Testosterone facilitates the sense of agency

ABSTRACT: Sense of agency (SoA) refers to feelings of being in control of one's actions. Evidence suggests that SoA might contribute towards higher-order feelings of personal control – a key attribute of powerful individuals. Whether testosterone, a steroid hormone linked to power in dominance hierarchies, also influences the SoA is not yet established. In a repeated-measures design, 26 females participated in a double-blind, placebo-controlled trial to test the effects of 0.5mg testosterone on SoA, using an implicit measure based upon perceived shifts in time between a voluntary action and its outcome. Illusions of control, as operationalized by optimism in affective forecasting, were also assessed. Testosterone increased action binding but there was no significant effect on tone binding**.** Affective forecasting was found to be significantly more positive on testosterone. SoA and optimistic expectations are basic manifestations of power which may contribute to feelings of infallibility often associated with dominance and testosterone.

Keywords: Sense of agency; testosterone, hormones; mood; power; embodied cognition.

1. INTRODUCTION

Sense of agency (SoA) refers to the feeling that arises when effected changes are attributed to one's own actions and not to other factors or persons (Haggard & Tsakiris, 2009). In healthy adults, voluntary actions are accompanied by strong feelings of being able to control how these actions influence the environment. The brain mechanisms underpinning the SoA are multifaceted, involving both low-level sensory-motor and top-down inferential processes and are recruited differently depending on the context and availability of information in causal chains of events (Blakemore et al., 1998; Farrer et al., 2002; Haggard & Clark, 2003; Moore & Haggard, 2008; Sato & Yasuda, 2005; Wegner, 2002;). Though the feeling of agency is

mostly taken for granted in one's everyday activities, aberrations in agency are seen in many self-limiting psychiatric disorders (Gentsch et al., 2012; Haggard et al., 2003; Obhi, Swiderski & Farquhar, 2013; Voss et al., 2010).

The feeling of personal control over events in the environment is thought to be foundational for sustaining motivated behavior and the basic sense of free will (Gentsch et al., 2015; Moore, 2016). It is therefore closely linked to the experience of power (Fast, Gruenfeld, Sivanathan, & Galinsky, 2009; Inesi et al., 2011). Many authors agree that the influence that power has on behaviour and perception (selective attention, processing flexibility and optimism, for example (Guinote, 2007; 2010; Anderson & Galisnsky, 2006) can be explained in large part by the effects power has on an individual's basic sense of control (Galinsky, Gruenfeld & Magee, 2003; Guinote, 2010; Keltner, Gruenfeld & Anderson, 2003). In fact, Obhi, Swiderski and Brubacher (2012) have shown that although power priming did not increase agency, individuals made to feel powerless experienced less agency over their actions. Such findings align closely with theories of embodied cognition, which assert that many complex mental states are grounded in more basic sensory-motor processes (Barsalou, 2008; Lackoff, 2012; Wilson, 2002). In other words, psychological meaning may derive from re-enactment of motor and perceptual states of the body. Perhaps, then, feeling powerful derives some of its phenomenology from more basic sensory-motor mechanisms of control. In this regard, the steroid hormone, testosterone, may be a potential modulator of the SoA because of its established role in the psychology of power (Ronay & von Hippel, 2009).

1.1 Testosterone and control.

Throughout mammalian species of both sexes, testosterone has been linked to control over the social environment, pro-active or "approach" social motivation and power in group hierarchies (see Eisenegger, Haushofer & Fehr, 2011; van der Westhuizen & Solms, 2015). In affective neuroscience, the term "social approach" refers to the active pursuit of something desirable, particularly in threatening social contexts where the tendency to avoid is resisted

(Terburg & van Honk, 2013). Testosterone tends to surge in social situations when one's status is threatened and its role in social approach motivation is evidenced by its link to social threat monitoring (Hermans, Ramsey & van Honk, 2008; Goetz et al., 2014; van Honk et al., 2001; van Honk et al., 1999), preference for high status (Josephs, Sellers, Newman & Mehta, 2006; van der Westhuizen & Solms, 2015b) and confidence (Baucom, Besch & Callahan, 1985), outgoingness (Dabbs & Ruback, 1988), assertiveness (Cashdan, 1995) or aggression (Cashdan, 2003). From an embodied cognition perspective, this kind of social agency may depend in part on the same brain mechanisms that support sensory-motor agency. In corroboration, Pfifster et al., (2014) have shown that the SoA can emerge from actions that have social consequences. Thus, in social contexts, increased sense of agency over the behaviour of another agent may give rise to feelings of authority. Given that testosterone is known to promote affective states related to social empowerment, this suggests that fluctuations in testosterone may in turn modulate sensory-motor agency.

