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Supplemental Data

Know Your Place: Neural Processing of Social Hierarchy in Humans

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SUPPLEMENTAL METHODS

Participant Training for Experiment #1 and Experiment #2

Because the "other players" in the two experiments were simulated and believability was imperative to the study, the training period prior to scanning was an elaborate procedure to make the situation socially immersive and ensure that the participant did not doubt the presence of other players. When the study volunteers were scheduled, they were told that they would be performing a simple computer task for monetary reward in the scanner at the same time as two other players performing the task outside the scanner and that, while both brain and behavioral data would be acquired from them, only behavioral data would be collected from the other players. The importance of arriving at the exact scheduled time was stressed, because the three people for a given session would be scheduled at 15 minute intervals to ensure that they did not meet in person to avoid personality confounds. Upon arrival, a digital photograph was taken of the participant, who was instructed to make a neutral face, which was inserted into the task. S/he was told that the other players had also had their pictures taken upon arrival, and that those would be seen in the experiment. The participant was escorted to his/her own training room and was led to believe that the other players were in separate rooms being trained by other researchers in the group. For both experiments, it was stressed to participants that they would be performing the task at the same time as – not *against* – the other players (as such, both of the players or neither of the players could win or lose in a given round of the task, and real and perceived task difficulty was the same when performing with both players). It was also stressed that the players in a given round would be able to see the performance of each other by linking the computers through a network (i.e., the other players would be seeing the same thing on the screen at the same time as the participant in the scanner). As an additional measure to ensure that the presence of the other players was perceived as "real", while the participant was being instructed on the task and design, a research assistant would interrupt to inform the training instructor of various "issues" that had arisen with another player (running behind in time, broken computer or other equipment, etc).

Experiment #2: "Unstable Hierarchy"

Additional Analysis: assessment of the saliency/value of the outcomes

In order to specifically separate the saliency or value associated with various aspects of the outcomes, as assessed by ventral striatal response, we conducted a general linear model analysis evaluating how well hierarchical value (valuable = 1, not valuable = -1) , reward (subject won = 1, subject lost = -1), and the other player rank (superior = 1, inferior = -1) associated with the outcomes predicted ventral striatal activity, an area known to process both positive and negative valuable stimuli. The dependent variable was parameter estimates extracted from *a priori,* structurally defined ventral striatal voxels [-9, 9, -6; 9, 9, -6] averaged within subjects for each possible outcome (8 total). In addition to hierarchical value, reward, and other player's rank, block regressors (of no interest) for each participant were entered into the model to account for within-subject effects.

Experiment #3: "Nonsocial Unstable Hierarchy"

Experimental Task

In order to isolate hierarchy-related brain activity specific to a *social* context in Experiment #2 (unstable hierarchy), we performed a post-hoc, modified version of the experiment (with 24 different participants), replacing the human other players with computer players that were programmed to perform better or worse than the participant on average. Rather than using photographs of human faces to represent the other players in the task, we used photographs of laptop computers. Other than replacing the other human players with computer players, all other aspects of the nonsocial paradigm and experimental set-up were identical to Experiment #2 (subject instruction, task design, and analysis).

The 24 participants (12 males, 12 females) were Caucasian, right-handed, healthy adults. The average age of participants (ages 20-41; mean = 27.9; S.D. = 5.6) was not significantly different (P = 0.146, two-tailed, independent-samples t test) than the average age of participants in Experiment #2 (ages 19-38; mean = 25.7; S.D. = 4.7). Participants had no history of any psychiatric or neurological disorders and gave written, informed consent for a protocol approved by the National Institute of Mental Health Institutional Review Board.

SUPPLEMENTAL RESULTS

Experiment #2: "Unstable Hierarchy"

Assessment of the Saliency/Value of the Outcomes

Activity in the ventral striatum was used to index saliency or value associated with different aspects of the outcomes, as this region is know to respond to both positively and negatively valuable or important events. A general linear model analysis revealed a highly significant relationship between the set of predictor variables (hierarchical value of outcomes, reward, and rank of the other player) and ventral striatal activity [left hemisphere: $F(26,191) = 23.146$, $R = 0.886$, *adjusted* $R^2 = 0.751$, $P < 0.001$; right hemisphere: $F(26,191) = 16.491$, $R = 0.850$, *adjusted* $R^2 = 0.678$, $P < 0.001$]. About 75% of variance in left ventral striatal activity and 68% of variance in right ventral striatal activity can be accounted for by hierarchical value of outcomes, reward, and rank of the other player. Each individual predictor variable contributed significantly to activity in the left ventral striatum (hierarchical value: standardized *beta* = 0.117, $P = 0.001$; reward: standardized *beta* = 0.159, $P < 0.001$; other player's rank: standardized *beta* = 0.084, $P = 0.022$) and the right ventral striatum (hierarchical value: standardized *beta* = 0.149, $P < 0.001$; reward: standardized *beta* = 0.189, $P < 0.001$; other player's rank: standardized *beta* = 0.097, $P = 0.019$). Critically, the contributions of hierarchical value and reward to ventral striatal activity were both larger and statistically indistinguishable $F(1,166) = 0.175$; $P = 0.676$], suggesting that the hierarchical value associated with certain outcomes was neurally considered as salient or valuable as monetary reward.

