# SI Appendix

## Brunnlieb et al.,

SI Materials and Methods

### Study 1 (behavior)

### 1. Task

### 1.1 Stag hunt game

#### 1.1.1 Strategy method

The strategy method stag hunt game is illustrated in figure 1B. *S* denotes the security level, the minimal payoff that a player can secure himself when choosing rabbit. We presented the stag hunt game matrix to our participants and asked them to indicate a value of parameter *S* where they would switch from the Rabbit to the Stag strategy. Then, each subject was randomly matched with a partner, and a value of *S* (between 0 and 150) was realized at random. Based on the drawn *S* value and the subjects' switching points, we determined whether each participant chose the Stag or Rabbit action and calculated their corresponding payoffs.

#### 1.1.2 Belief elicitation

Following the strategy method task, we presented the same sample of subjects 12 stag hunt games with different security levels (see table S1) in a pseudo-randomized order. In each stag hunt game, we asked participants to indicate the likelihood (between 0% and 100%) that their partner chose Stag. Beliefs were incentivized using the quadratic scoring rule mechanism, which is an incentive-compatible belief elicitation method (i.e., it is optimal for subjects to report their true beliefs) [s1].

#### 1.1.3 Lottery task

Subjects participated in an additional lottery choice task, commonly used to measure one's attitude towards risk (see [s2] and Table S2). In each round of the task, subjects had to choose between a risky lottery A, that potentially could yield the highest possible payoff but had a greater payoff variance, and a less risky lottery B, with a lower payoff variance. The stimulus of the lottery task was identical to the stag hunt task, except that the player's risk was generated by randomness rather than by a social interaction. We composed nine different lottery pairs by varying the probability of winning the high reward, as summarized in table S2. The earlier participants switched from the less risky lottery B to the risky lottery A, the more risk seeking they were; thus, later switching points thus indicates a more risk-averse behavior.

Following the task, participants drew a ball from a bingo cage to determine which lottery pair would be realized for payoff purposes. Then, subjects played whichever lottery (A or B) they had chosen, realized using a bingo cage that contained red and blue balls in frequencies that corresponded with the outcomes probabilities.

### 1.1.4 Social preferences task

The final task measured social preferences [s3], i.e., how concerned are the subjects regarding their partners' welfare. Each subject was presented with five different monetary allocations, for himself and an anonymous partner, and had to indicate his preferred distribution (see table S3). As people have different social preferences when they earn less than their partners [s4], the payoff to one's self was always greater than his partner's. The different outcomes posited a systematic trade-off between the payoffs to one's self and to his partner, such that at the most selfish option the partner received no payoff, and at the most pro-social option, the payoffs were almost equal. We realized the social preferences task payoffs by randomly selecting two participants from each session such that the choice of the first was implemented with the second participant as a partner.

### 1.1.5 Mood questionnaire

Participants completed the German version of the Multidimensional Mood state questionnaire [MDMQ, s5] that assessed three mental state dimensions: pleasantness, wakefulness, and calmness, measured by eight items per dimension scored from 1 ("definitely not") to 5 ("extremely"). The MDMQ were filled out before receiving intranasal AVP and were completed again after the experiment.

## 1.2. Data analysis

### *1.2.1 Stag hunt game*

To determine whether AVP increases human cooperative behavior, we entered the switching point decisions (*S*-values) elicited using the strategy method into a one way ANOVA and found a significant difference between the AVP and placebo groups (one way ANOVA, $F(1,57)= 5.522$ $p<0.023$, S4).

### *1.2.2 Beliefs*

We estimated a linear regression mixed model, where the dependent variable was the elicited belief in each game (between 0 and 100) and the independent variables were treatment (1=AVP, 0=Placebo) and security level (parameter S), clustered at the subject level. The treatment coefficient was negative and insignificant ($t=-0.49$, $p= 0.62$ normal Approximation), see table S6.