Several lines of evidence point to a potential role of testosterone in SoA. Firstly, in both male and female adults, grey matter volume in the insula, a brain structure which has been identified as a major substrate of the SoA (Farrer & Frith, 2002; Karnath & Baier, 2010), positively correlates with testosterone levels (Bos et al., 2011; Lentini et al., 2013). Secondly, the neurotransmitter dopamine not only maintains a great proportion of motivated behavior but has been linked to social dominance in several behavioral paradigms (Morgan et al., 2002; Winberg & Nilsson, 1992) and of significance, has also been shown to facilitate implicit feelings of volitional sensory-motor control (Moore et al., 2010). Testosterone is typically expressed in contexts where there is an opportunity to improve social status (Archer, 2006) and several studies have shown that it regulates the expression of dopamine in the brain (de Souza et al, 2009; Schroeder & Packard, 2000). Therefore, in such contexts, testosterone-mediated increases in dopamine may serve an adaptive role in social competition by facilitating feelings of personal control to encourage approach-related behaviour.

Finally, there is in fact some evidence, albeit indirect, to suggest that testosterone may encourage approach-related behavior by acting on signals that prospectively contribute toward agency at the time of action selection, i.e., before the actual effects emerge, which is a potentially *illusory* manifestation of agency (Chambon & Haggard, 2012). Prospective mechanisms may be related in some instances to incentive processing, based on findings that reward priming increases the sense of agency (Aarts et al., 2012). Of relevance here, is that testosterone is known to facilitate incentive processing (Hermans et al., 2010), decrease fearfulness (Hermans et al., 2006; van Honk, Peper & Schuuter, 2005) and increase the excitability of motor neurons (Bonifazi et al., 2004). From an embodied cognition perspective, the basic experience of agentive control may not only contribute to the feelings of infallibility often associated with testosterone, but they may also constitute an important self-fulfilling mechanism by which power and dominance is initially achieved.

1.2 Overview of aims.

Here we used the perceived attraction in time between a voluntary action and its outcome as an implicit marker of SoA (Haggard, Clark & Kalogeras, 2002). When one intentionally causes an event through one's own actions, the action and its consequence are experienced as being closer together in time. On the other hand, when we unintentionally cause an event (for example, if someone else causes us to move) we experience this unintentional movement and its consequence as further apart in time. This effect is known as 'intentional binding'. It is a widely used measure of SoA (see also Moore & Obhi, 2012, for a review).

In a placebo-controlled double-blind, repeated-measures study using 26 young women, we investigated if 0.5mgs of testosterone modulated intentional binding. We hypothesized that testosterone would increase intentional binding, in line with the idea that feelings of social control are founded upon more rudimentary experiences of sensory-motor control. While in real-world settings, testosterone tends only to surge in social contexts where status is at stake, in this experiment we artificially elevated testosterone levels to mimic the expression of

testosterone in social settings. Thus, although our experiment was not social in nature, the administration of testosterone in one condition functioned to simulate a physiological reaction that would normally occur in a socially competitive situation (Bateup, Booth, Shirtcliff & Granger, 2002; Carré & Olmstead, 2015).

In a subset of the participant sample, we also investigated whether testosterone affected affective forecasting (Baron, 1992, Loewenstein & Schkade, 1999; Wilson & Gilbert, 1992), given that more optimistic perceptions of one's emotional state in the future has been linked to illusions of control (Taylor & Brown, 1998). Since the future is largely beyond one's control, and predictions are based on reconstructed memories (Schacter et al., 2012), optimistic perceptions about the future can be measured by comparing current and future mood states (Wilson & Gilbert, 2003). As two possible mechanisms that facilitate approach-oriented behavior, we therefore hypothesized that testosterone would increase SoA and promote positive expectations about the future.

