Oxidative Stress and the Differential Expression of Traits Associated with Mating Effort in Humans

Nicholas M. Grebe[a], Melissa Emery Thompson[b], & Steven W. Gangestad[c]

[a]Department of Evolutionary Anthropology, Duke University, Durham, NC USA

[b]Department of Anthropology, University of New Mexico, Albuquerque, NM USA

[b]Department of Psychology, University of New Mexico, Albuquerque, NM USA

Send Correspondence to Nicholas Grebe, Department of Evolutionary Anthropology, Box 90383, 130 Science Drive, Durham, NC 27708 USA. Email: nicholas.grebe@duke.edu

Acknowledgments

The authors thank Elaine Guevara for her comments on a previous version of this manuscript.

Funding

This work was supported by a National Science Foundation Graduate Research Fellowship (DGE-1418062; fellowship to NMG).

Abstract: Oxidative stress is a physiological condition in which reactive oxygen species created through cellular respiration can potentially damage DNA and tissue. Oxidative stress may partially mediate trade-offs between reproductive effort and survival efforts. On the one hand, traits associated with reproductive effort, particularly costly male-male competition, are expected to raise oxidative stress. On the other hand, behavioral strategies may be a critical mediating mechanism, such that those who can better resist the physiological costs of oxidative damage exhibit increased mating effort. In a sample of 248 college students (173 men), we examined the associations between traits linked to mating effort—including personality features, athleticism, and history of illness—with levels of 8-OHdG, a biomarker of oxidative stress. 8-OHdG was measured twice, one week apart, once during active hours and once at awakening. In men, surgency, social dominance, and athleticism were all negatively associated with 8-OHdG levels in awakening, but not lab samples collected during active hours. In women, these same traits were positively associated with 8-OHdG levels, particularly in morning samples. Differences in associations based on sex and time of collection introduce additional complexities to understanding links between oxidative stress and mating effort.

1. Introduction

Organisms must pursue fitness-enhancing strategies given environmental conditions (e.g., abundance of resources, risk of extrinsic mortality) and individual conditions (e.g., mutation load, susceptibility to infection) that determine resource budgets. Thus, individuals modify the allocation of energy and effort towards certain classes of activities at the expense of others. Energy dedicated to costly activities, such as growth, reproduction, and immune responses, is energy not available for routine somatic maintenance, such as the avoidance or repair of oxidative damage. Consequently, there is long-standing theoretical and empirical support for trade-offs between survival and reproduction (e.g. Kirkwood & Rose, 1991; Friedman & Johnson, 1987; Clancy et al., 2001; Bartke & Brown-Borg, 2004; Blomquist, 2009). Oxidative stress may partially mediate these trade-offs. When individuals increase expenditure of energy on intrasexual competition or features that function to foster ability to win intrasexual competitions, they may suffer a decrease in expected lifespan because of increases in the unrepaired damage suffered from oxidative stress (see e.g. Speakman & Garratt, 2014).

1.1 Oxidative stress: Fundamentals

Aerobic respiration, through a series of redox reactions, leads to the synthesis of adenosine triphosphate (ATP), a main source of cellular energy. The chain also naturally produces reactive oxygen species (ROS) as byproducts, such as superoxide (O_2^-, an oxygen molecule with one electron missing). ROS can react with and damage DNA, lipids, and proteins. As adaptations, cells produce anti-oxidant enzymes, such as superoxide dismutase, to neutralize ROS. Conditions intrinsic and extrinsic to the organism can increase the rate at which ROS are produced or decrease the rate at which anti-oxidants are produced. Oxidative stress refers to a state during which the rate of ROS production outstrips the rate of ROS neutralization, leading to oxidative damage of DNA and tissues (Pizzino et al., 2017).

Oxidative stress has been claimed to play a role in the etiology of numerous diseases (e.g., cancer, Parkinson's, Alzheimer's, atherosclerosis, heart disease, and perhaps schizophrenia and major depression; e.g., Henchcliff & Beal, 2008; Colton et al., 2002; Che et al., 2010; Maes et al., 2011). The free radical (i.e., ROS) theory of aging (Harmon, 1956) proposes that aging – somatic breakdown – results in part from accumulated oxidative damage. Consistent with this idea, most mutations in somatic as well as germ cell DNA result from oxidative damage (at least in some organisms; Kujoth et al. 2007; Denver et al., 2009). At the same time, more recent evidence indicates the free radical theory is only partially correct, as oxidative stress also serves functions pertaining to somatic maintenance. Hence, for instance, phagocytes adaptively produce ROS to kill pathogens and protect the soma from harm. Transient oxidative stress is a part of normal (even adaptive) physiological functions, such as autophagy (Filomeni et al., 2015) and responses to physical exercise (Radak et al., 2008). Regulation of oxidative stress rather than ROS suppression per se may be the target of selection (Garratt & Brooks, 2012).

1.2 Recent interest within life history theory: Trade-offs, individual differences, and signaling of condition

1.2.1 Individual differences in proneness to oxidative stress

Though oxidative stress is implicated in the pathogenesis of serious diseases, within non-clinical populations a great deal of individual variation exists. Individual differences in proneness to oxidative stress or its impacts may arise in a number of ways. As oxidative stress reflects a balance between ROS production and anti-oxidant production, variations in each of these two components can affect proneness to oxidative stress.

First, individuals may differ in the rates at which they produce ROS. Increased rate of ROS production can result from (a) *de novo* mitochondrial and nuclear DNA mutations (e.g. Ishikawa et al., 2008), (b) polymorphisms (see e.g. Cuevas et al., 2019), (c) the presence of metal ions and other

toxins that affect oxidation (Beyersmann & Hartwig, 2008), and (d) metabolic rate (Finkel & Holbrook, 2000).

Second, individuals may differ in their rates of anti-oxidant production and/or repair capacities. Decreased rate of anti-oxidant production and repair can result from (a) *de novo* mutations or polymorphisms (see Garratt et al., 2014), (b) diet (Benzie, 2003), (c) overall energy budget or energy balance, (d) trade-offs with other fitness-enhancing activities (Brooks & Garratt, 2017), and (e) disruption of anti-oxidant processes (e.g., see comments on sleep below).

1.2.3 Sexually selected signals, reproductive effort, and oxidative stress

Based on the arguments presented above, to the extent that two individuals differ in their proneness to oxidative stress and resulting damage, all else equal, the individual less prone to oxidative stress will pay a lower cost for sexual signaling and, more generally, investments in reproductive effort (e.g., intrasexual competition). In turn, a lower cost in sexual signaling should result in a greater investment in signaling or investments in reproductive effort (e.g., Kokko et al., 2002). The "honesty" of some sexually selected signals, then, may be partially explained by a negative association between signal "strength" (degree of investment in a signal) and costs incurred from oxidative stress. (For a recent overview of more general effects of mitochondrial efficiency [e.g., with low production of ROS] on whole-organism performance, see Heine & Hood, 2020.) [1]

These ideas have guided numerous research programs on non-human animals to date. Findings and their possible interpretations are highly varied. Results in some species are consistent with signals being indicators of proneness to oxidative damage. In one experiment, for instance, superoxide dismutase knockout mice (where knockout reduces anti-oxidant production) had

[1] Some researchers have proposed that investing in secondary sexual traits requires increases in androgens, which decreases resistance to oxidative stress (e.g. Alonso-Alvarez et al., 2007)—this idea is distinct, though not mutually exclusive, from a framework that more generally appeals to energetic trade-offs.

deficiencies in sexual signal expression and energy production (Garratt et al., 2014). In some bird species, plumage coloration is linked to mitochondrial function, where ROS are produced; the coloration itself might even physically use up anti-oxidant carotenoids (e.g., Hill et al., 2019; see also Alonso-Alvarez et al., 2004, 2007; Hill, 2014; Henschen et al., 2016; Cantanero et al., 2020). Other research suggests that sexual signals may reflect sperm quality, as affected by local oxidative stress (see, e.g., Friesen et al., 2020). At the same time, other studies have failed to find associations between signal expression, reproductive effort, and markers of antioxidant capacity or oxidative damage (e.g., Henschen et al., 2018). Some have emphasized the lack of evidence that female reproductive effort in particular—which one would expect to be costly—incurs costs in the form of oxidative damage (e.g., Speakman & Garratt, 2014; but see Marcinkowska et al., 2020, who suggest that heightened oxidative damage is related to greater female facial attractiveness).

