disorder, and none reported having been intoxicated with alcohol within at least two weeks before fMRI. Written informed consent was obtained from all participants according to ethics guidelines of the University of British Columbia, and the study was approved by the Internal Review Board.

Tasks

The 14-min fMRI spanned two video conditions. One was a 4-min neutral stimulus and the second was the personal stimulus. fMRI acquisition for each condition was preceded by a 1-min rest period. The neutral video was followed by the 8-min self-reference video, a film of either personal failure or success. Participants provided online ratings of their subjective level of sadness (fail condition) or happiness (success condition) while undergoing fMRI using a visual analog scale (0–7), which was present on the screen at all times with the instruction to "Use the response pad to indicate your current level of sadness (happiness)." The participants pressed one button to increase their rating of subjective distress (left index finger) and the second to decrease it (right index finger).

The neutral video condition displayed other athletes racing and training and was designed to enable a within-subject control condition to contrast with activations to personal video of recent success or failure. No athlete had viewed the video sequences in the 2-month period preceding their participation. While the use of video in coaching has since become a widespread practice, up to the time of this research, national team athletes were not viewing video in any systematic way; none in our sample had ever seen the actual video used in this experiment with the unique composite of start, finish, final standings, the scoreboard clock showing their time, or celebratory or despondency clips (as taken from TV footage). The final 480-s video content was constrained to a 3:1 ratio of (a) racing to affective content yielding 360 s of racing stimulus and (b) 120 s of affective content.

Instructions were the same for each group: The athletes were asked to reexperience the way they felt during and immediately after their own swimming performance (i.e., sadness, embarrassment, dejection, and guilt [fail condition], or elation, pride, confidence, and optimism [success condition]).

Measures

Positive and Negative Affect Schedule. Immediately after scanning, participants also completed a modified version of the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988) in which they rated the intensity of subjective experience for seven states (sad, anxious, angry, tired, relaxed, energetic, happy) on a scale from 0 (*not at all*) to 7 (*very much so*). The sad and happy scales were isolated for this postscan mood assessment.

Image Acquisition. Echo-planar images were collected on a Philips Gyroscan Intera 3T scanner, equipped with a SENSE coil. Conventional spin-echo T_1-weighted sagittal localizers were used to view head position and to graphically prescribe the functional image volumes. Functional image volumes sensitive to the Blood Oxygen-Level Dependent (BOLD) contrast signal were collected with a gradient echo sequence (TR/TE 2000/30 ms, 90° flip angle, FOV 216 mm × 143 mm × 240 mm (AP, FH, RL), 3.00 mm slice thickness, slice gap 1 mm, and 36 axial slices.

Image Processing. Statistical Parametric Mapping software (SPM2, Wellcome Institute of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm/) was used for image reorientation, realignment, normalization into Montreal Neurological Institute (MNI) space, and smoothing with a Gaussian kernel (8 mm FWHM) to compensate for intersubject anatomical differences and optimize the signal to noise ratio. The BOLD response was modeled using Finite Impulse Response functions (FIR) estimated for each of eight continuous 30-s epochs within each 4-min block. Voxel-by-voxel whole brain contrasts showing significant effects of viewing failed performance have been reported in Davis et al. (2008).

ROI Analysis. Figure 1 shows the location of the two a-priori regions of interest (ROIs) in right premotor cortex (Talaraich coordinates: x = 26, y = 1, z = 42) and left sensorimotor cortex (x = –29, y = –17, z = 43), which were employed on an a-priori basis. Binary masks of such activation clusters were created (MatLab in-house software, Laboratory for Neuroimaging, UBC). First, individual subjects' mean estimated magnitude of response (beta value) was extracted for each condition (fail video/fail group, neutral video/fail group, success video/success group, neutral video/success group) and averaged over each task duration (4 min). Mean Beta values for each ROI were entered in 2-way repeated-measures ANOVAs with factors being Group (fail and success) and Condition (neutral video and personal video). Significance values were adjusted with the Greenhouse-Geisser epsilon method, and post hoc comparisons used the Bonferroni method. Finally, we employed the two ROIs within each athlete group to perform simple correlations with mean mood ratings for the same epochs.