2. METHODS

Ethical approval was granted by the University of Cape Town's Human Research Ethics committee (HREC REF 868/2014) as well as the Medical Control Council of the South African Department of Health (TT/01/2011). All data was collected in accordance with the Declaration of Helsinki. Informed consent was obtained prior to commencement of the study and debriefing took place upon completion of data collection. There were no reports of negative side effects from the testosterone or placebo administration and no participant withdrew from the study.

2.1 Participants.

26 females, ranging between the ages of 18 and 30 from diverse ethnic backgrounds, were recruited to participate in the study in exchange for $35. Males were excluded because the time course of effects for the current testosterone administration protocol have been reliably

established in women only (Tuiten et al., 2000). Testing was performed during the pre-ovulatory phase of the menstrual cycle since androgen levels are relatively constant during this time. Participants were given a calendar and asked to track their menstrual cycle and were only allowed to be tested during the first ten days following the end of menstruation. Regrettably, we were not able to get serum or saliva samples to confirm basal testosterone levels. However, studies have shown that, controlling for factors like sexual activity, exercise and interpersonal conflict, testosterone levels are found to be highly reliable over a two week period (Liening et al., 2010). Finally, individuals taking any form of hormonal contraception or other form of medication were excluded from participation, as were those with a history of psychiatric illness.

2.2 Materials and Procedure.

Participants were tested on two occasions within a one-week period[1] in a repeated measures, double-blind, placebo-controlled design. Drug condition order was counter-balanced across participants, who were randomly assigned to the testing schedule and assigned a participant code. To control for hormonal fluctuations in diurnal cycles, testing sessions were standardised to 2pm. Each testing day required participants to report to the lab exactly 4 hours prior to the experimental session at which time they received sublingual administration of testosterone or placebo. This schedule was based on previous research which has shown the efficacy of sublingual testosterone administration to peak 4-6 hours later (Tuiten et al., 2000). The testosterone sample was comprised of 0.5mg of testosterone, 5mg of the carrier hydroxypropyl beta cyclodextrin, 5mg ethanol and 5ml of water. For the placebo samples, only the testosterone was omitted. Participants were made aware of that both testosterone and placebo formulas were identical to the taste. During the interval, participants were requested to refrain from engaging in strenuous or sexual activity, to avoid smoking or consuming caffeine. Before leaving, a scan of the participant's right hand was taken to measure the

[1] Specific testing days within the one week period were allocated on a convenience basis for each participant, but never on consecutive days.

second-to-fourth digit ratio. Low ratios are thought to reflect greater prenatal exposure to testosterone in relation to estradiol (Lutchmaya et al., 2004) and have been found in other studies to moderate the effects of testosterone (Montoya et al., 2011; van Honk et al., 2011).

At the start of the experimental session, participants completed two versions of the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988). The scale consists of 2 subscales, each with 10 positive and 10 negative words, respectively that describe different emotions and feelings, for instance, “Excited,” “Nervous,” “Proud”. Scores are summed for each subscale and then divided by 10 to get a mean value to represent each subscale. To assess current mood state, participants were asked to read each word and rate on a scale of 1-5 the extent to which they currently felt that way. In a second version, participants were asked to think about their future in a general sense and rate the degree to which they believed the word described their anticipated future mood state. The PANAS has been used previously in such a manner to determine affective forecasting (Wilson & Gilbert, 2003).

SoA was operationally defined in terms of “intentional binding”, defined above and illustrated in Figure 1. In this classic task (see Moore & Obhi, 2012 for a review), participants are required, at a time of their choosing, to make voluntary button presses that trigger a tone. They are asked to watch a clock face at the centre of a computer screen, measuring 2.8cm in diameter and marked with conventional 5 “minute” intervals. A clock hand of 11mm rotated constantly at a speed of 2560ms per revolution.

Participants received both written and verbal instructions and had the opportunity to perform 5 practice trials. In agency conditions (operant blocks), participants made voluntary key presses that caused a tone after a 250ms delay. Participants judged the time of their key press or the subsequent tone, reporting the position of the clock hand when these events happened by typing the time into a response box at the end of each trial when the clock hand stopped rotating after a random interval between 1500 and 2500ms. Judgements were blocked (30 trials each), so participants only made a single type of estimate on each trial in each block.