Researchers have proposed a number of reasons why links between sexual signaling, reproductive effort, and oxidative stress are complex and potentially variable across species, even if the conditions under which they apply are not well understood. Individuals in better condition may often be able to suppress oxidative damage, but for variable reasons—e.g., greater efficiency in energy production (and hence less need to produce anti-oxidants) or greater capacity to produce anti-oxidants. Depending on the relative importance of these two forces, both condition and signal expression could be negatively *or* positively correlated with anti-oxidant production (see Martinez-Lendech et al., 2018, for evidence of both, depending on the anti-oxidant, in the same study). As well, condition-dependent differences in the *marginal* costs of signal production (per unit energetic investment) need not translate into differences in the *total* costs. Individuals with "bigger" signals likely invest more energy in the signal. They may pay a lower cost in the form of oxidative stress per unit investment, which leads the signal to be honest, but the total oxidative stress they produce may still be greater (see Getty, 2006; Kokko et al., 2002, for discussions of viability sexual signaling in

general; as Kokko et al., 2002, note, more fit males may be less healthy and die earlier when sexual selection leads them to invest much more very heavily in mating [e.g., signaling and competition] than less fit males). In addition, not all signals are maintained by realized costs. Some signals may be relatively cheap to produce, but are honest because they become costly for individuals of low quality (e.g., when they provoke intrasexual competition and males in poor condition suffer costs of competitions). Yet other signals may be honest because they are inextricably linked with physiological processes (e.g., resistance to oxidative stress), not because they are costly (see Weaver et al., 2017). Individuals in better organismal condition may be better able to absorb the costs of oxidative stress generated adaptively (e.g., in its role in immune function). Finally, signal honesty may be maintained though costs not mediated at all by oxidative stress. Research and theory to date linking oxidative stress and signaling has been highly generative and fruitful, but much more is needed to fully understand the nature of these links.

1.2.4 Behavioral traits and oxidative stress

Behavioral traits may also reflect oxidative stress. Relative to their wild-type counterparts, transgenic fruit flies with overexpression of anti-oxidant mechanisms are better able to maintain mating and locomotor performance when exposed to a potent oxidative stressor (Teets et al. 2019). In a study of rhesus macaques, dominant males had lower levels of oxidative damage biomarkers when compared to less dominant males (Georgiev et al., 2015). In house sparrows, Losdat et al. (2019) found that socially dominant males produced sperm of greater motility, purportedly mediated by relative investments in soma versus sperm antioxidant protection. In yet other species, however, associations are opposite: more dominant individuals or individuals strongly expressing sexually selected signals pay a cost for these traits in the form of greater ROS production or reduced antioxidant capacity (e.g., Border et al., 2019; Arai et al., 2018); as noted above, they may be better able to maintain better somatic condition in the face of oxidative stress, which may explain why the

signals are honest indicators of condition). These associations pose the possibility that some degree of variation in behavior, particularly among traits that reflect interest and investment in intrasexual competition and mating effort, may be explained by differential ability to regulate oxidative stress.

1.3 Variation in Biomarkers of Oxidative Stress in Humans

Several biomarkers have been used by researchers to study natural variation in oxidative stress. The most widely used biomarker of oxidative damage to DNA is 8-OHdG (8-hydroxydeoxyguanosine). It is an oxidized nucleoside of DNA (specifically, guanosine), which gets excised through DNA repair and then eliminated through urination. In the oxidative stress literature, it is generally assumed that this repair process, even if incomplete, is proportional to the amount of damage incurred. One should expect to see high 8-OHdG levels if high rates of damage were incurred (Cooke et al., 2000; Valavinidis et al., 2009), and indeed, 8-OHdG has been found to be elevated in smokers and those exposed to more environmental toxins (e.g. Chuang et al., 2003), as well as in clinical populations with shortened telomeres (e.g. Ma et al., 2013).

Several studies have examined the stability of markers across time, including 8-OHdG levels. Longitudinal measurements of these biomarkers, ranging in duration from 2 days to 30 days, yield intraclass correlations of .51 to .96 (Nam et al., 2019; Alajbeg et al., 2017; Wang et al., 2019; Martinez-Moral & Kannan, 2019; Pilger et al., 2002). One can estimate, on these bases, that a single day's assessment of 8-OHdG has ~40% of its variance due to between-individual variability (i.e., a validity for assessing individual differences in 8-OHdG of the √.4 or ~.6). (Notably, individual differences in 8-OHdG are substantial, with coefficients of variation routinely exceeding 75% e.g., Alajbeg et al., 2017; Martinez-Moral & Kannan, 2019).

1.4 Current Research Questions

The current study explored a number of associations of interest between levels of oxidative stress, behavioral traits, and traits related to athleticism and health.

1.4.1 Oxidative stress, male dominance, and male athleticism

Our primary questions concerned associations between putative measures of men's overall investment in mating effort (i.e., their effort in obtaining and keeping mates) and oxidative stress, as assessed through 8-OHdG: (a) Does male surgency or, relatedly, social dominance, as assessed by self-report personality measures, predict levels of 8-OHdG?; (b) Does male athleticism or overall health, as assessed by self-report measures, predict levels of 8-OHdG? Regarding (a), we assessed a number of personality features postulated to partially reflect mating effort and/or investment, particularly in men: extraversion and energetic temperament (e.g. Nettle; 2005; Penke & Jokela, 2016), self-rated mate value (e.g. Fisher et al., 2008), and social dominance (e.g., Ainsworth & Maner, 2012). Regarding (b), male athleticism is a potentially important manifestation of somatic mating effort (e.g. Ellison, 2003). More broadly, reports of overall health, while not direct reflections of mating effort, may still provide information on i) overall phenotypic condition, which positively influences the total resource budget available for organisms to allocate to mating effort, and/or ii) investments in somatic maintenance, which reduce available resources for mating effort.

The nature of our study was exploratory. If traits associated with male intrasexual competition are positively associated with resistance to oxidative stress, as they are in rhesus macaques (Georgiev et al., 2015), dominant and athletic men should have lower oxidative stress levels, purportedly as a function of better mitochondrial performance (a lower rate of ROS production) or greater capacity to neutralize ROS. At the same time, we recognize that, by virtue of the energetic costs of engaging in mating effort, dominant or athletic men could also experience greater levels of oxidative stress (e.g., Arai et al., 2018; Border et al., 2019).

We assessed urinary 8-OHdG at two time periods for each participant. First, we collected urine during a lab session, which took place during an active time of the day (hereafter referred to as the "lab sample"). Second, we asked each participant to bring in a urine sample collected at first-of-

the-morning void (hereafter called the "awakening sample"). Levels of 8-OHdG in the latter sample reflects oxidative damage incurred during sleep, as well as oxidative DNA damage accumulated during the day but repaired overnight. These samples have the advantage of being relatively unaffected by recent physical activity, and thus might be expected to be more stable representations of individual variation. We explored whether male dominance and male athleticism is differentially associated with 8-OHdG levels between the two sampling sessions.

1.4.2 Oxidative stress and sex differences in associations

Though we targeted men to examine associations of features relevant to reproductive effort with 8-OHdG, we also explored whether similar associations would be observed in women. As the traits we examine are more pronounced in men, and are more directly hypothesized to associate with oxidative stress, we expected that the predicted pattern for men would be absent or weaker for women.

1.4.3 Other contributions to 8-OHdG concentrations

Among numerous potential internal and external influences, in the present study we were able to examine two particular factors have received attention for their links to oxidative stress: sleep disruption and anti-oxidant activity. We examined whether these forces might partially or fully mediate links between 8-OHdG and mating effort.

Periods of sleep offer organisms the opportunity to both suppress the rate at which new oxidative damage occurs (as metabolic expenditures are reduced during sleep) and actively repair DNA and other forms of cellular damage (e.g., Anafi et al., 2013). Hence, for instance, Anafi et al. (2013) examined a host of genes in peripheral mouse tissues that show "sleep-specific" changes in expression in tissue and found that many function to buffer tissue from oxidative stress as well as genes that enhance oxidative repair (on a similar pattern in *Drosophila melanogaster*, see Damulewicz et al., 2019). An important function of sleep—one prominent benefit that led it to evolve in most

animal species—may be the opportunity for oxidative repair. Sleep disruption, then, appears to have a two-fold effect: It induces oxidative stress (e.g., Brown & Naidoo, 2010; Gulec et al., 2012; Ramanathan et al., 2002; Villafuerte et al., 2015); at the same time, it inhibits repair of oxidative damage, such that, for instance, night shift workers clear less 8-OHdG (which, once again, gets excised from damaged DNA and excreted through urination; Bhatti et al., 2017). Thus, we asked whether individuals who reported greater levels of sleep disruption experienced greater levels of oxidative stress, as reflected in higher levels of 8-OHdG.