### *1.2.3 Lottery task*

As a measure of risk attitude, we determined the switching point between the risky and the safe lotteries for each subject. We found no AVP effect on the switching point (one way ANOVA, $F(1,56)= 0.339$ $p=0.563$) .

As all the indirect effects of AVP on a subject's state that are independent of the social context (i.e. mood, calmness, blood pressure, hydration status and levels of other hormones that might interact with AVP, such as the HPA axis-related hormones [s6] would be present in *both* tasks, these potential effects of AVP cannot be responsible for the increased risk taking amid the social context of stag hunt game under AVP treatment.

#### *1.2.4 Social preferences*

We found no significant AVP effect on social preferences (Mann-Whitney U-test two-sided, $p=0.233$, $u=358.50$, $z=-1.193$), but there was a weak tendency of the AVP group towards more selfish allocations (see figure S2 and table S6).

#### *1.2.5 Mood*

We estimated mixed-effect general linear models with the MDMQ scores of the pre- and post-exposure as a within-subjects factor and the experimental condition (AVP vs. placebo) as a between-subjects factor. We found no significant differences between the AVP and Placebo groups (pleasantness: $F(1,57)=0.48$, $p=0.490$; wakefulness: $F(1,57)=1.27$, $p=0.264$; calmness: $F(1,57)=0.24$, $p=0.629$). There were no significant differences between pre- and post-exposure (pleasantness: $F(1,57)=0.21$, $p=0.649$; wakefulness: $F(1,57)=0.28$, $p=0.601$; calmness: $F(1,57)=0.04$, $p=0.845$) and also no significant drug × (pre/post) interaction ($F(1,57)=0.24$, $p=0.626$).