Assessment of the Game Phase of the Experimental Paradigm

Viewing a superior individual compared to viewing an inferior individual elicited multiple brain activations when the hierarchy was unstable (Experiment #2) that did not result when the hierarchy was stable (Experiment #1). In addition to the difference of hierarchy stability, the game phase of the paradigm was also changed in Experiment #2. To ensure that the detected fMRI signal associated with viewing the superior and inferior other players was not somehow contaminated by the signal associated with the subsequent game phase, leading to the unique activations elicited in Experiment #2, differential neural activity associated with playing the game with a superior player compared to playing the game with an inferior player was assessed in a post-hoc analysis, modeling the game phase with two separate regressors based on the rank of the other player in the round. As strong evidence against any contamination, areas of the brain uniquely activated when viewing a superior compared to inferior player in Experiment #2 (e.g. sensorimotor cortex, SMA, amygdala, posterior cingulate, MPFC) were not significantly activated during the game phase when participants were playing with a superior player compared to with an inferior player (statistical threshold: $P < 0.001$, uncorrected; voxel extent = 20), with the exception of the thalamus. This provides strong evidence that the game itself is not responsible for differential results between Experiment #1 (stable hierarchy) and Experiment #2 (unstable hierarchy).

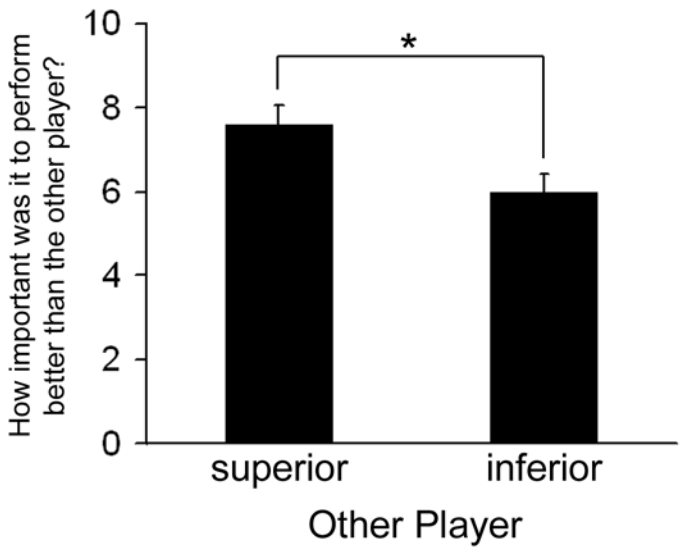

Figure S1. Ratings for how important is was to perform better than the other player when the other player was superior and when the other player was inferior, measured on a scale from 1 (not at all) to 10 (extremely). The bar plots represent means and standard errors across participants. It was significantly ($P < 0.001$; $t(22) = 5.044$; two-tailed; paired t test) more important for participants to perform better than the superior player compared to the inferior player.