For each condition, the task always began with an operant block, followed by 30 trials of a baseline condition. Action and Tone condition order was counter-balanced between participants. In the baseline action block participants made voluntary key presses that did not produce a tone, and participants reported the time of the key press. In the baseline tone block participants made no key presses. Instead, a tone would sound at a random time on each trial and participants reported the time of the tone.

Action binding is found by subtracting the mean time estimate in the baseline action condition from the mean time estimate of actions in the operant condition. Action binding is indicated by a positive difference. Tone binding is found by subtracting the mean time estimate in the baseline tone condition from the mean time estimate of tones in the operant condition. Tone binding is indicated by a negative difference.

Figure 1. The intentional binding task where perceptual shifts reflect binding.

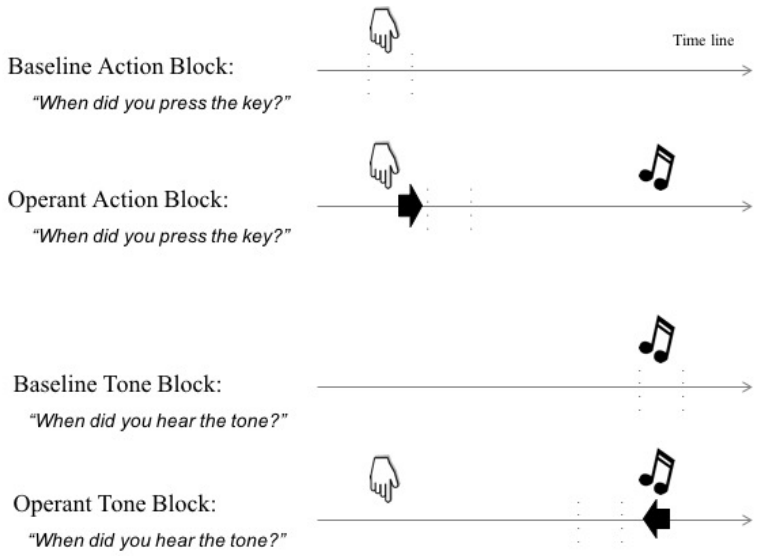


Figure 1. In the Operant Action block, a tone follows the key press. When asked "When did you press the key?", intentional binding is reflected by a shift in temporal awareness (dotted lines) toward the tone so that the participant reports a time that is later in time than the press actually occurred. For example, if the key press occurred at 15ms, the participant may report 25ms. In the Operant Tone condition, a tone always follows a voluntary key press. When asked, "When did you hear the tone?" there is an anticipatory effect and the participant tends to report the onset time of the tone as being earlier. For example, if the tone occurred at 45ms, the participant may report "30ms". In baseline

conditions, time reporting is not influenced by the action-effect relationship and tends to be more accurate.

3. RESULTS

Prior to analysis, outlying trials (>3 SD) in the intentional binding task were removed from each participant's individual data sets under the assumption that unusually large discrepancies between computer-recorded onset times and estimations made by participants reflect lapses in concentration. 16 outliers were removed and no participant recorded more than 2 such errors in a data set. Additionally, in both the Tone and Action Binding mean data sets, there was one outlying participant, leaving a final sample size of 25 for each condition.

3.1 Intentional binding.

Descriptive statistics for separate baseline and operant blocks, and action binding and tone binding across testosterone and placebo conditions are displayed in Table 1. Global binding was calculated by subtracting tone binding from action binding.

Table 1 Mean shifts in time perception across testosterone and placebo treatment conditions

	Placebo		Testosterone	
	M	SD	M	SD
Action baseline	6.32	(72.38)	5.36	(50.13)
Action operant	22.12	(72.32)	43.8	(67.43)
Tone baseline	9.2	(58.36)	-9	(58.31)
Tone operant	-90.16	(114.7)	-102	(112.9)
Action Binding	15	(31.68)	38	(47.22)
Tone Binding	-99	(98.68)	-93	(101.92)