## Study 2 (behavior and brain imaging)

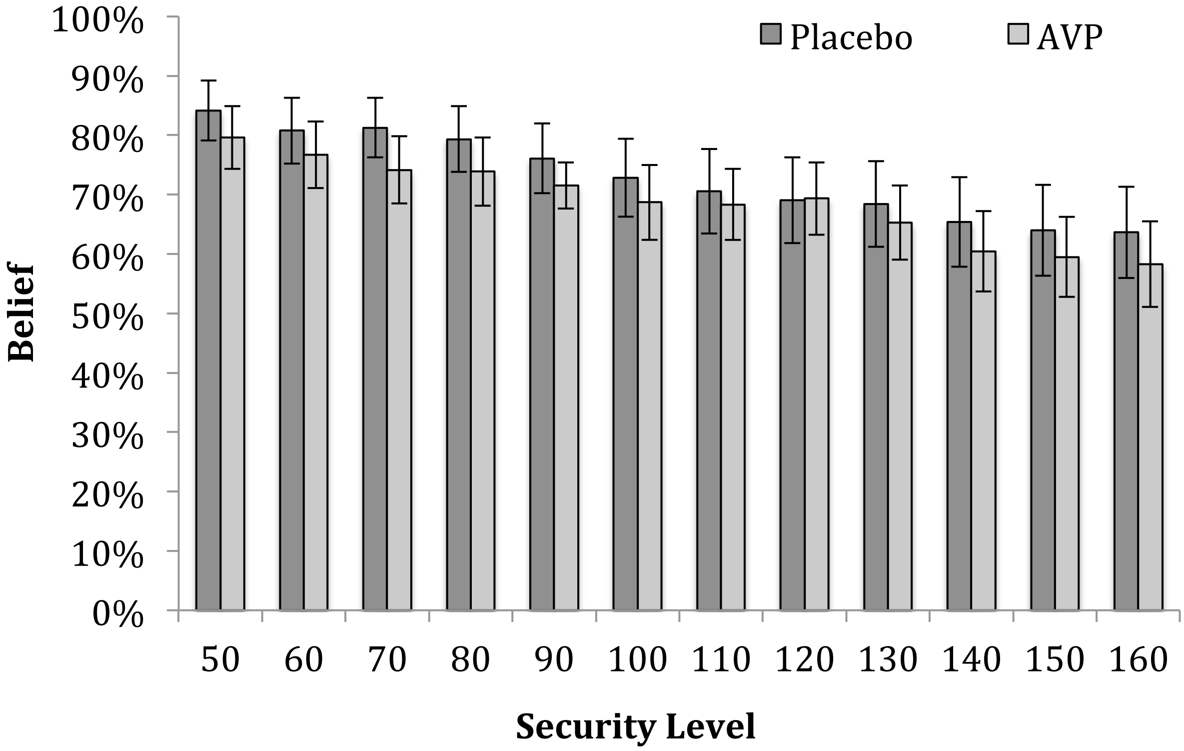
## 2. Material and Methods

### 2.1 fMRI data acquisition

We performed scanning using a 3-T Siemens Magnetom Trio syngo MR 2004A Scanner. In each of the 5 runs, we recorded 168 volumes (32 transversal slices, 3.5 x 3.5 x 3.5) parallel to the anterior-posterior commissure line (AC-PC). Functional images comprised of the following parameters: Gradient-Echo-EPI-sequence; TR=2000 ms; TE=30 ms; FOV = 224 mm; flip angle = 80 °; matrix = 64x64; slice thickness=3.5 mm; interslice gap=0 and for the structural images: T1-weighted MPRage: 256 x 256 matrix; FOV=256 mm; 192 1-mm sagittal slices.