Second, we assessed urinary uric acid levels. Uric acid functions as a powerful anti-oxidant in circulating blood that suppresses superoxide levels (Davies et al., 1986). Most animal species degrade uric acid via uricase, though some primates (humans included) lack uricase; Ames et al. (1981) hypothesized that uric acid originated as an adaptation to extend lifespan in the primate lineage. Thus, we examined whether urinary uric acid levels might mediate associations between 8-OHdG and male traits. At the same time, uric acid is not necessarily an anti-oxidant, and may even function as a pro-oxidant in some contexts (Sautin et al., 2007). It is involved in immune defense, and may upregulate inflammatory responses via the production of the NLRP3 inflammasome (Braga et al., 2017). Uric acid's dual roles in redox-dependent inflammation and anti-oxidant function may help explain its U-shaped association with all-cause mortality, as well as mortality due to cardiovascular disease and cancer (Cho et al., 2018).

2. Methods

2.1 Participants

2.1.1 Study 1

We recruited 98 male participants in Study 1, all taking a psychology course at University of New Mexico, for which they partially fulfilled a research requirement. Participants were confined to a relatively narrow age group (mean age= 20.1, SD = 2.9 years).

2.1.2 Study 2

We recruited 75 heterosexual couples (mean age = 21.27, SD = 5.37 years) to participate in Study 2; at least one member of the couple came from a psychology student subject pool at University of New Mexico. This study was designed to investigate relationships between several physiological biomarkers and aspects of participants' romantic bonds (a separate component of this study was reported in Grebe et al., 2017). All participants reported being in an exclusive romantic relationship with their partner lasting at least one month; the mean reported relationship length was 24 months (SD = 23 months). In total, 33 women were naturally cycling, 38 used some form of hormonal contraception, 1 had undergone a hysterectomy, and 3 did not report this information (see [Grebe et al., 2017]).

2.2 Procedure

Participants in both studies attended an in-person laboratory session, typically during the early afternoon hours (average starting time in Study 1: 12:30 h; SD = 2:47; in Study 2: 13:36 h; SD = 2:38). Couples in Study 2 came into the lab together, but completed procedures in separate rooms. After providing informed consent, participants completed the questionnaires described below. Following questionnaires, but before leaving the lab, participants were asked to provide a urine sample. Finally, participants were given collection materials and instructed to return one week later to drop off a second urine sample, taken from their first-morning void.

2.3 Psychological Self-Report Measures

All participants (total N = 248) completed a battery of self-report measures concerning their lifestyle, personality, and health that served as the primary predictors of interest. We separate these measures into two broad categories: those designed to identify aspects of personality, and those designed to assess participants' overall health and athleticism. In some cases, romantic partner reports on these same measures were available.

2.3.1 Personality Measures

We focused on five measures designed to assess individual differences in dominant or energetic aspects of personality (a full list of items for these measures is available as an appendix in the ESM, and we provide descriptive statistics for these measures in Table S1). Though these do not constitute the entirety of personality measures participants completed, other scales tap facets of personality (e.g. magical ideation, conscientiousness, openness to experience) less clearly related to investment in mating effort, our construct of interest. Nevertheless, in robustness analyses (see ESM Tables S2-S4) we use all available personality measures to conduct factor analyses and examine associations with oxidative stress; these supplemental analyses support the robustness of the key results we report in the main text. Our five 'core' personality measures were as follows:

1. The social potency scale from the Multidimensional Personality Questionnaire (Tellegen, 1982) is a 26-item measure of social dominance. Example items include: "People consider me forceful;" "I am quite good at convincing others to see my way;" average $\alpha = 0.81$ across the two studies. The romantic partners of participants in Study 2 completed the same measure re-worded to concern a partner. E.g., "People consider him (her) forceful;" $\alpha = 0.89$. Self-reports correlated with partner-reports, $r = 0.48$ and 0.43, $p < .001$, for men and women, respectively.
2. A 16-item measure of non-submissiveness was created and administered to tap individual differences in unwillingness to tolerate, without a counter-response, actions by others aimed to diminish one's status or social standing; example items include "When other men [women] "cross the line" with me, I am not afraid to enter into a conflict with them;" "Most people probably respect me for my willingness to stand up for myself;" $\alpha = 0.79$ in Study 1, and $\alpha = 0.84$ in Study 2. The romantic partners of participants in Study 2 completed the same measure re-worded to concern a partner; $\alpha = 0.91$. Self-

reports correlated substantially with partner-reports, $r = 0.55$ and 0.39 for men and women, respectively.

3. Participants rated themselves on various physical features relative to other adults of the same age and sex (17 items); three questions on an "energetic" subscale asked participants how they perceived their relative levels of energy, vigor, and lethargy (reverse-scored); $\alpha = 0.74$ across both studies. Correlations between self- and partner reports were $r = 0.44$ for men and 0.33 for women.
4. A six-item mate value scale asked participants for their self-rated attractiveness, and the extent to which members of the opposite sex notice/are attracted to them; $\alpha = 0.91$.
5. The 60-item NEO Five-Factor Inventory (McCrae and Costa, 2004) was administered to participants to measure the "Big Five": Openness to Experience, Conscientiousness, Extraversion, Agreeableness, and Neuroticism. We used the extraversion dimension in our main analyses ($\alpha = 0.78$ and 0.85 across the two studies), which consistently shows links with reproductive success in men (Penke & Jokela, 2016).

Correlations between these personality measures are presented in Table 1.

Table 1. Correlations between self-reported personality measures.

	Social Potency	Non-submissiveness	Extraversion	Energetic Temperament	Mate Value
Social Potency	–				
Non-submissiveness	0.51	–			
Extraversion	0.51	0.28	–		
Energetic Temperament	0.31	0.27	0.52	–	
Mate Value	0.28	0.34	0.36	0.40	–

2.3.2 Health/Athleticism Measures

Participants also completed a number of items and/or measures related to their health and athleticism (a list of items and descriptive statistics can be found in the ESM). Some of these measures pertain to investments in sexually selected signals (a), while sleep patterns may explain variation in oxidative stress, independent of investment in such signals (b).

(a) In the aforementioned 17-item measure where participants rated themselves on various physical features relative to other adults of the same age and sex, they also provided reports on their relative coordination (four items), muscularity (three items), and athleticism (three items); α for self-reports ranged from 0.77 - 0.83. Partner-reports were available for these measures; partner reports correlated with self-reports at $r = 0.53$ for coordination, 0.48 for muscularity and 0.60 for athleticism. Additional measures included a 7-item subscale on perceived vulnerability to disease (Duncan, Schaller, & Park, 2009; α = 0.85 and 0.92 in the two studies), and individual items that asked about how often participants had a fever exceeding 100 °F in the past two years, how often they had been prescribed antibiotics in the past two years, and relative amount of school days missed due to illness as a child. Correlations between these measures are presented in Table 2.

(b) In Study 2, participants also provided information on their current sleep patterns (three items; α = 0.60) for which we calculated a composite score, with higher scores representing a greater frequency of sleep problems.

Table 2. Correlations between self-reported health measures.

	Muscularity	Coordination	Athleticism	PVD	Fever	Antibiotics	Sick from School
Muscularity	–						

Coordination	0.53	–					
Athleticism	0.56	0.62	–				
PVD	-0.25	-0.34	-0.33	–			
Fever	-0.11	-0.10	-0.14	0.37	–		
Antibiotics	-0.07	-0.00	-0.08	0.43	0.43	–	
Sick from School	-0.17	-0.19	-0.13	0.50	0.22	0.29	–

2.3.3 Factor Analysis of Questionnaire Measures

We performed two separate factor analyses on the measures detailed in section 2.3.1 and 2.3.2: one for personality measures, and one for health/athleticism measures. Factor analyses were performed using the *psych* package in R, with principal axis factoring and oblimin rotation. Table 3 displays the resulting pattern matrices for both factor analyses. We computed regression-based factor scores from these analyses and used them as predictors of 8-OHdG in subsequent analyses. For personality measures, parallel analysis suggested three factors (i.e., it revealed three eigenvalues greater than the mean expected given random data), which collectively accounted for 57% of the variance. The first two factors, which each individually accounted for 25% of the variance, were readily interpretable. The first personality factor extracted contained strong loadings (> 0.5) for extraversion, energetic temperament, and mate value, which we interpret and label hereafter as a "surgency" factor. The second personality factor contained strong loadings on social potency and non-submissiveness, which we interpret as a "dominance" factor. These first two factors were correlated with one another at $r = 0.56$. The third factor did not contain any loadings over 0.5; due to difficulty in interpreting this factor, we elected not to use it as a predictor of oxidative stress in our main analyses. See ESM (Table S5) for results using this factor. For health measures, parallel analysis suggested extracting two factors, which accounted for 27% and 21% of the variance,

respectively, and were both readily interpretable. The first factor contained strong loadings on muscularity, coordination, and athleticism, which we hereafter call an "athleticism" factor. The second factor contained strong loadings on perceived vulnerability to disease, frequency of fever and antibiotic usage in the past two years, and frequency of staying home from school with illness, which we interpret as a "vulnerability to illness/disease" factor. These two factors were moderately negatively correlated (r = -0.29).