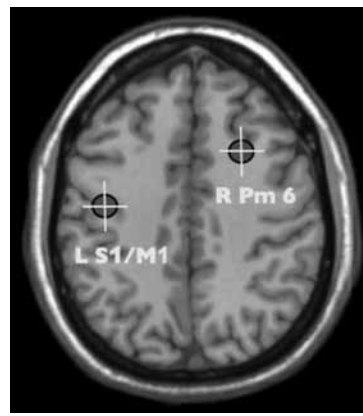

Figure 1 — Horizontal slice at z = + 42 showing the location of the Regions of Interest (ROIs) in R Pm6 (x = + 26, y = +1, z = + 42) and L Sensorimotor1/2 (x = –27, y = –17, z = + 43). Adapted from Davis et al. (2008).

Hormonal Measures. Testosterone and cortisol were measured from saliva samples taken immediately before and after the fMRI session. Saliva was collected in polystyrene tubes pretreated with sodium azide. Salivation was stimulated with sugar-free gum (Trident, cherry flavor). The saliva samples were frozen at –20 °C until assay. Circadian variation was not a factor in this experiment, as all contrasts were made on a within-subject basis. Moreover, subjects were randomly scheduled to appointments between 9:00 a.m. and 3:00 p.m., with success and failure having equal subject representations in the morning and afternoon fMRI sessions.

Hormone concentrations were measured by radioimmunoassay at the Endocrine Core Laboratory, Yerkes National Primate Research Center, Emory University. All samples were measured in duplicate, using a modified kit from Diagnostic Systems Laboratories (Webster, TX). The cortisol assays had interassay coefficients of variation of 2.91% at .26 ug/dL and 4.39% at 1.94 ug/dL, and intra-assay coefficients of variation of 8.7% and 5.2%. The testosterone assays had a sensitivity of 2–500 pg/mL at 200 uL dose. The interassay coefficients of variation were 8.77% at 0.65 ng/mL and 6.88% at 5.06 ng/mL. The intra-assay coefficient of variation was 6.54% at 98.82 pg/mL.

Results

Mood Response

To specifically evaluate the mood manipulation, participants also provided online mood ratings on an 8-point Likert scale during fMRI, from the beginning to the conclusion of fMRI. As shown in Table 1, analyses of these scores confirmed the efficacy of the videos to provoke differential mood responses. Fail videos (M = 3.8, SD = 0.04) elicited higher sadness ratings than neutral videos (M = 1.1, SD = 0.02) for fail athletes, $F(1,12) = 33.7$, $p < .001$. Similarly, success videos elicited higher happiness ratings (M = 4.3, SD = 1.2) than neutral videos (M = 1.8, SD = 0.8) for success athletes, $F(1,10) = 18.16$, $p < .001$.

In addition, after fMRI, as measured on the PANAS and summarized in the Table 1 one-way ANOVA data, success athletes reported feeling significantly happier, $F(1,24) = 25.29$, $p < .001$, and less sad, $F(1,24) = 9.91$, $p < .01$, than fail athletes.

fMRI

Right Premotor Cortex. Mean BOLD activation in the right premotor cortex (BA6—x = 26, y = 1, z = 42) during the personal video was significantly greater for the success (0.29) than for the fail group (–.10), $F(1,24) = 9.50$, $p = 0.005$. Analyses confirmed no significant group differences in mean BOLD activity during viewing of the Neutral Video, $F(1,24) = 0.30$, *ns* (see Figure 2). There was no effect due to gender, $F(1,24) = 1.40$, *ns.*

Left Sensorimotor Cortex. Similarly, the personal video mean BOLD signal activations for the success group (0.02) were significantly higher in the left sensorimotor cortex (BA4/1—x = –29, y = –17, z = 43) than those for the fail group (–.27), $F(1,24) = 8.14$, $p = 0.009$. Again, analyses confirmed no significant group differences in mean BOLD activity during the viewing of the neutral video, $F(1,24) = 0.04$, *ns* (see Figure 2). There was no effect due to gender, $F(1,24) = 1.40$, *ns.*

Table 1 Mood Manipulation: Mean Online and PANAS Ratings

Within Group Mood	Online Self M *(SD)*	Online Neutral M *(SD)*
Fail (sadness)	3.8 *(0.04)*	1.10 *(0.02)*
F (1,12)	33.70 [a]	
Success (happiness)	4.30 *(1.20)*	1.80 *(0.80)*
F (1,10)	18.16 [a]	
Between Group Mood	**PANAS Sad M *(SD)***	**PANAS Happy M *(SD)***
Fail (n = 14)	2.14 *(1.70)*	2.43 *(1.99)*
Success (n = 12)	0.42 *(0.90)*	5.83 *(1.34)*
F(1,24)	13.85 [a]	22.15 [a]