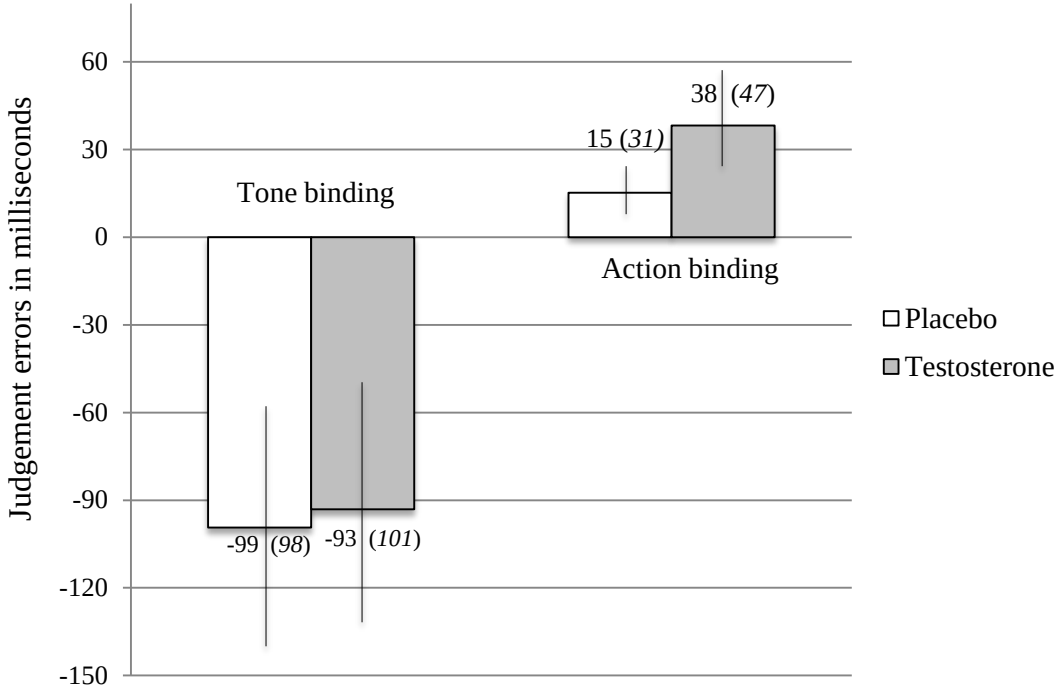
Values indicate milliseconds.

Given that the direction of shifts in temporal awareness for action and tone operant blocks (indicated by errors in time estimation) were consistent with the concept of binding, we ran one-tailed paired *t*-tests to see whether the binding effect was present. In both the placebo

(t(24) =-2.334, p=.028, d =.22) and the testosterone conditions (t(24)= -4.067 , p=.000, d =.65), there was a significant difference between the action baseline and action operant blocks. Significant tone binding was also found on both placebo (t(24)= 5.027, p=.000, d = 1.09) and testosterone testing days (t(24)= 4.560, p=.000, d = 1.03).

Based on a Wilcoxon signed rank test, there was no significant difference between testosterone and placebo days for global binding (Z = -.31, p = .76, r = .06). However, we opted for separate analyses of action and tone binding given that recent studies suggest that the two processes reflect cues that can be recruited in dissociable ways during the integration of agency (Kranick et al., 2013; Wolpe et al., 2013). Without doing so, meaningful data is lost. Differences in the effects on binding between testosterone versus placebo testing days were analyzed by assessing action binding and tone binding in two separate Wilcoxon signed rank tests. For action binding, the test indicated that binding was significantly increased during the testosterone condition (*Mdn* =29) compared to placebo (*Mdn* =15), Z = -2.32, p = .026, r = -.46. However, no significant difference between testosterone (*Mdn* = -88) and placebo (*Mdn* = -82) was observed for tone binding Z = -.79, p = .43, r = -.16. For mean, instead of median values of binding scores, refer to Table 1 and Figure 2. Plots of means and individual data points on both testing days can be found in the supplementary section.

Figure 2. Mean binding scores for testosterone and placebo conditions.



*Note, values reflect mean scores and not median values as reported in text. SD in parentheses. Error bars reflect standard error of the mean.

We next asked whether or not the effect of testosterone on binding was specific to action binding and significantly larger than the effect on tone binding. To do this, one must run a multiple comparison test to assess whether the change in magnitude from placebo to testosterone is statistically different between action and tone binding (Nieuwenhuis, Forstmann & Wagenmakers, 2011). We therefore quantified the net increase in binding from placebo to testosterone and ran a t-test to compare the difference between action and tone binding. Although descriptively, the average increase in binding was larger for action binding (M=23, SD= 50.1) than tone (M= -5.8, SD= 106.7), due to large variance in the data, statistically, this increase in action binding was not significantly different from the change in tone binding (($t(24)= 1.24$, p=.11, d = .34). The data therefore does not support a claim that the effect of testosterone on SoA was specific to action binding.