Table 3. Pattern matrices for factor analyses of self-report measures, estimated using principal axis factoring and oblimin rotation. Loadings > 0.50 bolded.

Personality Measures			
Factor	*Surgency*	*Dominance*	*Factor 3*
Social Potency	-0.03	**0.82**	0.21
Non-submissiveness	0.11	**0.65**	-0.28
Extraversion	**0.54**	0.20	0.43
Energetic Personality	**0.72**	-0.05	0.08
Mate Value	**0.59**	0.05	-0.16
Health Measures			
Factor	*Athleticism*	*Vulnerability to Illness/Disease*	
Muscularity	**0.67**	-0.03	
Coordination	**0.79**	0.02	
Athleticism	**0.80**	-0.01	
PVD	-0.22	**0.69**	
Fever	0.02	**0.54**	

Antibiotics	0.15	**0.70**
Sick from School	-0.08	0.49

2.4 Assessment of Urinary Oxidative Stress Biomarkers

We collected two urine samples per participant. During the laboratory session of both studies, participants were asked to provide a 10 ml urine sample that we immediately froze at −20 °C. Average time since waking for this urine sample was 5.55 hours (SD = 2.81 hours). For the first-of-the-day (awakening) urine sample 7 days after the initial session (average time since waking: 1.43 hours; SD = 1.92 hours), participants either brought the sample to us immediately after collecting it, or froze it until it could be delivered, nearly all within 24 h. Upon delivery, we froze each sample at −20 °C. Although in principle biomarker levels could change if not immediately frozen, 8-OHdG concentrations have been reported to be stable even if kept at room temperature for 24 h (Matsumoto et al., 2008). All assays were performed in the Hominoid Reproductive Ecology Laboratory at the University of New Mexico.

In both studies, 8-OHdG was assayed in duplicate using ELISA kits manufactured by the Japan Institute for the Control of Aging (8-OHdG Check, distributed in the U.S. by Genox, Torrance, CA). The sensitivity of this 8-OHdG assay was 0.5 ng/ml. Levels of 8-OHdG were standardized against creatinine (Taussky, 1954), performed in triplicate, with overly dilute samples excluded from further analysis because they produce inflated estimates (creatinine < 0.10 mg/ml, N = 5). In Study 1, the inter-assay coefficient of variation (CV) was 11%, and the intra-assay CV, calculated from sample replicates, averaged 6.6%. In Study 2, the inter-assay coefficient of variation (CV) was 15%, and the intra-assay CV averaged 9.1%.

After accounting for missing 8-OHdG measurements because of excessively dilute urine samples, errors in substituting a sample of saliva (collected for assaying separate biomarkers), or

participants failing to return for their follow-up session, we obtained an 8-OHdG measurement from 233 urine samples provided at the laboratory session, and 199 samples provided in the morning one week after the session. The within-individual correlation of 8-OHdG measurements across the two sampling sessions was modest, yet statistically significant ($r(186) = 0.22$, $p = 0.002$).

In Study 2, uric acid was assayed using Invitrogen Amplex Uric Acid ELISA kits (Thermo Fisher Scientific, Carlsbad, CA), which have a sensitivity of 100 nmol/L. Urine samples were diluted 1:40 before assaying. Intra-assay CVs averaged 3%, and the inter-assay CV was 4.4%. We obtained a uric acid measurement from 123 samples provided at the laboratory session, and 97 samples provided from the first morning void one week later. The within-individual correlation of uric acid measurements across the two sampling sessions was similar to that for 8-OHdG ($r(78) = 0.23$, $p = 0.038$).

2.5 Statistical Analyses

To assess predictors of 8-OHdG in our overall sample (Study 1 and Study 2 combined), we conducted a series of linear mixed-effect models in R using the *lme4* package (Bates, Machler, Bolker, & Walker, 2015). Participant ID was included as a random intercept in all models to account for the non-independence of repeated measurements. We ran a separate model for each of the four factors identified from factor analyses of questionnaire measures: two for personality, two for health. These computed factor scores served as the main predictors of interest. For personality factors, higher scores on the "surgency" and "dominance" factors corresponding to lower 8-OHdG concentrations in men would be in line with results from male rhesus macaques (Georgiev et al., 2015); we also examined whether these associations would extend to women. For health factors, we predicted the "athleticism" factor would negatively predict 8-OHdG, whereas the "susceptibility to illness/disease" factor would positively predict it.

Each model contained the same set of covariates: sampling session (lab sample vs. awakening sample), sex, relationship status (single vs. in a committed relationship), study, a binary variable assessing whether participants reported regular exposure to environmental toxins (e.g. fumes, heavy metals), and a binary variable that asked whether participants currently smoked. These latter two covariates have consistently been linked to elevated 8-OHdG levels (Pilger & Rudiger, 2006; Sakano et al., 2009; Gangestad et al., 2010; exclusion of these variables does not affect primary results reported). While we did collect information on participants' use of multivitamins and other dietary supplements that could in principle affect anti-oxidant capacities, analyses showed that users of these supplements did not differ in their 8-OHdG concentrations from non-users (all $p > 0.654$; see Table S6), a finding consistent with previous research (Gangestad et al., 2010). For these reasons, we elected to not include supplement use in our main analyses; this choice does not meaningfully affect the results we present below. We also included several interaction terms between the personality/health factor predictors and our covariates. We specified two-way interactions between personality/health factors and sampling session, sex, and study—i.e., we tested whether the effect of a given factor on 8-OHdG depended on sampling session, sex, or study. We also specified three-way interactions of personality/health factor × sampling session × sex, and personality/health factor × sampling session × study; these asked whether the two-way interaction between a given factor and sampling session itself depended on either sex or study. To elucidate significant interactions, we calculated simple slopes using the *emmeans* package (Lenth et al., 2020).

All of the raw data and analysis scripts needed to reproduce our results can be found in an OSF project repository at https://osf.io/zjb5p/.