[a]$p < .01$

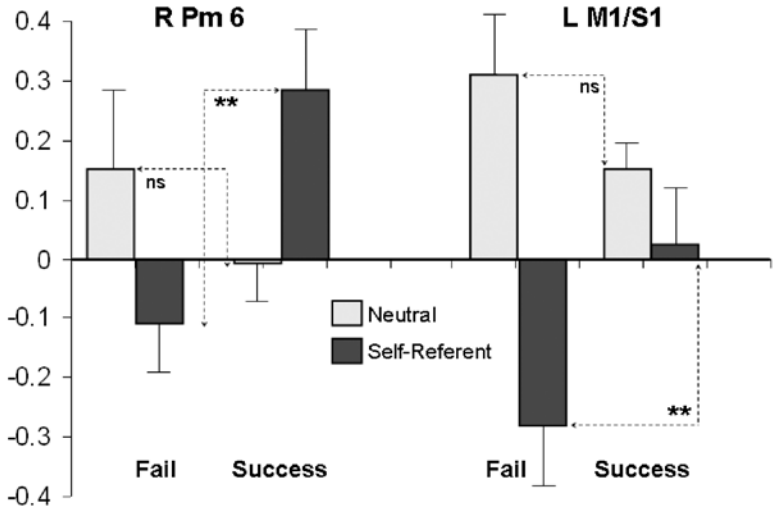

Figure 2 — Mean BOLD activation in R Pm6 and L M1 as a function of Group (Fail vs. Success) and Type of Video (Neutral or Time 1 vs. Self-Referential or Time 2). $^{**}p < .005$. Note significant increase in BOLD response between success and fail self-referential video conditions.

Hormonal Response

The T/C ratio was used to assess relative hormonal changes at Time 2 relative to Time 1 (Time) across fail and success (Condition) using repeated-measures ANOVAs. There were significant main effects of Time, $F(1,22) = 11.29$, $p < .01$, and Condition, $F(1,22) = 8.51$, $p = 0.01$. There was also a significant Time × Condition interaction, $F(1,22) = 4.38$, $p < 0.05$. Table 2 reviews the within-group testosterone,

Table 2 Means (SDs) for Testosterone (pg/ml), Cortisol (ug/dl) and T(pg/ml):C(ug/dl) Pre and Post fMRI

	Testosterone M (*SD*)	Cortisol M (*SD*)	T/C M (*SD*)
FAIL Time 1—Pre fMRI			
Male (n = 4)	119.19 (35.18)	0.63 (0.29)	197.76 (30.55)
Female (n = 10)	20.26 (9.49)	0.41 (0.08)	49.29 (20.83)
Total (n = 14)	48.53 (49.99)[a]	0.47 (0.19)[b]	91.70 (73.21)[2]
FAIL Time 2—Post fMRI			
Male (n = 4)	113.62 (30.29)	0.55 (0.13)	247.81 (48.69)
Female (n = 10)	21.49 (10.06)	0.37 (0.10)	56.82 (17.14)
Total (n = 14)	53.52 (55.18)[a]	0.42 (0.13)[b]	111.39 (93.63)[2]
SUCCESS Time 1—Pre fMRI			
Male (n = 7)	111.74 (24.79)	0.38 (0.12)	310.74 (72.65)
Female (n = 5)	19.49 (17.75)	0.45 (0.17)	58.03 (65.68)
Total (n = 12)	73.30 (52.01)[1]	0.41 (0.14)[c]	205.44 (146.22)[3]
SUCCESS Time 2—Post fMRI			
Male (n = 7)	149.18 (39.76)	0.33 (0.14)	535.72 (253.51)
Female (n = 5)	18.03 (17.63)	0.30 (0.18)	80.41 (86.18)
Total (n = 12)	94.53 (74.40)[1]	0.32 (0.15)[c]	346.01 (304.50)[3]

Note. [a, b, c] nonsignificant differences between means with the same letter superscript

[1, 2, 3] $p < .05$. significant differences between means with the same numeric superscript

cortisol, and T/C Time and Condition means and highlights the importance of T/C as related to Time where there were significant prepost differences for both fail and for success athletes ($p < .05$).