Looking at the placebo condition only, there were no significant correlations between 2D:4D and action (r = .05, n =25, p = .79) or tone binding (r = -.16, n =25, p = .44).

3.2 Mood data.

We then investigated whether testosterone and placebo conditions differed in terms of current mood states and affective forecasting. Refer to Table 2 for descriptive statistics. We tested these variables separately using two Wilcoxon Signed-Ranks tests because they represent different constructs. That is, current mood states measured participants' feelings at the time of testing while predicted mood states involve memory and may reflect cognitive biases (Wilson & Gilbert, 2003). Not all participants provided complete sets of these data over both testing days, leaving a total sample size of 17. There was no significant difference across the two treatment conditions (placebo *Mdn* = 3.11; testosterone *Mdn* = 2.90) for positive items of the PANAS assessing *current* mood state Z = -.36, p = .716, r = -.08; however, scores for positive items for *future* mood state were significantly higher in the testosterone condition (*Mdn* = 3.33) compared to placebo (*Mdn* = 3.11) Z = -2.11, p = .035, r = -.497. No significant differences were found for negative items between the two treatment conditions, regardless of time. We then created composite PANAS scores to reflect overall positive affect for current and future moods by subtracting negative scale scores from positive scores. A two-tailed paired samples t-test indicated a significant difference between placebo and testosterone in affective forecasting (t(16)= 3.099, p=.007, d = .61) but not in terms of current mood states (t(16)= .435, p=.669, d = .08). Participants had an average score for current mood state of 1.54 (SD=1.17) on the day of testosterone administration, and 1.45 (SD = .91) on placebo. When treated with testosterone, participants imagined a more positive future, with a mean score of 2.0 (SD = .69) compared to only 1.50 (SD= .93) when given placebo.

Finally, on the placebo day, we found no significant correlations between action binding (r(16) = .08, p = .76) and current mood state, nor affective forecasting (r(16) = .03, p = .89). Nor were there any significant correlations between tone binding and current (r(16) = .35, p = .17) or future mood state (r(16) = .39, p = .12).

Table 2. Descriptive statistics for mood data

	Placebo		Testosterone	
	M	SD	M	SD
Current Mood				
Positive	1.33	(.85)	1.20	(.95)
Negative	1.00	(.61)	1.00	(.52)
Composite	1.45	(.91)	1.54	(1.17)
Affective Forecast				
Positive*	1.44	(.81)	2.43	(.71)
Negative	1.00	(.61)	1.00	(.32)
Composite*	1.5	(.93)	2	(.69)

Composite values represent overall positive affect. The asterisk indicates significant differences between testosterone and placebo testing days. Composite variables reflect overall positive affect.

4. DISCUSSION

In the current study, we investigated the effect of 0.5mg testosterone on the sense of agency, as measured in terms of intentional binding. Several mechanisms have been described to explain the link between testosterone and behaviors that facilitate control over the environment (Eisenegger, Haushofer & Fehr, 2011; Terburg & van Honk, 2013). It is however unknown whether testosterone also influences more basic feelings of sensory-motor control. To the best of our knowledge, this is the first study to directly investigate the hormonal basis of SoA and here we demonstrate a facilitation of implicit feelings of control by a 0.5mg dosage of testosterone in young women.

Under both testosterone and placebo conditions, participants demonstrated the "intentional binding" effect. Although significant binding occurred on both testing days, confirming the validity of the task, our statistical analyses showed that action binding during the testosterone condition was significantly increased compared to placebo. However, there was no significant effect of testosterone on the magnitude of perceptual shifts for tone binding. These results suggest that testosterone facilitates the SoA, but because there was no statistically significant difference in the magnitude of change from placebo to testosterone between the two binding

conditions, the current findings unfortunately have no bearing on the small but growing literature suggesting that tone and action binding are, to some extent, driven by dissociable mechanisms (Kranick et al., 2013; Wolpe et al., 2013).