3. Results

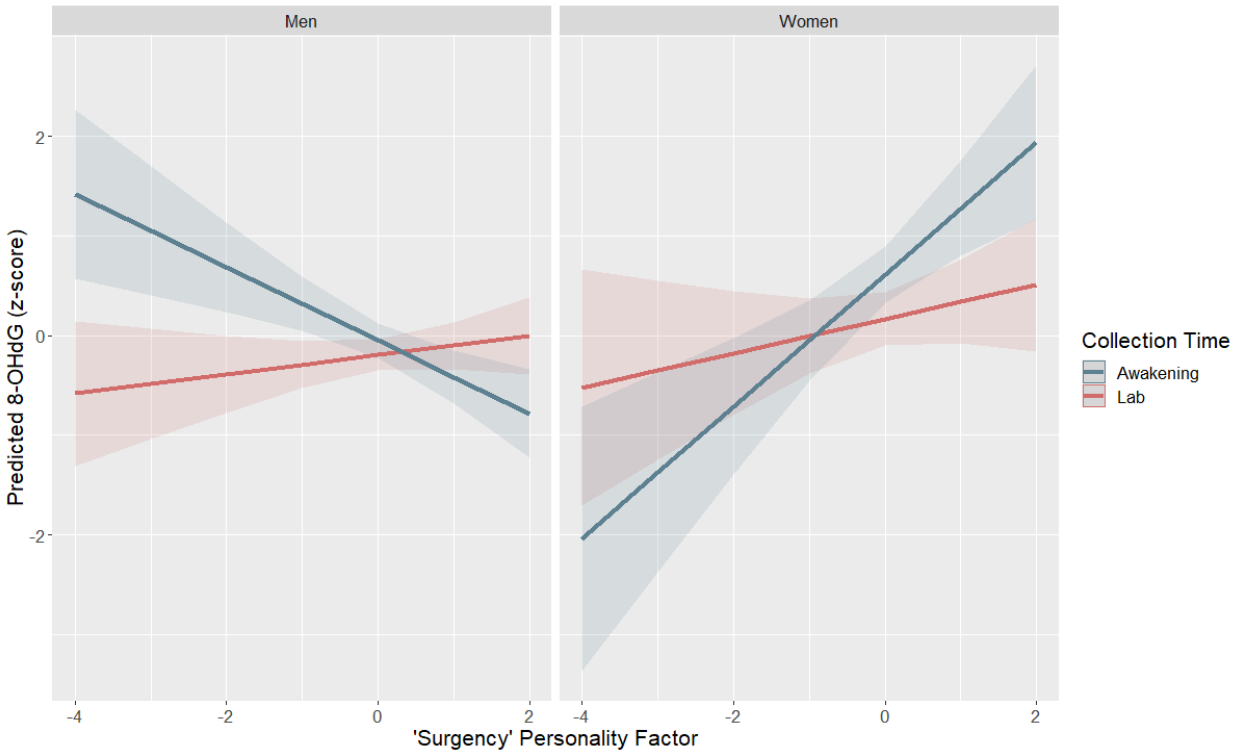
3.1 Oxidative Stress and Personality

For the "surgency" personality factor, the main effect of this factor on 8-OHdG concentrations was not significant ($t(237) = 1.35$, $p = 0.177$), though its interaction with sex was strongly significant ($t(235) = 3.81$, $p < 0.001$), such that the overall relationship between this factor and 8-OHdG was negative for men, but positive for women. Furthermore, this two-way interaction was qualified by an interaction with sampling session (i.e., a three-way personality factor × sex × sampling session interaction; $t(224) = -3.89$, $p < 0.001$). Decomposing this interaction, within men, the simple slope between 8-OHdG and "surgency" was negative and significant for awakening samples (-0.37 ± 0.11), but non-significantly positive for lab samples (0.10 ± 0.09). In contrast, these same simple slopes for women were positive for both awakening samples (0.67 ± 0.17) and lab samples (0.18 ± 0.15), though only significant in the former group. See Figure 1 and Table 4.

Table 4. Results of model (N_{obs} = 420) predicting 8-OHdG from computed "surgency" personality factor.

Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.04	-0.45 – 0.54	0.863
Sampling Session	-0.24	-0.59 – 0.12	0.198
'Surgency' Personality Factor	0.38	-0.17 – 0.94	0.176
Sex	0.26	0.13 – 0.39	**<0.001**
Study	0.03	-0.29 – 0.35	0.844
Toxin Exposure	0.34	-0.03 – 0.70	0.073
Smoking Status	0.24	-0.03 – 0.51	0.080
Relationship Status	0.05	-0.12 – 0.22	0.557
Sampling Session × Personality Factor	-0.25	-0.70 – 0.20	0.269
Sampling Session × Sex	-0.08	-0.18 – 0.03	0.170
Sex × Personality Factor	0.28	0.13 – 0.42	**<0.001**
Sampling Session × Study	0.05	-0.15 – 0.25	0.593
Personality Factor × Study	-0.15	-0.45 – 0.15	0.325
Sampling Session × Sex × Personality Factor	-0.24	-0.36 – -0.12	**<0.001**
Sampling Session × Study × Personality Factor	0.15	-0.09 – 0.40	0.219

Figure 1. Associations between the "surgency" personality factor and urinary 8-OHdG concentrations. The sex-specific personality × sampling session interaction effects are as follows: For men, γ = 0.21, t = 3.74, p = 0.002; for women: γ = -0.18, t = -1.72, p = 0.091.

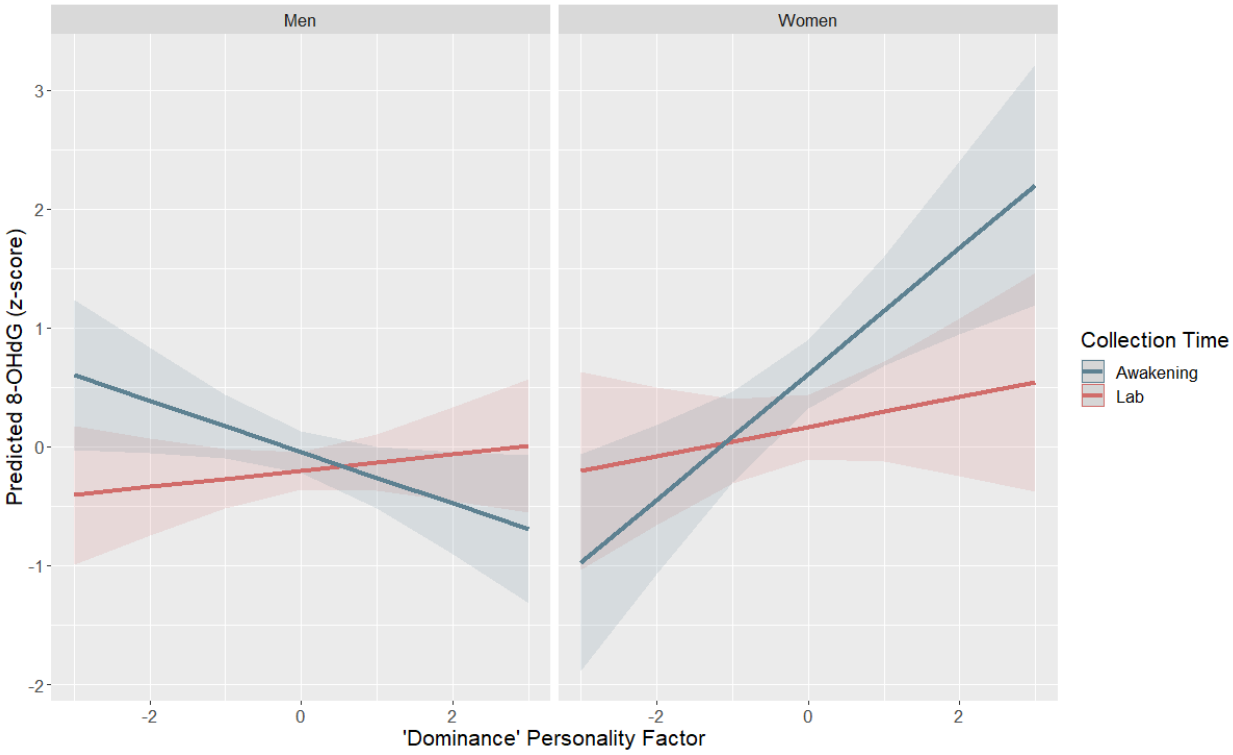


In our model using the second personality factor extracted ("dominance"), findings parallel those for the "surgency" factor. The main effect was once again not significant (t(226) = 1.12, p = 0.262), though the two-way interaction with sex (t(226) = 2.92, p = 0.004), as well as the three-way personality factor × sex × sampling session interaction; t(217) = -2.99, p = 0.003) indicated that trends differed as a function of sex and sampling session. Within men, the simple slope between 8-OHdG and "dominance" was negative and significant for awakening samples (-0.22 ± 0.10), but slightly positive (and non-significant) for lab samples (0.07 ± 0.09). In contrast, these same simple slopes for women were strongly significantly positive for awakening samples (0.53 ± 0.16), but non-significant for lab samples (0.12 ± 0.14). See Figure 2 and Table 5.

Table 5. Results of model (N_{obs} = 420) predicting 8-OHdG from computed "dominance" personality factor.

Predictors	*γ*	*CI*	*p*
(Intercept)	0.01	-0.49 – 0.50	0.972
Sampling Session	-0.21	-0.58 – 0.15	0.250
'Dominance' Personality Factor	0.32	-0.24 – 0.87	0.261
Sex	0.26	0.12 – 0.39	**<0.001**
Study	0.06	-0.26 – 0.37	0.719
Toxin Exposure	0.31	-0.06 – 0.68	0.100
Smoking Status	0.25	-0.02 – 0.53	0.074
Relationship Status	0.06	-0.10 – 0.23	0.471
Sampling Session × Personality Factor	-0.13	-0.59 – 0.33	0.588
Sampling Session × Sex	-0.07	-0.18 – 0.04	0.195
Sex × Personality Factor	0.20	0.07 – 0.33	**0.004**
Sampling Session × Study	0.04	-0.16 – 0.24	0.701
Personality Factor × Study	-0.12	-0.42 – 0.18	0.437
Sampling Session × Sex × Personality Factor	-0.17	-0.29 – -0.06	**0.003**
Sampling Session × Study × Personality Factor	0.06	-0.19 – 0.31	0.636

Figure 2. Associations between 'dominance' personality factor and urinary 8-OHdG concentrations. The sex-specific personality × sampling session interaction effects are as follows: for men: γ = 0.14, *t* = 2.30, *p* = 0.023; for women: γ = -0.18, *t* = -1.97, *p* = 0.054.