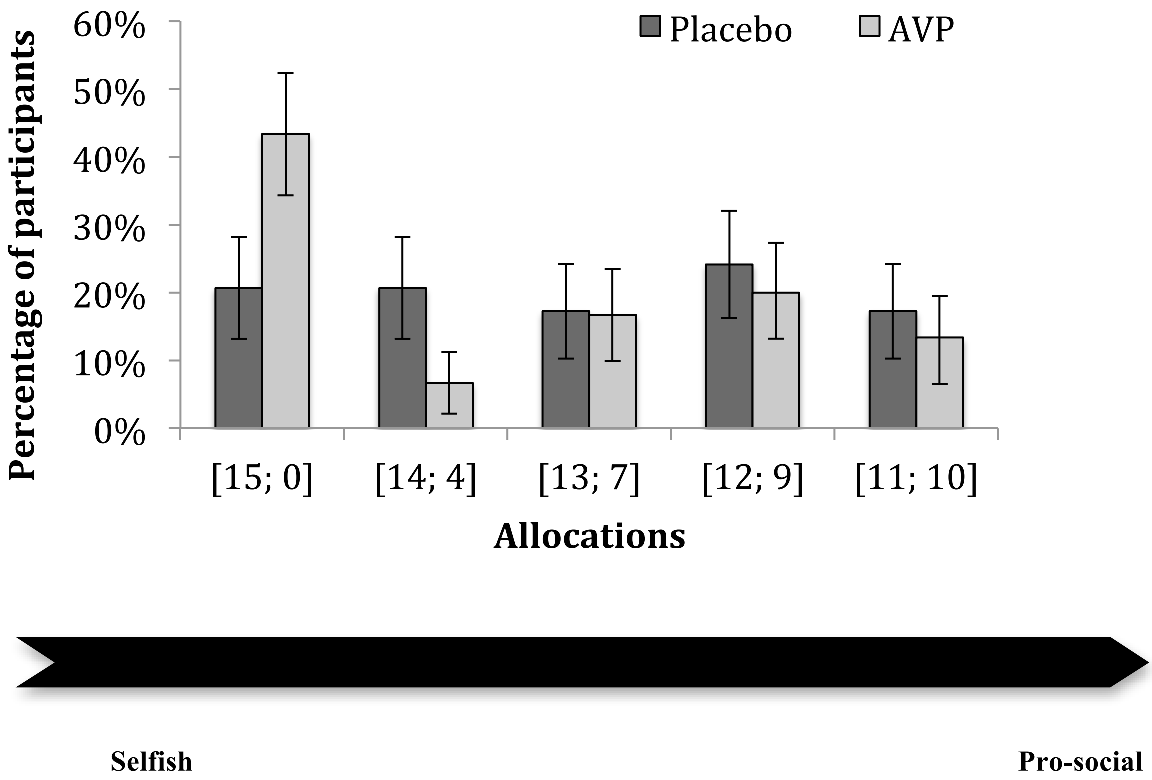
**Supplementary figures:**

**Figure S1: Elicited beliefs for all stag hunt games**



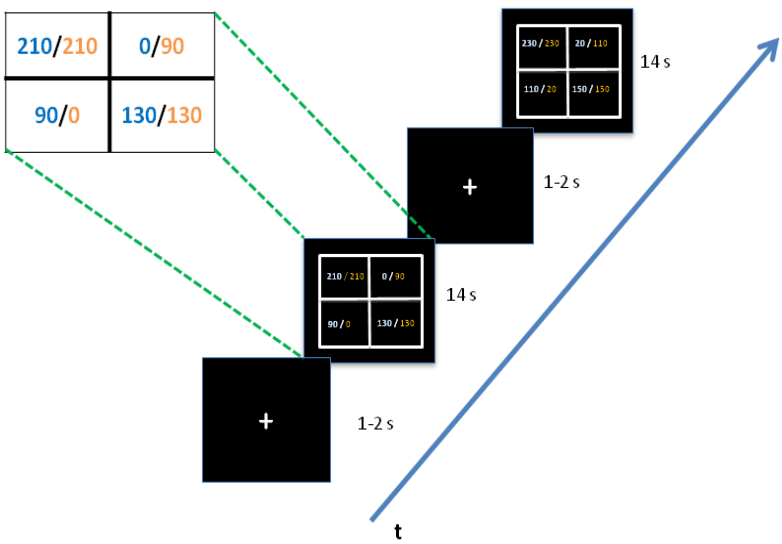

Participants reported the likelihood that their partners chose cooperation (Stag). The figure illustrates the mean beliefs for each security level value.

**Figure S2: Social preferences**



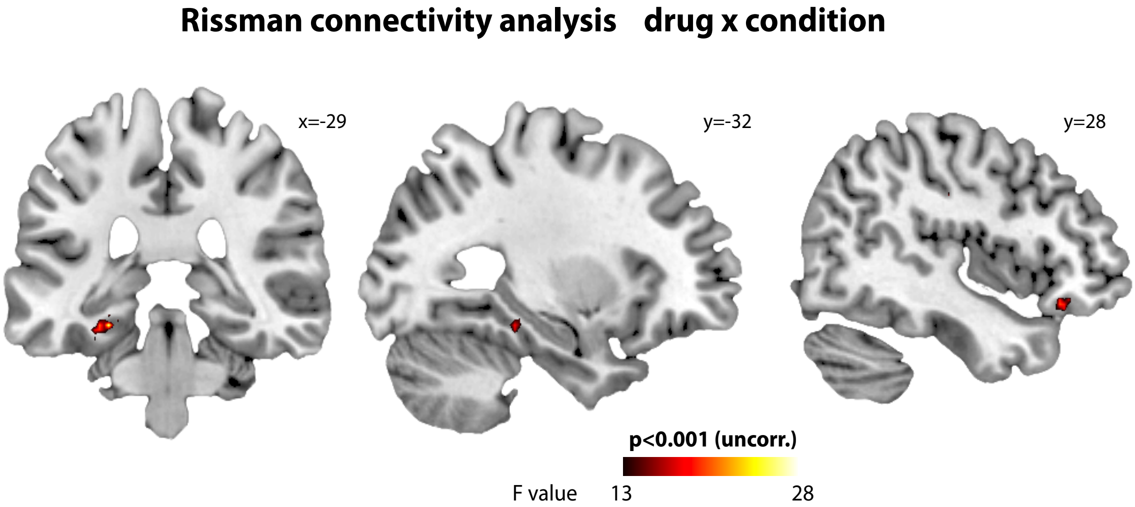

Each subject chose one of 5 different monetary allocations to himself and his anonymous partner.