Action binding was significantly increased on the testosterone-treatment day, but our data do not show any explained variance on binding for 2D:4D digit ratio (a proxy for pre-natal effects of testosterone on the brain), despite this variable explaining substantial variance in other studies involving the effects of testosterone on cognition (mind reading and social decision making) (Buskens et al., 2016; Carré et al., 2015; Montoya et al., 2013; van Honk et al., 2011). Of note, unlike these previous studies, our measure of SoA had no social component. Our findings suggest that the effect of testosterone on the SoA appears to depend on current testosterone and not pre-natal sex hormone priming in the brain (though see Olsson et al., 2016). In support of this view, studies have shown that although children with autism spectrum disorder tend to have lower 2D:4D ratios (Milne et al., 2006) – an indicator of higher prenatal testosterone exposure – they exhibit normal agency over action (David et al., 2008). Together, these findings suggest that 2D:4D digit ratios are not related to the SoA. It may therefore be the case that prenatal effects of hormones interact exclusively in tasks involving social cognition.

The modulation of SoA by testosterone is consistent with the idea that basic sensory-motor experiences of personal control may contribute toward the experience of power (Obhi, Swiderski & Brubacher, 2012). In fact, many agree that the SoA is a basic mechanism constituting the feeling of free will and self-determination (Haggard & Tsakiris, 2009; Moore, 2016), which may have real consequences in the social sphere. Indeed, testosterone dynamics tend to be associated with personal freedom and social mobility. Karsh and Eitam (2015) have recently demonstrated that the experience of agency is desirable and rewarding in much the same way as tangible rewards, suggesting that it may function to sustain behavioral persistence even when outcomes are uncertain. An increase in SoA by testosterone may therefore explain some of the rewarding effects of testosterone (Hermans et a., 2010). The

current findings therefore underscore the relationship between basic sensorimotor processes and more high-level emotional states, like those instantiated by testosterone (for e.g. social power, for review see Eisenegger et al., 2011), suggesting that mental experiences are grounded and embodied in physical experience (Barsalou, 2008; Lackoff, 2012; Varela et al., 1992). In this view, the phenomenology associated with power may derive in part from the physical and perceptual experiences of the body that are recruited during interaction.

Given that testosterone is a male-type steroid hormone and that indices of power and social dominance tend to be higher in men (Pratto, Sidanius & Levin, 2006), the current findings might be interpreted to imply that men experience increased SoA. To the best of our knowledge, no studies have focused their research question exclusively on sex differences in the SoA but one study (Caspar et al., 2017) found no effect of gender on a similar implicit measure of agency using the interval estimates procedure. However, though males have up to ten times as much circulating testosterone, females are thought to be more sensitive to the hormone (Dabbs & Dabbs, 2000), implying that different levels of testosterone can produce similar effects in men and women. Instead, differences between the sexes in terms of when and how much testosterone is released may determine the extent to which testosterone produces an effect. For instance, as with many other social contexts, testosterone response to competition differs between men and women (Kivlighan, Granger & Booth, 2005). We may therefore expect a difference in agency between men and women under these conditions, but not when simply tested at baseline.

In terms of more precise mechanisms by which testosterone has a purported effect on action binding, we can only speculate. Wolpe et al. (2012) argue that action binding increases as a function of the reliability of outcomes. Yet, in our study, reliability was consistently high, begging the question of why action binding differed across placebo and testosterone conditions? Drawing on Moore and Haggards' (2008) ideas, that the Bayesian inference process that generates the SoA is context dependent, it may be that testosterone changes the perceived predictability of actions. For instance, if motor predictions are strong, this alone can

lead to binding. Wolpe et al. (2014) argue that trait optimism, a key feature of powerful personalities (Anderson & Galisnksy, 2006), predicts the exaggerated reliability of priors that predict successful perception of goal-directed action, thus explaining the "illusion of superiority" in which self-actions are perceived as being more successful than others'. Over-confidence in decision-making has been linked to narcissistic personality traits (Campbell, Goodie & Foster, 2004), which have been found to predict both intentional binding (Hascalovitz & Obi, 2015) and testosterone response (Lobbestael et al., 2014; Pfattheicher, 2016), suggesting that the effect of testosterone reported here on the SoA may be mediated, at least in part, by its influence on motor priors. Future studies will be required to test this hypothesis directly by adding a probabilistic component to the task design in which the reliability of action-outcomes is varied to directly assess the role of predictability in testosterone's effect on agency.