3.2 Oxidative Stress and Health/Athleticism

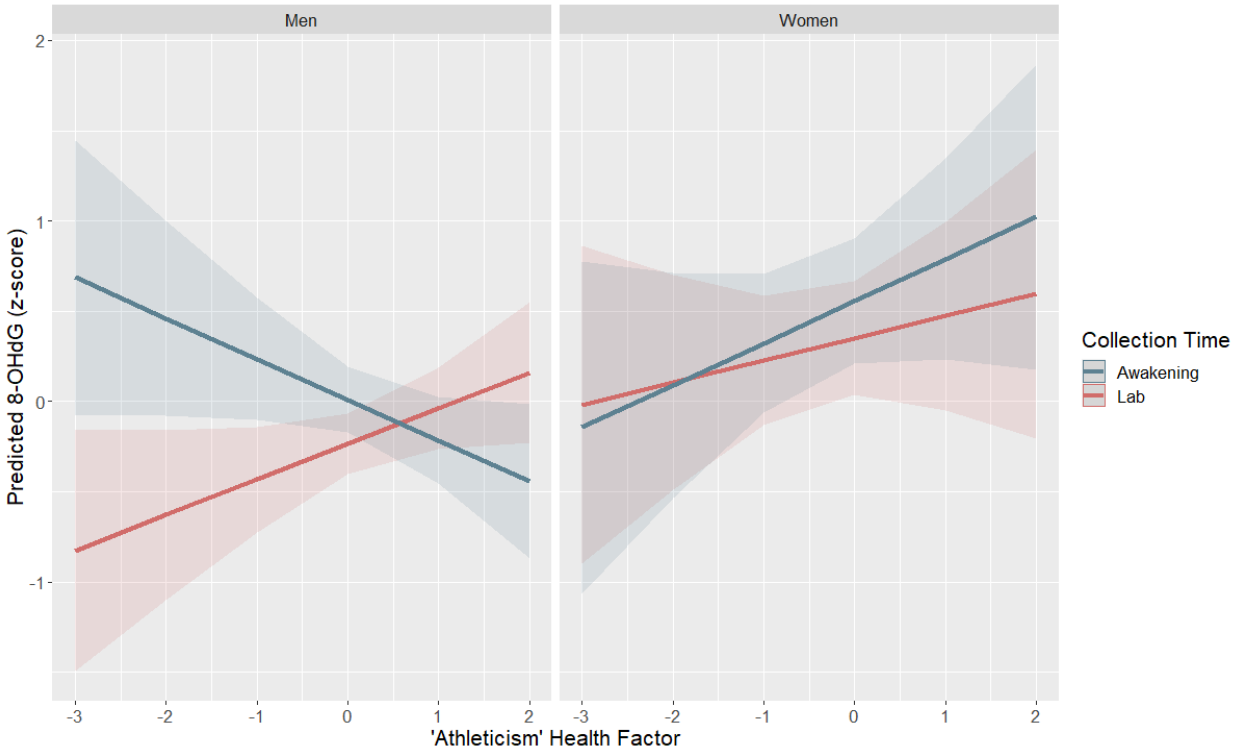
We also found a similar set of relationships as above for our "athleticism" health factor. The main effect of this factor was nearly nil $t(229) = -0.08$, $p = 0.941$). The two-way interaction with sex also fell short of significance ($t(222) = 1.20$, $p = 0.230$), but both three-way interactions included in the model were significant predictors—for the "athleticism" × sex × sampling session interaction: $t(211) = -2.02$, $p = 0.044$; for the "athleticism" × study × sampling session interaction: $t(217) = 3.06$, $p = 0.003$. Decomposing these interactions, within men, the simple slope between 8-OHdG and athleticism was negative for awakening samples (-0.23 ± 0.11), but positive for afternoon samples (0.20 ± 0.10). These trends were largely driven by a strongly negative slope in one study (reflected by the three-way interaction with study; see Table 6). Within women, simple slopes for the athleticism

factor were positive, but non-significant, for both awakening samples (0.23 ± 0.17) and afternoon samples (0.12 ± 0.16). See Figure 3 and Table 6.

Table 6. Results of model (N_{obs} = 416) predicting 8-OHdG from computed "athleticism" health factor.

Predictors	*γ*	*CI*	*p*
(Intercept)	0.09	-0.46 – 0.64	0.755
Sampling Session	0.01	-0.38 – 0.40	0.960
'Athleticism' Health Factor	-0.02	-0.60 – 0.55	0.941
Sex	0.28	0.13 – 0.43	**<0.001**
Study	0.02	-0.33 – 0.37	0.910
Toxin Exposure	0.37	-0.02 – 0.76	0.062
Smoking Status	0.28	-0.01 – 0.56	0.054
Relationship Status	0.04	-0.13 – 0.22	0.619
Sampling Session × Health Factor	-0.56	-1.02 – -0.11	**0.016**
Sampling Session × Sex	0.01	-0.11 – 0.13	0.877
Sex × Health Factor	0.10	-0.06 – 0.25	0.230
Sampling Session × Study	-0.08	-0.29 – 0.14	0.485
Health Factor × Study	0.06	-0.26 – 0.39	0.692
Sampling Session × Sex × Health Factor	-0.13	-0.26 – -0.00	**0.044**
Sampling Session × Study × Health Factor	0.40	0.14 – 0.66	**0.003**

Figure 3. Associations between 'athleticism' health factor and urinary 8-OHdG concentrations. The sex-specific athleticism × sampling session interaction effects are as follows: for men, γ = 0.17, *t* = 2.90, *p* = 0.004; for women: γ = 0.11, *t* = 1.02, *p* = 0.313.



Lastly, in contrast to the above set of results, the "susceptibility to illness/disease" factor yielded uniformly null results: its main effect did not significantly predict 8-OHdG ($t(233) = 0.00$, $p = 0.999$), and we did not observe a significant two-way interaction with sex ($t(212) = 0.29$, $p = 0.770$) or a significant three-way health factor × sex × sampling session interaction ($t(204) = 0.83$, $p = 0.408$).

3.3 Testing the Robustness of Three-Way Personality/Health × Sex × Sampling Session Interactions

The strong, directionally consistent interactions we observe between personality/health factors, sex, and sampling time are intriguing, yet unexpected. To explore the sensitivity of these effects, we re-ran the models from sections 3.1 and 3.2 substituting a continuous measure of

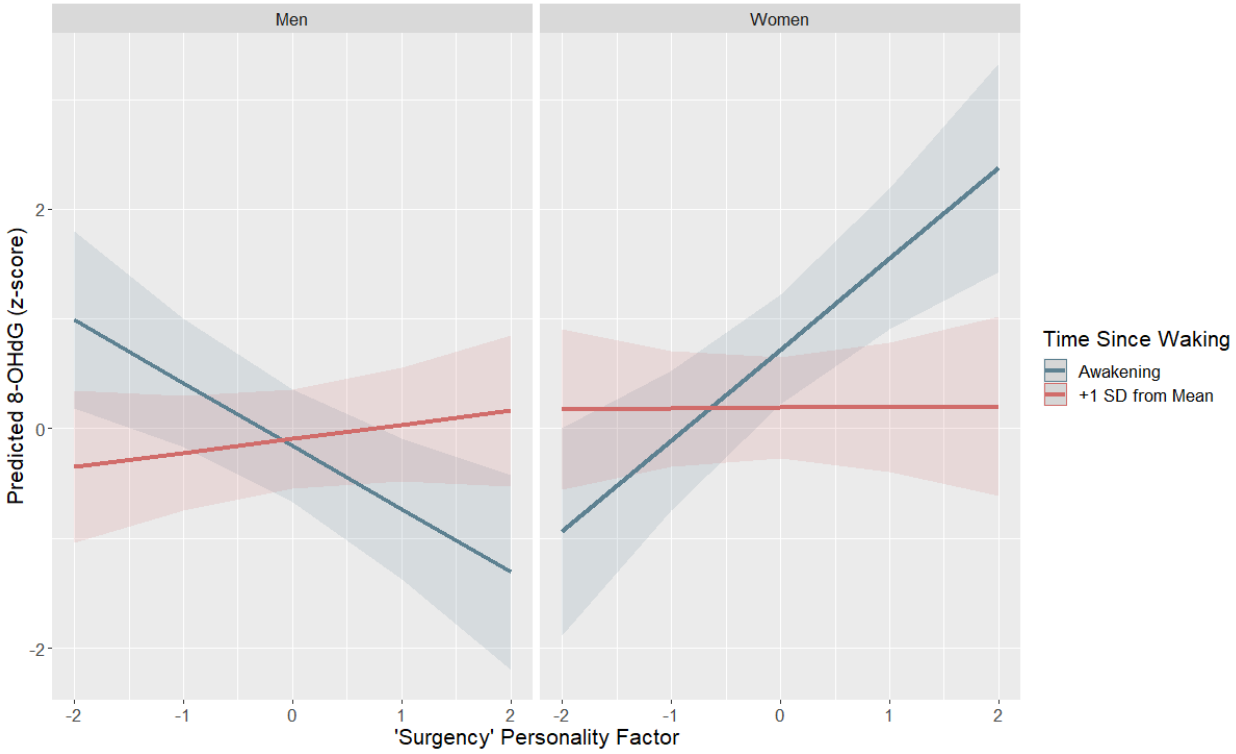
sampling time—time since waking—for the binary 'sampling session' variable used above. Models were otherwise identical to those presented above.