With differences in hormonal systems between men and women, the interpretation of gender effects in these results awaits future research beyond this preliminary study. Unfortunately, gender and group size differences preclude detailed analysis of these T/C data and leave important questions: Future, planned research, will determine, for instance, whether the ratio of T/C is as important for BOLD changes for successful women as for successful men.

Still, while the Gender and Time interaction was significant, $F(1,22) = 7.31$, $p = 0.01$, the within-group post hoc tests of gender differences in T/C change from Time 1 to Time 2 suggest that these differences were not significant for either the success condition, $F(1,11) = 4.76$, *ns*, or the fail condition, $F(1,14) = 1.05$, *ns*. Thus, it may be that gender was not the basis for the T/C change, but this remains conjecture because there were only five female athletes in our success group and only four male athletes in the fail group.

Throughout, the T/C changes were in the expected directions for all groups with increases in T/C for success at Time 2 relative to Time 1 for success. Still,

and in keeping with our cautionary approach to this data analysis, paired samples *t* tests showed that a confident interpretation of this finding is premature. The mean testosterone difference between Time 1 and Time 2 for successful men was significant, $t(7) = 3.52$, $p < 0.05$, as was the difference in T/C, $t(7) = 1.67$, $p < 0.05$. As expected, paired contrasts for failed men yielded nonsignificant mean differences as shown in Table 2; for the Time 1 to Time 2 contrast, testosterone differences were not significant, $t(3) = 0.99$, *ns*, and T/C differences were, likewise, not significant, $t(3) = 1.76$, *ns*. For successful women, there was a similar finding on testosterone, $t(4) = 0.39$, *ns*, and for T/C, $t(6) = 3\ 1.67$, *ns*. The same result was found for failed women on testosterone, $t(4) = 0.63$, *ns*, and on T/C, $t(4) = 1.49$, *ns*.

Correlation Between Neural and Hormonal Responses

A percentage T/C gain from Time 1 to Time 2 was computed, (T/C Time 2—T/C Time 1)/T/C Time 1. This percentage T/C gain had a significant positive correlation with the Personal Video BOLD signal in right premotor cortex BA6 (R Pm 6), $r = 0.41$, $p < 0.05$, but not left sensorimotor cortex BA4/1 (L M1/S1) activity ($r = 0.1$, *ns)*. Figure 3 shows T/C changes between Time 1 and Time 2.

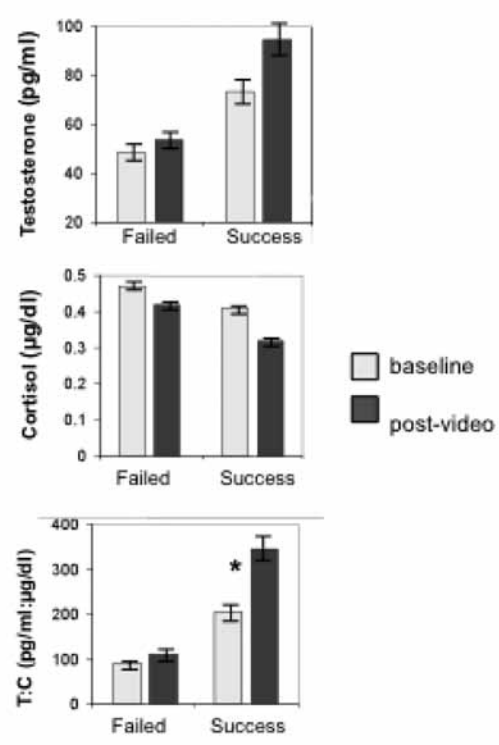

Figure 3 — Means as a function of group for Testosterone (T), Cortisol (C), and T/C at baseline (Time 1) and postvideo (Time 2). *$p = 0.02$

Discussion

With a unique sample of internationally competitive athletes, the majority of the success group had medaled on numerous occasions, and in a follow-up, which complements our first report (Davis et al., 2008), the current study extended the earlier work to establish that watching a personal video of successful competitive performance yields the expected neural inverse of watching failure, a contrast that had not been demonstrated to date. While viewing videos, successful athletes became significantly happier and failed athletes became more sad. After fMRI successful athletes were significantly happier and less sad than their failed counterparts.

In differential patterns of mood, neural, and endocrine activity after self-reference viewing of failure, success athletes were not only happier but they also showed greater activation in right premotor cortex (BA6) and left sensorimotor cortex (BA4/1), and had a greater increase in the ratio of testosterone to cortisol (T/C) than did failed athletes. T/C gain was correlated with right premotor BOLD activity.