**Figure S3: Time course of the fMRI study**

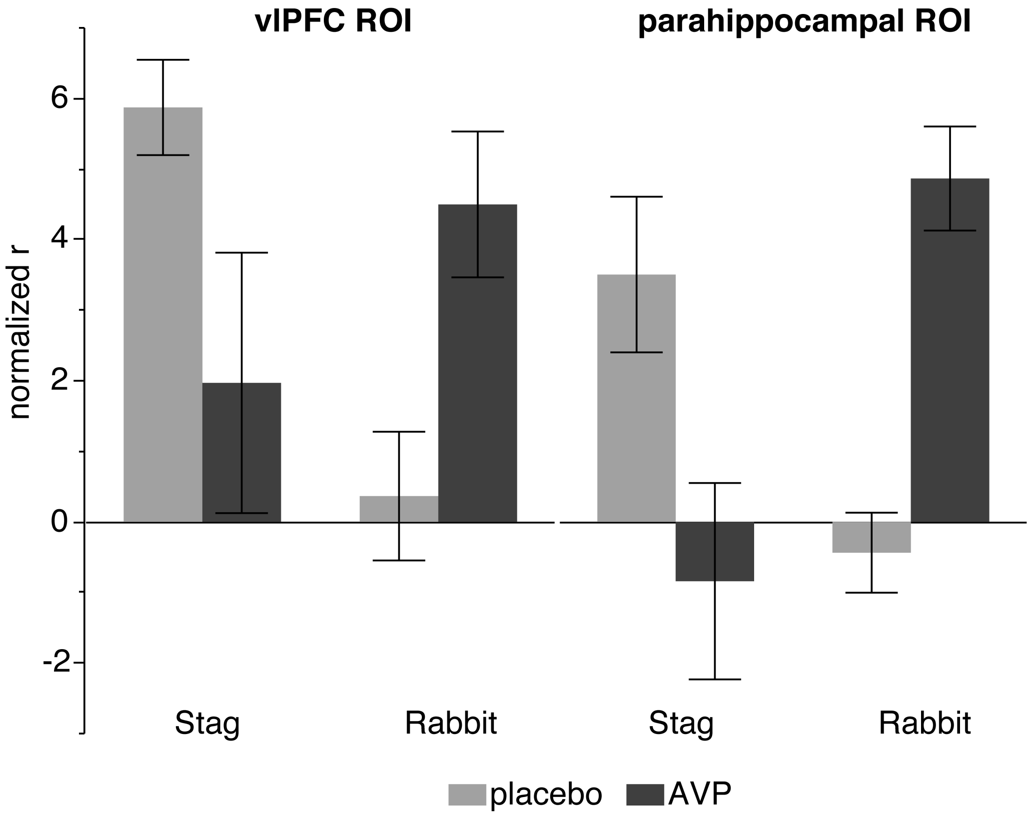



Each trial comprised the presentation of a fixation cross (1-2s), followed by the stag hunt game (14s). Participants had to indicate their choice of strategy by pressing a button.