In general, these alternative models reflect results already presented. For the "surgency" factor, the three-way interaction with sex and time since waking was stronger than the comparable interaction with sampling session: $t(261) = -4.94$, $p < 0.001$; see Figure 4. Setting time since waking to zero, the estimated simple slope of the "surgency" factor was strongly negative for men (-0.37 ± 0.13), and strongly positive for women (1.04 ± 0.24). At 1 SD above the mean time since waking (here, 7.14 hours), trends were non-significantly positive for both men (0.18 ± 0.11) and women (0.05 ± 0.19).

Results were similar for the "dominance" factor, with a stronger three-way interaction when substituting a continuous time measure: $t(265) = -4.38$, $p < 0.001$. Here, the slope at awakening was negative for men (-0.20 ± 0.14), and strongly positive for women (1.01 ± 0.22). At 1 SD above the mean time since waking, these slopes were non-significantly positive for men (0.10 ± 0.12) and near zero for women (-0.01 ± 0.19).

Results for the comparable three-way interaction with the "athleticism" factor also strengthened: $t(241) = -3.60$, $p < 0.001$. At awakening, the slope of "athleticism" was significantly negative for men (-0.40 ± 0.15) and positive for women (0.49 ± 0.24). At 1 SD above the mean time since waking, these slopes were significantly positive for men (0.28 ± 0.13) and near zero for women (-0.07 ± 0.20).

Figure 4. Associations between 'surgency' personality factor and urinary 8-OHdG concentrations, separated by sex and a continuous measure of time since waking.



3.4.1 Robustness to Outliers

One might additionally wonder whether our pattern of results is driven by individuals with extreme 8-OHdG measurements. We thus re-ran the models reported in sections 3.1 to 3.3 above, using a log-transformed quantity of 8-OHdG as the dependent variable. The full results are presented in our ESM (Tables S7-S9). The key personality/health factor × study × sampling session interactions all weakened slightly but remained strongly significant, showing a qualitatively similar pattern of results.

3.5 Potential Mediators of Condition – Oxidative Stress Relationships

Additional measures were collected, mostly in Study 2, that might have added, independent influences on oxidative stress. Below, we investigate whether these factors might mediate the time- and sex-dependent relationships seen in sections 3.1 and 3.2.

3.5.1 Uric Acid

In a model predicting 8-OHdG from uric acid concentrations, as well as its interactions with sampling session and sex, we observed a strong sampling session × uric acid interaction ($t(166) = 3.68$, $p < 0.001$), but not a significant session × uric acid × sex interaction ($t(166) = 1.58$, $p = 0.117$). Once again, the direction of associations differed markedly between sampling sessions: uric acid negatively predicted 8-OHdG in morning samples (-0.32 ± 0.13), but positively predicted it in afternoon samples (0.26 ± 0.09).

We next entered these uric acid terms into our models predicting 8-OHdG from personality and health factors. The key interaction effects— personality/health factor × study × sampling session—remained significant in all three instances: **surgency factor:** ($t(105) = -3.55$, $p < 0.001$); **dominance factor:** ($t(97) = -2.75$, $p = 0.007$); **athleticism factor:** ($t(97) = -2.68$, $p = 0.009$), suggesting that concentrations of uric acid do not meaningfully influence observed relationships between oxidative stress and personality/health dimensions.

3.5.2 Sleep Quality

We did not find a significant main effect of sleep problems in predicting 8-OHdG ($t(136) = 1.51$, $p = 0.132$, nor an interaction with sampling session $t(130) = 0.58$, $p = 0.562$. When entering sleep effects into our models predicting 8-OHdG from personality and health factors, the key personality/health factor × study × sampling session interactions remained significant in all three instances: **surgency factor:** ($t(123) = -3.65$, $p < 0.001$); **dominance factor:** ($t(121) = -2.82$, $p = 0.006$); **athleticism:** ($t(118) = -2.28$, $p = 0.025$). Once again, sleep quality does not appear to mediate the observed relationships between oxidative stress and personality/health dimensions.

4. Discussion

4.1 Summary of Associations

Our study explored two alternative scenarios for associations between oxidative stress and putative measures of investment in mating effort. On one hand, surgent, dominant, and athletic men

could possess a greater ability to regulate oxidative stress, reflected by lower levels of 8-OHdG, consistent with associations found in rhesus macaques (Georgiev et al., 2015); on the other hand, high activity levels of these men could produce associations in the opposite direction. As a comparison, we investigated these same features in women, predicting weaker or absent associations. Our results showed that surgent, dominant, and athletic men tended to produce low levels of 8-OHdG in first-of-the-morning urine. Provisionally, we interpret this pattern to have one or both of two explanations. First, surgent, dominant, and athletic men may experience relatively little oxidative damage throughout the day to be repaired. Second, surgent, dominant, and athletic men may experience relatively little oxidative damage as a function of basal metabolic processes experienced overnight. In turn, these associations may be attributable to multiple underlying processes, including a smaller number of ROS-producing mutations and/or relatively low levels of environmental toxins. In either of these scenarios, men's surgency, dominance, and athleticism partly reflects underlying condition—fundamentally, the capacity to efficiently convert energy into fitness-enhancing activity. An explanation for these associations may lie in the role of oxidative stress in the production of sexually selected signals. Individuals who suffer lower costs to energy production in the form of oxidative stress will be selected to energetically invest, over development, more heavily in capacities resulting in surgency, social dominance, and athleticism.

By contrast, women's surgency, social dominance, and athleticism positively covaried with levels of 8-OHdG measured in urine collected at awakening. Why do women show a very different pattern? The pattern for men in the scenarios above results from selection for investment in traits (i.e., surgency, dominance, and athleticism) that may boost mating success in men that can physiologically "afford" them due to efficient oxidative stress regulation. To some degree, despite sex differences, women may have ancestrally benefited from investments in developing these phenotypes, too. At the same time, there is reason to suspect that these investments would not have

been contingent on condition in the same way we propose they would have been for men. If women who possess relatively high levels of surgency, dominance, and athleticism are not ones who pay low costs for energy production in the form of oxidative stress, there is no reason to expect negative associations between them and oxidative stress. And indeed, because these traits—and many others that reflect increased mating effort—may be associated with higher levels of energy production, one might expect that women who possess them generate greater levels of ROS, which would result in greater oxidative damage and greater need for repair. One recent study presents evidence consistent with this notion: women whose faces were judged as more attractive also had higher oxidative stress, suggesting a possible cost of maintaining this phenotype (Marcinkowska et al., 2020). (By contrast, Gangestad et al. [2010] found male facial attractiveness to covary positively with a biomarker of oxidative stress; Foo et al. [2017] did not detect an association for either sex.)

We emphasize that these interpretations are provisional and require corroboration, both via direct replication, and via extensions that collect additional phenotypic information pertaining to mating effort (e.g., anthropometric measurements). We offer them because they may lead to fruitful directions for future research At the same time, in light of the complexities of associations between sexual signals, reproductive effort, and oxidative stress, some of which we reviewed in the introduction, we fully recognize that alternative explanations are possible. Furthermore, consistent with the notion that there is still much to be resolved in this literature, we also find unexpected, major differences in patterns based on when and how oxidative stress biomarkers are sampled, which we discuss below.

4.2 Implications for Understanding the Moderating Effect of Collection Time

Strong sex-specific associations between personality/health and oxidative stress were qualified by time of sampling. For men, negative associations of surgency, social dominance, and athleticism with levels of 8-OHdG measured in awakening samples disappeared when examining

samples collected during lab sessions later in the day. Surgent, dominant, and athletic women had relatively high levels of 8-OHdG in both awakening and active samples, though associations were weaker in the latter set of samples.