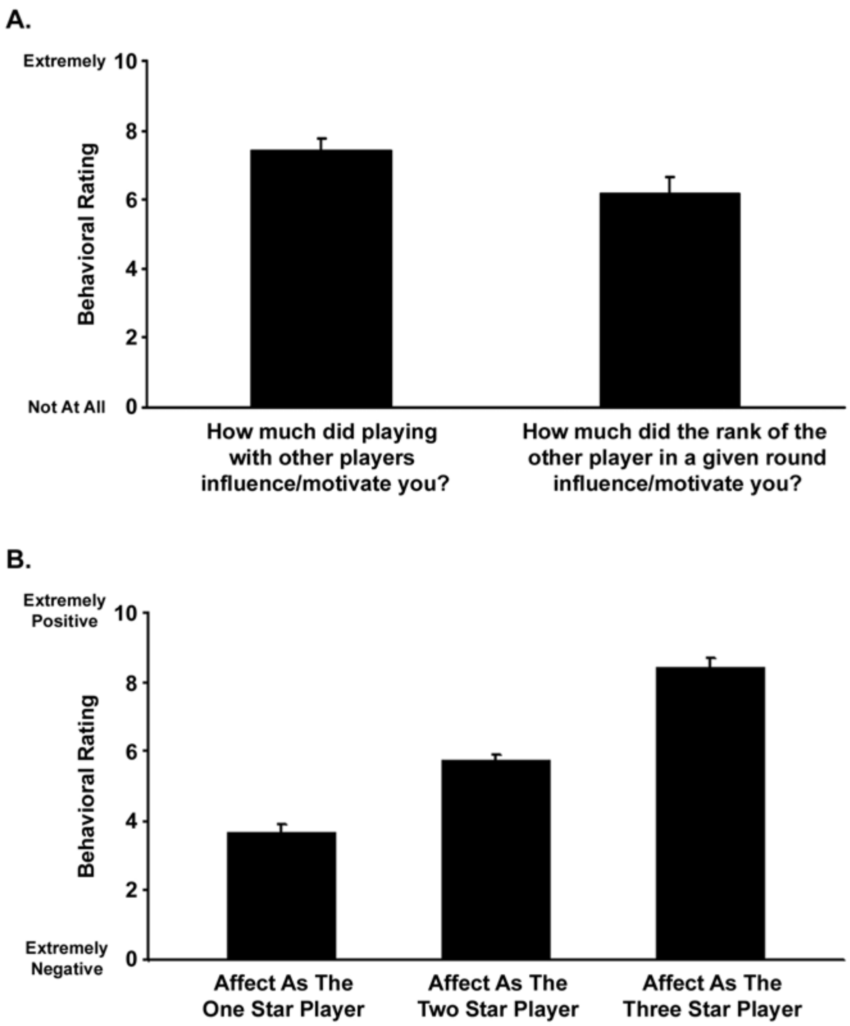

Figure S2. Ratings indicative of strong engagement in the virtual social hierarchy setting. The bar plots represent means and standard errors across participants. **(A)** On a scale from 1(not at all) to 10 (extremely) participants indicated that they were strongly influenced/motivated by performing the task with other players (mean rating = 7.42; s.e. = 0.350) and that they were also strongly influenced/motivated by the rank of other player in a given round of the task (mean rating = 6.17; s.e. = 0.491). **(B)** On a scale from 1 (extremely bad) to 10 (extremely good), participants indicated that they felt better, the higher ranked they were. The ratings were significantly different between the status levels ($F[2,46] = 101.967$, $P < 0.001$; one-way, repeated-measures ANOVA) and post-hoc comparisons (Bonferroni adjusted) revealed that all of the ratings for the three status levels were significantly different from each other ($P < 0.001$).