Neuroimaging of Self-Referential Sadness and Happiness

By using video for self-reference, a unique sample of elite athletes who had collectively won 61 medals at World Championships and Olympic Games, and a focus on competitive performance, these findings are quite distinct from earlier work with both (a) patient groups where autobiographically-induced sadness decreased activity in right prefrontal cortex while increasing activity in ventral anterior cingulate and insula (Liotti, Mayberg, McGinnis, Brannan, & Jerabek, 2002) and (b) healthy subjects using evoked sadness and happiness within the same experiment, but with heterogeneous groupings and a lack of focus on achievement (Bechara, Damasio, & Damasio, 2000; George et al., 1995; Habel, Klein, Kellermann, Shah, & Schneider, 2005; Lane, Whyte, Terry, & Nevill, 2005; Pelletier et al., 2003; Schneider, Habel, Kessler, Salloum, & Posse, 2000).

Although gender differences in the neuroimaging correlates of induced self-generated sadness and happiness have been identified (Habel et al., 2005; Schneider et al., 2000), albeit not consistently, we elected to preserve the quality of our subject sample and the generalizability of our findings to elite sport performance by including, for instance, only failed athletes with prior international ranking and only success athletes with international medal success. These strict subject inclusion rules yielded a very limited number of these unique athletes from which to draw, and we were therefore unable to assemble equal group sizes with balanced gender composition. Nonetheless, controls for gender effects on the significant BOLD activations and hormonal levels in self-reference permit the preliminary conclusion that the success-failure dimension is critical to understanding neural and hormonal relationships within the framework of competitive challenge.

Some have argued that conscious awareness of one's subjective state during emotional processing involves cognitive evaluation, which may down-regulate an affective response while also suppressing the subcortical/limbic activity found in neuroimaging studies of induced emotions (Bechara et al., 2000; Damasio et al., 2000; Liotti et al., 2000). These researchers conclude on the basis of this reasoning that subjective mood ratings should be collected at the end of an emotional block

and not during it (Northoff et al., 2009). Our estimates of correlation between affect and subcortical/limbic activity may, therefore, be conservative ones, because we had instructed our athletes to process affect by "allowing" their feelings and to rate changes in subjective affect. Critically, an online recording of affective ratings allows for more fine-tuned correlations with brain activity, since subjective intensity ratings peak and wane at different times, both between athletes and within an athlete (this research is in preparation).

Hormonal Responses to Self-Referential Sadness and Happiness

In highlighting the importance of the T/C ratio, we have stepped beyond approaches focusing on absolute cortisol or testosterone. One-dimensional hormonal shifts related to mood have been well-documented, and published findings generally support the expectation that endocrine activity correlates with mood changes. This literature is especially robust in relation to the particular sadness-cortisol connectivity (Drevets et al., 2002; Ottowitz et al., 2004), but there has also been support for a general mood-cortisol relationship (e.g., Stalder, Evans, Hucklebridge, & Clow, 2010). With testosterone, a very important recent study by Carré and Putnam (2010) builds on this literature in demonstrating a positive testosterone response to viewing a celebrated team success. Moreover, there is evidence to support an integrative model with testosterone in the T/C ratio relating to a happy (face) stimulus (e.g., Hermans et al., 2008) and to angry/fearful stimuli (van Wingen, Mattern, Verkes, Buitelaar, & Fernandez, 2010).

In the present data, the T/C ratio, with testosterone and cortisol taken as a functional unit, was related to positive mood and to motor activation. In the context of the challenge hypothesis, a motivation to win and a desire to dominate are major influences on absolute testosterone levels in postcompetitive self-reference. Following the suggestion that the neural effects of stress vary with the availability of an individual's coping resources (Taylor et al., 2008), our failed athletes, with lower T/C values, can be interpreted to have a shown pattern of neural response that was inverse to those seen in their successful counterparts. Perhaps the failed athletes lacked the mental skills or resources with which to evaluate and regulate the (hormonal and neural) response to negative mood, stress, or competitive setback. This possibility awaits future study.