**S4: Drug (AVP, placebo) x condition (Stag, Rabbit) interaction (seed: left dlPFC)**




**S5: Mean normalized correlation coefficients for the two experimental conditions (Stag, Rabbit) and groups (AVP, placebo) from the functional ROIs located at the ventrolateral prefrontal cortex and parahippocampal gyrus.**



**Supplementary tables:**

**Table S1: Stag-hunt games**

| Stag hunt game | A/A | B/S | S/B | D/D |
|---|---|---|---|---|
| **1** | 210/210 | 0/50 | 50/0 | 170/170 |
| **2** | 210/210 | 0/60 | 60/0 | 170/170 |
| **3** | 210/210 | 0/70 | 70/0 | 170/170 |
| **4** | 210/210 | 0/80 | 80/0 | 170/170 |
| **5** | 210/210 | 0/90 | 90/0 | 170/170 |
| **6** | 210/210 | 0/100 | 100/0 | 170/170 |
| **7** | 210/210 | 0/110 | 110/0 | 170/170 |
| **8** | 210/210 | 0/120 | 120/0 | 170/170 |
| **9** | 210/210 | 0/130 | 130/0 | 170/170 |
| **10** | 210/210 | 0/140 | 140/0 | 170/170 |
| **11** | 210/210 | 0/150 | 150/0 | 170/170 |
| **12** | 210/210 | 0/160 | 160/0 | 170/170 |

The twelve stag hunt games presented to elicit the beliefs about the likelihood that ones' partner chose the cooperative strategy.

**Table S2: The lottery choice task**

| **Lottery A**<br><br>[200, p; 0, 1-p] | **Lottery B**<br><br>[110, p; 170, 1-p] |
|---|---|
| [200, 0 %; 0, 100%] | [110, 0%; 170, 100%] |
| [200, 10 %; 0, 90%] | [110, 10%; 170, 90%] |
| [200, 20 %; 0, 80%] | [110, 20%; 170, 80%] |
| [200, 30 %; 0, 70%] | [110, 30%; 170, 70%] |
| [200, 40 %; 0, 60%] | [110, 40%; 170, 60%] |
| [200, 50 %; 0, 50%] | [110, 50%; 170, 50%] |
| [200, 60 %; 0, 40%] | [110, 60%; 170, 40%] |
| [200, 70 %; 0, 30%] | [110, 70%; 170, 30%] |
| [200, 80 %; 0, 20%] | [110, 80%; 170, 20%] |
| [200, 90 %; 0, 10%] | [110, 90%; 170, 10%] |
| [200, 100 %; 0, 0%] | [110, 100%; 170, 0%] |

We derived lottery pairs with the corresponding payoffs of stag hunt game 7 (see table S1). For example, lottery A would yield a reward of 200 eurocents with probability of p, and 0 eurocents with probability of (1-p); lottery B would yield a reward of 110 eurocents with probability of p and 170 eurocents with probability of (1-p).

**Table S3: Social preferences (your payoff; partners' payoff)**

| **Allocation** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Payment to self** | 15 | 14 | 13 | 12 | 11 |
| **Payment to other** | 0 | 4 | 7 | 9 | 10 |

*Selfish* *Pro-social*

Participants were asked to choose one of the five monetary allocations. The upper row is the payoff to self and the bottom row is the payoff of the partner.

**Table S4: Strategy method (mean switching point)**

| | ***Mean*** | ***SD*** | ***Minimum*** | ***Maximum*** |
|---|---|---|---|---|
| ***Placebo*** | 90.10 | 60.09 | 0 | 150 |
| ***AVP*** | 121.33 | 40.41 | 10 | 150 |

**Table S5: Lottery task**

| | ***Mean*** | ***SD*** | ***Minimum*** | ***Maximum*** |
|---|---|---|---|---|
| ***Placebo*** | 61.38 | 15.97 | 30 | 90 |
| ***AVP*** | 64.14 | 19.91 | 0 | 100 |

Results of lottery task switch point from risky to riskless choice. Earlier switch points indicate a more risk seeking subject (Lotteries: [200, p, 0, 1-p] vs. [110, p, 170, 1-p].