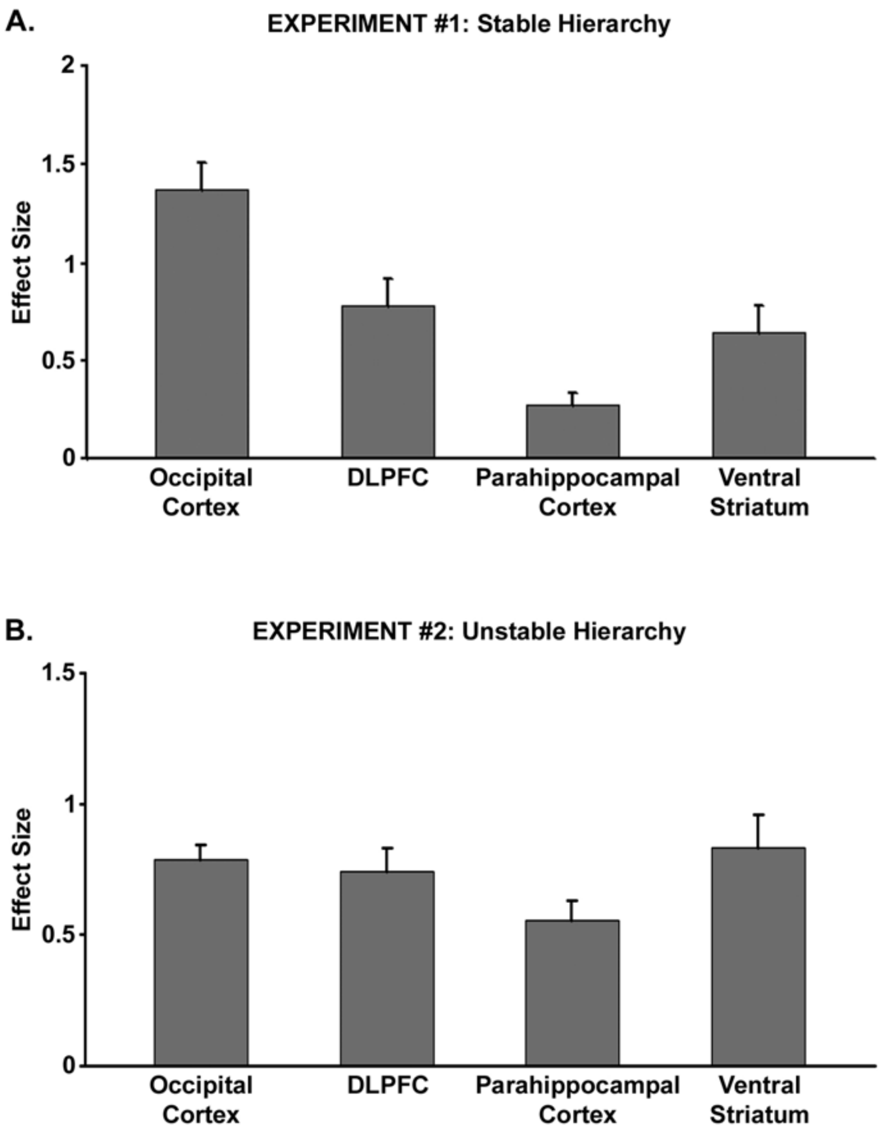

Figure S3. Effect sizes (parameter estimates) for the contrast, "superior player > inferior player", from brain regions activated in both Experiment #1 and Experiment #2. The bar plots represent means and standard errors across participants. The parameter estimates were extracted from the peak voxels in each activated region for **(A)** Experiment #1: stable hierarchy and **(B)** Experiment #2: unstable hierarchy.

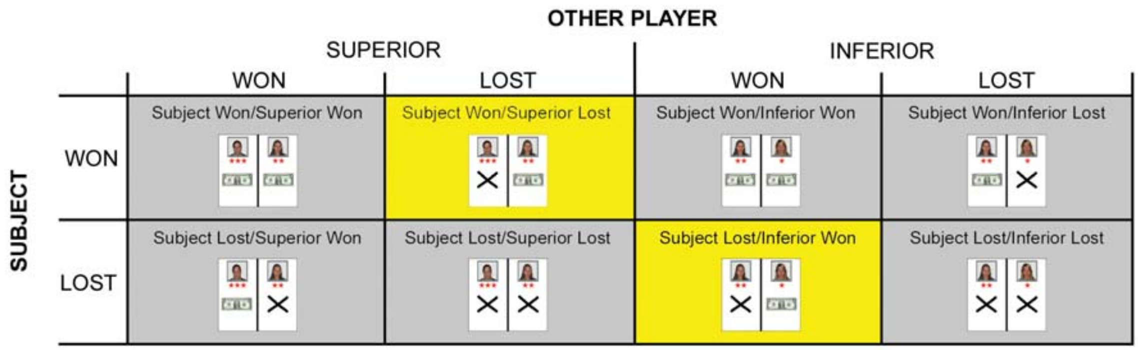

Figure S4. Each of the possible outcomes (taking into account the relative rank of the other player) in Experiment #2. Outcomes highlighted in yellow are outcomes associated with hierarchical value and are of particular interest. The outcome, subject won/superior lost (performing better than a more superior individual), possesses positive hierarchical value, while the outcome, subject lost/inferior won (performing worse than an inferior individual), possesses negative hierarchical value.

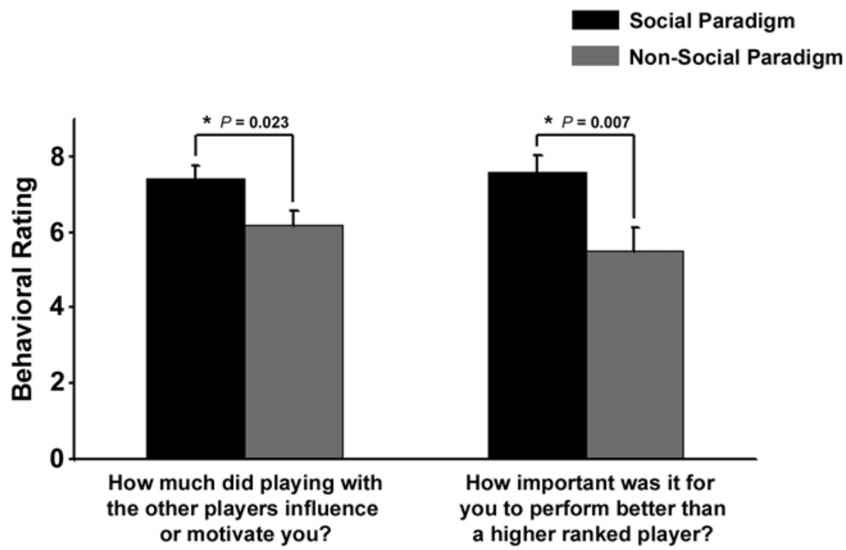

Figure S5. Ratings in the social and non-social paradigms for how influential it was to perform the task at the same time as other players and how important it was to perform better than the other player when the other player was superior. The bar plots represent means and standard errors across participants. Both questions were measured on a scale from 1 (not at all) to 10 (extremely). On average, participants in the social paradigm provided significantly higher ratings for both questions compared to the ratings provided by participants in the non-social paradigm.