One can reasonably ask whether these moderation effects are robust and meaningful. There are several reasons to think that they are. First, moderation by sex and sample was significant and consistent across three related factors (surgency, dominance, athleticism). Second, in analyses that substituted time since awakening for the crude binary of "sampling session", moderation effects consistently strengthened, supporting the interpretation that this is the relevant difference driving effects. Third, our results remained similar in analyses predicting log-transformed 8-OHdG concentrations, suggesting outliers were not responsible for our observed pattern of effects. Finally, we observed a similar moderation effect for uric acid: effects differed between awakening and lab sessions (though, in this instance, this interaction was not moderated by sex). This effect of uric acid was independent from the effects of surgency, dominance, and athleticism. Nonetheless, the fact that time since awakening moderated this effect too bolsters the idea that time of sampling importantly moderates associations with 8-OHdG. While further studies are needed to establish the robustness and generalizability of these moderation effects, below we offer our provisional interpretation of what they might reflect in our studies.

Concentrations of 8-OHdG in urine do not capture instantaneous levels. Rather, they reflect the accumulation of 8-OHdG filtered out of circulating blood by the kidneys and stored in the bladder between last void and current void. For a first-morning void, this time span consists of a long, inactive period—sleep. By contrast, urine collected during daytime hours has largely accumulated during relatively short, active periods. Based on this observation, perhaps the most straightforward explanation for diverging associations is that an awakening measure of oxidative stress represents a more stable, and thus desirable, estimate of accumulated damage compared to

daytime samples more affected by metabolic demands of daily activities (e.g., exercise). The fact that medical biomarker research favors first-morning voids for similar reasons (e.g. Witte et al., 2009; Heerspink et al., 2010) supports this interpretation.

We do entertain a second interpretation that specifically implicates sleep. Much somatic repair occurs during sleep, and indeed, one primary function of sleep across a wide range of taxa may be to permit allocation of energy to repair processes for oxidative damage (Anafi et al., 2013). At the same time, sleep itself slows the accumulation of oxidative damage, as the rate of metabolic expenditure slows. From this reasoning, it follows that someone with relatively low levels of 8-OHdG accumulated during sleep (i.e., found in first-morning voids) (a) experiences relatively low levels of oxidative damage throughout the day, to be repaired at night, and/or (b) produces relatively low levels of oxidative damage through basal metabolic processes. This interpretation is provisional and requires additional tests. We did not detect effects of sleep quality in our sample but future research may further investigate its impact.

4.2.1 Associations with Uric Acid

Because oxidative stress can be affected by the action of anti-oxidants, we considered whether concentrations of uric acid influenced the relationships we examined. While we did not find that uric acid mediated links between 8-OHdG and the traits we examined, we did find that uric acid covaried with 8-OHdG differently in awakening and active daytime samples, providing an independent piece of evidence that time of sampling affects associations with 8-OHdG. The effects of uric acid on oxidative damage can reverse, from anti-oxidant to pro-oxidant, in response to cellular environments (Sautin et al., 2007; So & Thorens, 2010), and prior evidence suggests that circadian rhythms have a strong influence on these roles (Stringari et al., 2015; Kono et al., 2010). Our examination of the role of anti-oxidants was limited in this study. Future research would benefit

from considering a wider range of anti-oxidant assays, which can provide a triangulated estimate of different components underlying an organism's anti-oxidant system (Constantini, 2011).

4.3 No Detected Associations with Susceptibility to Infectious Disease

In contrast to individual differences in surgency, social dominance, and athleticism, susceptibility to infectious disease did not substantially covary in our study with 8-OHdG, either in men or women, or in awakening or lab samples. Future research may examine these associations further, as well as assess associations between current infectious status and 8-OHdG levels. We note here that our results are based on two samples of young adults from a non-clinical, industrialized population. This poses a constraint on generalization for all of the conclusions we have presented, but it may be particularly relevant for measures of susceptibility to infectious disease. Clinical populations, unsurprisingly, have an elevated susceptibility to infectious disease (WHO, 2011), and distributions of immune function biomarkers and disease susceptibility differ markedly between industrialized and non-industrialized populations, which has important consequences for patterns of energetic investment (e.g. Blackwell et al., 2016). A broader sampling of the range of infectious disease burden in future research will permit a fuller examination of its role in oxidative stress and energetic trade-offs.

4.4 Future Directions

We suggest several future directions:

First, what processes might mediate effects on 8-OHdG production overnight for men and women? As we discuss above, surgent, dominant, and athletic men may produce less 8-OHdG because they incur lower levels of oxidative damage at peak energy expenditure during active hours. Alternatively, they may incur lower levels of oxidative damage at basal metabolic rates. One way to examine the potential role of the former would be to document or control energy production—calories burned—during active hours. As calories burned increase, oxidative damage, as assessed by

8-OHdG production, should also increase (cf. Pontzer et al., 2015). But male surgency, dominance, and athleticism may moderate these impacts, such that, per unit caloric expenditure, surgent, dominant, and athletic men may experience a lower rate of increase in 8-OHdG production. In turn, these effects could potentially be mediated by typical activity levels, as greater levels of exercise appear to lead to more effective regulation of oxidative stress (e.g., Gomez-Cabrera et al., 2007; see also Garratt & Brooks, 2012). More generally, oxidative stress appears to be curvilinearly related to activity levels, with moderate levels increasing ability to regulate oxidative balance, and high (prolonged or intense) levels leading to greater damage (Soulsbury & Halsey, 2018). Adjudicating between these possibilities requires an ability to control for activity levels, which we did not have in the current study.

Second, future research may explore the long-term effects of differential oxidative stress on health outcomes using longitudinal designs. These long-term effects on health have important theoretical implications, as they may help elucidate the nature of energetic trade-offs. As well, they may have important practical implications for understanding differential aging and proneness to disease.

Third, from a theoretical perspective we have focused on features that may affect the nature of trade-offs and their impact on oxidative stress in men. Future research may target factors that affect trade-offs in women. For men, we focused on reproductive effort in the form of male intrasexual competition and its impact on oxidative stress, and, perhaps by extension, longevity. Women's reproductive effort, with implications for oxidative stress and trade-offs with longevity, may take different forms. At a basic physiological level, for instance, women's reproductive hormones may affect rates of oxidative stress. One large project, the BioCycle Study, was designed to investigate the association between women's ovarian hormone concentrations and levels of oxidative stress, as assessed by F_2-isoprostanes. Results indicated that estradiol levels, which

promote readiness for reproduction (Ellison, 2003), are associated with elevated levels of oxidative stress (Schisterman et al., 2010). Girls who experience earlier pubertal timing tend to have more regular cycles, with higher levels of estradiol through at least the early 20s (e.g., Apter & Vihko, 1983; Apter, Reinila, & Vihko, 1989; Vihko & Apter, 1984). Earlier pubertal timing represents an earlier onset of the reproductive period, at a cost of a slower but longer period of growth, which may be most adaptive under conditions favoring current (vs. future) reproduction (e.g., Coall & Chisholm, 2003). Do women who experience earlier pubertal timing, then, experience greater levels of oxidative stress? In fact, the BioCycle study also revealed a robust negative association between age at menarche and mean F_2-isoprostane levels across the cycle among naturally ovulating women (Schisterman et al., 2010). Might they also produce the highest levels of 8-OHdG, and especially at night? Might these impacts on oxidative stress mediate associations between pubertal timing and later health outcomes, such as cancer incidence (Wu et al., 2020)?

4.5 Conclusion

In a large sample of young adults, we report preliminary evidence linking oxidative stress to several indices of investment in mating effort. Surgent, dominant, and athletic men appeared to accumulate lower concentrations of an oxidative stress biomarker overnight, consistent with a scenario in which individuals with more favorable energetic affordances are better able to invest in certain sexually selected signals. By contrast, we observe opposing, positive associations among women that are more consistent with the accumulation of physiological costs incurred from greater investments in energy production. While robust to a number of sensitivity checks, the pattern of effects we report nonetheless requires further confirmation in additional studies, especially given a history of inconsistent associations in the literature on oxidative stress and sexual signals. To the extent that our findings are robust, they have important implications for understanding the role oxidative stress plays in mediating investments between reproductive effort and maintenance

processes, suggesting that the bases for biomarker—trait predictions are best made in a sex- and time-specific manner.

Data Accessibility Statement

All of the raw data and analysis scripts needed to reproduce our results can be found in an OSF project repository at https://osf.io/zjb5p/.

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