**Table S6: Stag hunt game beliefs**

| | ***Dependent variable: Beliefs*** |
|---|---|
| AVP | -4.137<br>(8.322) |
| Security level | $-0.192^{***}$<br>(0.017) |
| Constant | $93.150^{***}$<br>(6.184) |
| Sub. random effects | YES |
| Observations | 708 |
| Log Likelihood | -3,045.575 |
| Akaike Inf. Crit. | 6,101.149 |
| Bayesian Inf. Crit. | 6,123.961 |

*Note:* $^{*}$p<0.1 $^{**}$p<0.05 $^{***}$p<0.01

**Table S7: Social preference task: allocation decisions frequencies**

| Allocation | AVP | Placebo |
|---|---|---|
| [15; 0] | 13 (43.3%) | 6 (20.69 %) |
| [14; 4] | 2 (6.67%) | 6 (20.69%) |
| [13; 7] | 5 (16.67%) | 5 (17.24%) |
| [12; 9] | 6 (20%) | 7 (24.14%) |
| [11; 10] | 4 (13.33%) | 5 (17.24%) |

**Table S8: Stag hunt basis games, study 2**

| **Basis games** | **A/A** | **B/S** | **S/B** | **D/D** |
|---|---|---|---|---|
| **1** | 210/210 | 0/40 | 40/0 | 130/130 |
| **2** | 210/210 | 0/50 | 50/0 | 130/130 |
| **3** | 210/210 | 0/70 | 70/0 | 130/130 |
| **4** | 210/210 | 0/80 | 80/0 | 130/130 |
| **5** | 210/210 | 0/90 | 90/0 | 130/130 |
| **6** | 210/210 | 0/110 | 110/0 | 130/130 |
| **7** | 210/210 | 0/120 | 120/0 | 130/130 |

The seven variations (“basis games”) of the stag hunt game. The basis games differ only with respect to their security level parameter C. All payoffs are in Eurocents.

**Table S9: Variations of stag hunt basis game, study 2**

| | **Choice A** | **Choice B** |
|---|---|---|
| **Choice A** | A+10n<br>A+10n | B+10n<br>C+10n |
| **Choice B** | S+10n<br>S+10n | D+10n<br>D+10n |

Subjects played each of the stag hunt basis game 15 times, each version was realized by adding an integer multiple [0...14] to all of the payoffs in the matrix.

**Table S10: Stag hunt game decisions, logistic regression, study 2**

**(fit by maximum likelihood, Laplace Approximation)**

***Dependent variable: Choice (Stag=1)***

| | **β** | **Marginal effect** |
|---|---|---|
| AVP | 0.867** <br>(0.338) | 0.21 |
| Security level | -0.014*** <br>(0.002) | -0.0034 |
| AVP × Security level | -0.006** <br>(0.003) | -0.0015 |
| Constant | 0.767*** <br>(0.237) | |
| Sub. Random effects | YES | |
| Observations | 3,150 | |
| Log Likelihood | -1,992.877 | |
| Akaike Inf. Crit. | 3,995.754 | |
| Bayesian Inf. Crit. | 4,026.030 | |

*Note:* * $p<0.1$ ** $p<0.05$ *** $p<0.01$

**Table S11: Linear regression analysis: Stag hunt game response times, study 2.**

| | |
|---|---|
| ***Dependent variable: Response time (milisecond)*** | |
| Stag | -2,017.225<br>(2,509.054) |
| AVP | 510.119<br>(5,316.041) |
| Security level | -97.692***<br>(19.493) |
| Stag × AVP | -3,358.451**<br>(1,566.168) |
| Stag × Security level | 65.309**<br>(28.597) |
| Constant | 55,264.350***<br>(4,093.556) |
| Sub. Random effects | yes |
| Observations | 3,150 |
| Log Likelihood | -35,809.290 |
| Akaike Inf. Crit. | 71,634.580 |
| Bayesian Inf. Crit. | 71,683.020 |
| *Note:* | *p<0.1 **p<0.05 ***p<0.01 |