Testosterone and mood

While current mood states were not significantly influenced by testosterone, our results show that perceptions about future affective states were minimally, but significantly, more optimistic in the testosterone condition. Consistent with the null finding for current mood, previous research shows that when asked directly, participants administered testosterone fail to reliably report any changes in affect (Eisenegger et al., 2010). However, affective forecasts may involve cognitive biases and here they were found to be more positive on the testosterone day than on placebo.

Several studies indicate that optimism is, in fact, linked to the perception of control (Darvill & Johnson, 1991; Fontaine, Manstead & Wagner, 1993; Guarrera & Williams, 1987; McKenna, 1993). For instance, powerful individuals tend to believe more than others that they have control over their futures (Guinote, Brown & Fiske, 2006; Heine et al., 1999; Lachman & Weaver, 1998). Of note, we did not find a relationship between binding scores and predictions about future affect. This implies distinct mechanisms underpinning the effect

of testosterone on agency and future affect. For instance, Markowitsch and Staniloiu (2010) have proposed that, with respect to memory processing, which is recruited when forecasting the future (Schacter et al., 2012), the amygdala functions to bias cues so that encoded events of a particular emotional significance can be successfully searched for and reactivated. Given that testosterone is known to activate the amygdala (see Heany et al., 2015 for review) and facilitate social approach behaviour (Radke et al., 2015), this suggests a mechanism via which salience is attached to more positive memories in response to testosterone administration. Enhanced activation of the amygdala may therefore mediate the effects of testosterone on positive perceptions of future affect, an idea corroborated by evidence linking the amygdala to optimistic thinking (Sharot et al., 2007) and testosterone to enhanced self-efficacy (Costa, Serrana & Salvador, 2016) and could be tested directly in future imaging studies by comparing recall of positive versus negative autobiographical details in testosterone-treated participants. Together with the finding of increased SoA, these results suggest that testosterone might also support the early, prospective sense of agency which is especially important in threatening or ambiguous social settings, like competition, where a proactive response may be advantageous.

Limitations

There are several limitations to the current research which should be addressed in future replication studies. We were not able to assess salivary or plasma levels of testosterone. However, based on previous studies that demonstrate a ten-fold increase in women's circulating testosterone in response to 0.5mg of the hormone (Tuiten et al., 2000), we can infer with a reasonable degree of confidence that the significant increase in action binding that was seen on testosterone-treatment days was an effect of the administration, given that all other variables were held constant. Secondly, although we counter-balanced action versus tone conditions across participants and between testing days, we did not counter-balance baseline and agency blocks. Even so, our intentional binding scores on placebo days are comparable to other studies (Moore et al., 2012; Kranick et al., 2013) and we surmise that

because a significant difference arose between placebo and testosterone days in action binding, this effect is unlikely simply accounted for by order.

Finally, it will be worthwhile to probe alternative measures of implicit SoA (e.g. sensory attenuation) but also explicit, meta-cognitive ratings of agentive experience. Ultimately, the investigation into how testosterone modulates the SoA in social contexts will offer information that is most ecologically useful. In the social world, where authorship is often ambiguous (de Bézenac et al., 2015; Pacherie, 2013) the SoA may play an important role in the feeling of responsibility and achievement, which may translate into an experience of power.

5. CONCLUSION

To conclude, we show that 0.5mg of testosterone enhances the feeling of a sense of agency and induces the perception of a brighter future. We found this significant effect of testosterone on SoA exclusively for action binding, and not tone binding. Because intentional binding on placebo did not predict positivity in affective forecasting, it appears that testosterone influences SoA and optimism via distinctive brain mechanisms. Although our effects sizes were modest, the pattern of results reported here contributes to the literature on the embodiment of social power and highlights an important link between testosterone and the experience of control. That is, feelings of agency associated with power and assertiveness may emerge out of more basic sensorimotor processes linked to control over the body. This rudimentary form of empowerment may constitute a key mechanism by which testosterone-fueled dominance is initially achieved. Future studies that explore the effects of testosterone on other parameters of embodiment, such as ownership and interoceptive processing, are needed for further investigation of this proposal.

6. Acknowledgements

DvdW received support from the Oppenheimer Memorial Trust and South Africa's National Institute for the Humanities and the Social Sciences.

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