Remembering that in the overall full sample, T/C was related to BOLD activations (see below), irrespective of gender; and with extreme caution, a case-illustration of two female athletes is used to highlight the importance that practitioners conceptualize testosterone and cortisol as a functional unit when considering hormonal-neural connectivity. These two women had each become spectacularly successful by the time of fMRI, having each competed in two Olympic Games and collectively winning eight Olympic and 15 World Championships medals. While their T/C levels were similar after competition fMRI self-reference, inspection of the data suggests that they took very difference paths to T/C change. The two had nearly identical T/C levels post self-reference fMRI; for athlete 1, T/C was 52.6, and for athlete 2, T/C was 48.8. From baseline, however, the differences were dramatic: Athlete 1 had gained in testosterone between time 1 and time 2 by roughly 230%, while athlete 2 had a reduction in cortisol by roughly 80% from baseline.

The example of these two subjects may have heuristic value, pointing to the dynamic properties of the T/C ratio and highlighting the importance of both the HPG (hypothalamus- pituitary-gonadal axis) and the HPA (hypothalamus-pituitary-adrenal axis) to individual differences in competitive challenge response and self-reference (cf., recent work on psychopathy by Glenn, Raine, Schug, Gao, & Granger, 2011). Planned future research will evaluate whether, for some athletes, competitive stress management will involve testosterone regulation through the HPG axis, while for other athletes, competitive stress management will involve cortisol regulation through the HPA axis. Success for one athlete may correspond to an elevation of T/C through the use of calming and meditative methods (to target C), while success for others may correspond to modified testosterone though boosting the intentional determination to dominate, win, and obtain reward (targeting testosterone).

The relative increase in testosterone with success self-reference may reflect a transient "readiness to engage" in competition an interpretation that is consistent with results of Carré and Putnam (2010). This response fits a challenge hypothesis interpretation (Wingfield, 2005) and renders a prediction that testosterone should be high around times of challenge and generally inverse to changes in cortisol (Bernhardt, Dabbs, Fielden, & Lutter, 1998; Eriksen, Murison, Pensgaard, & Ursin, 2005; Oliveira et al., 2009). It is important that while women in our study had lower testosterone levels than the men did, with correspondingly lower T/C ratios, the relative *gain* among successful women in T/C from baseline (Time 1) to postfMRI (Time 2) was consistent with this expectation, a result that awaits future study but which is supported by Bateup, Booth, Shirtcliff, and Granger (2002), who had also reported a consistent testosterone elevation tendency in success responding for both sexes.

As discussed, there were unavoidable gender differences between the unique study groups in this follow-up; the results can only be taken to suggest a possibility that testosterone drives the T/C ratio change because (notwithstanding the case example provided) cortisol levels did not change significantly between Time 1 and Time 2 for either group, while testosterone did (see Table 2 and Figure 3). This expectation requires follow-up, but is supported by data showing a role for testosterone in the prediction of T/C for both men (Kivlighan, Granger, & Booth, 2005) and women (Hamilton, van Anders, Cox, & Watson, 2009).

A Link Between Neural and Hormone Activity

This was the first study to evaluate mood variation together with hormonal change and cortical activity as an athlete viewed a personal competitive stressor. Although it would be logically expected that hormonal variability covaries with neural activity, this possibility requires future attention in larger samples of the success-fail continuum. Although we found no other data relating to happiness and success, it has been reported that there may be an inverse coupling of amygdala and ventromedial prefrontal cortex activity in sad adults (e.g., Urry et al., 2006) and that resulting elevations of cortisol among sad patients may be mediated by neural changes, which increase bioavailability (Römer et al., 2009). One expects the inverse would hold for successful, happy subjects.

The increase in testosterone, noting its role in both T/C and motor cortex activation following success self-reference, is consistent with this hypothesis and

suggests that an athlete who mentally prepares for competitive challenge by viewing personal success may succeed in future competitive performance by virtue of unique motor activations coupled to T/C shifts.

Conclusion

Our data are the first to suggest that testosterone and cortisol covary with neural activity during self-reference of competitive stress among athletes. Directionality appears dependent on the valence of the affective response and on the competitive outcome. Of central importance is that variation in T/C, stimulated by self-reference, corresponds to BOLD activations of premotor cortices. Pending replication, our findings may justify targeted interventions that can be expected to activate T/C change, while stimulating neural "readiness" for competitive challenge.

Conflict of Interest Statement

There were no biomedical financial conflicts of interest and there were no other conflicts of interest, directly or indirectly, for any of the researchers to declare.

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Ethics

This research was approved through internal ethics reviews at the University of British Columbia and, therefore, was performed in accordance with the ethical standards set in the 2008 revision of Declaration of Helsinki. All subjects gave written informed consent for participation.

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