**Table S12: Brain regions that showed increased neural activity for the comparison Placebo > AVP and the contrast Stag vs. Rabbit choices.**

| Laterality | Brain region | Brodmann area | x | y | z | T | cluster size |
|---|---|---|---|---|---|---|---|
| **p<0.001 (uncorr.)** | | | | | | | |
| L | Dorsolateral prefrontal cortex | 44 | -54 | 18 | 34 | 5.1 | 62 |
| **L=left, R=right; T=peak T-value; x, y, z =MNI coordinates; cluster size in voxels** | | | | | | | |

**Table S13: Brain regions that showed increased functional connectivity with the left dlPFC for AVP > Placebo for Stag choices.**

| Laterality | Brain region | Brodmann area | x | y | z | T | cluster size |
|---|---|---|---|---|---|---|---|
| **p<0.001 (uncorr.)** | | | | | | | |
| L | Pallidum | 48 | -22 | -2 | -2 | 4.29 | 15 |
| R | Cingulate gyrus | | 10 | 6 | 50 | 4.28 | 70 |
| L | Cingulate gyrus | 24 | -2 | 0 | 48 | 3.72 | |
| R | Medial frontal gyrus | 6 | 4 | -2 | 54 | 3.48 | |
| R | Superior frontal gyrus | 6 | 16 | -2 | 62 | 3.75 | 12 |
| **L=left, R=right; T=peak T-value; x, y, z =MNI coordinates; cluster size in voxels** | | | | | | | |

**Table S14: Brain regions indicating enhanced functional connectivity with the left dlPFC for AVP > Placebo for "rabbit" choices.**

| Laterality | Brain region | Brodmann area | x | y | z | T | cluster size |
|---|---|---|---|---|---|---|---|
| **p<0.001 (uncorr.)** | | | | | | | |
| L | Parahippocampal gyrus | 30 | -22 | -34 | -14 | 5.82 | 111 |
| L | Parahippocampal gyrus | 37 | -24 | -42 | -14 | 4.10 | |
| L | Parahippocampal gyrus | 37 | -32 | -38 | -12 | 3.97 | |
| L | Calcarine | 17 | -18 | -60 | 8 | 4.43 | 24 |
| L | Amygdala | 34 | -28 | 2 | -14 | 4.31 | 27 |
| R | Middle Cingulum | 23 | 4 | -4 | 34 | 4.30 | 78 |
| R | Anterior cingulate gyrus | 24 | 4 | 12 | 30 | 4.06 | |
| R | Middle Cingulum | 32 | 10 | 16 | 36 | 3.65 | |
| R | Inferior frontal gyrus | 45 | 54 | 40 | 0 | 4.23 | 12 |
| R | Middle frontal gyrus | 46 | 50 | 48 | 4 | 3.64 | |
| L | Middle occipital gyrus | 19 | -40 | -80 | 14 | 4.15 | 17 |
| L | Middle occipital gyrus | 19 | -34 | -86 | 14 | 3.93 | |
| L | Middle temporal gyrus | 20 | -58 | -22 | -14 | 3.94 | 14 |
| L | Lingual gyrus | 19 | -18 | -50 | -2 | 3.87 | 12 |
| R | Middle temporal gyrus | 21 | 64 | -22 | -12 | 3.82 | 11 |

**L=left, R=right; T=peak T-value; x, y, z =MNI coordinates; cluster size in voxels**

**Table S15: Brain regions showing a drug x condition interaction**

| Laterality | Brain region | Brodmann area | x | y | z | F | cluster size |
|---|---|---|---|---|---|---|---|
| **p<0.001 (uncorr.)** | | | | | | | |
| L | Parahippocampal gyrus | 30 | -26 | -32 | -14 | 27.12 | 24 |
| R | Ventrolateral prefrontal cortex | 47 | 42 | 30 | -14 | 24.75 | 34 |
| R | Ventrolateral prefrontal cortex | 47 | 32 | 36 | -10 | 15.61 | |

**L=left, R=right; T=peak T-value; x, y, z =MNI coordinates; cluster size in voxels**

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