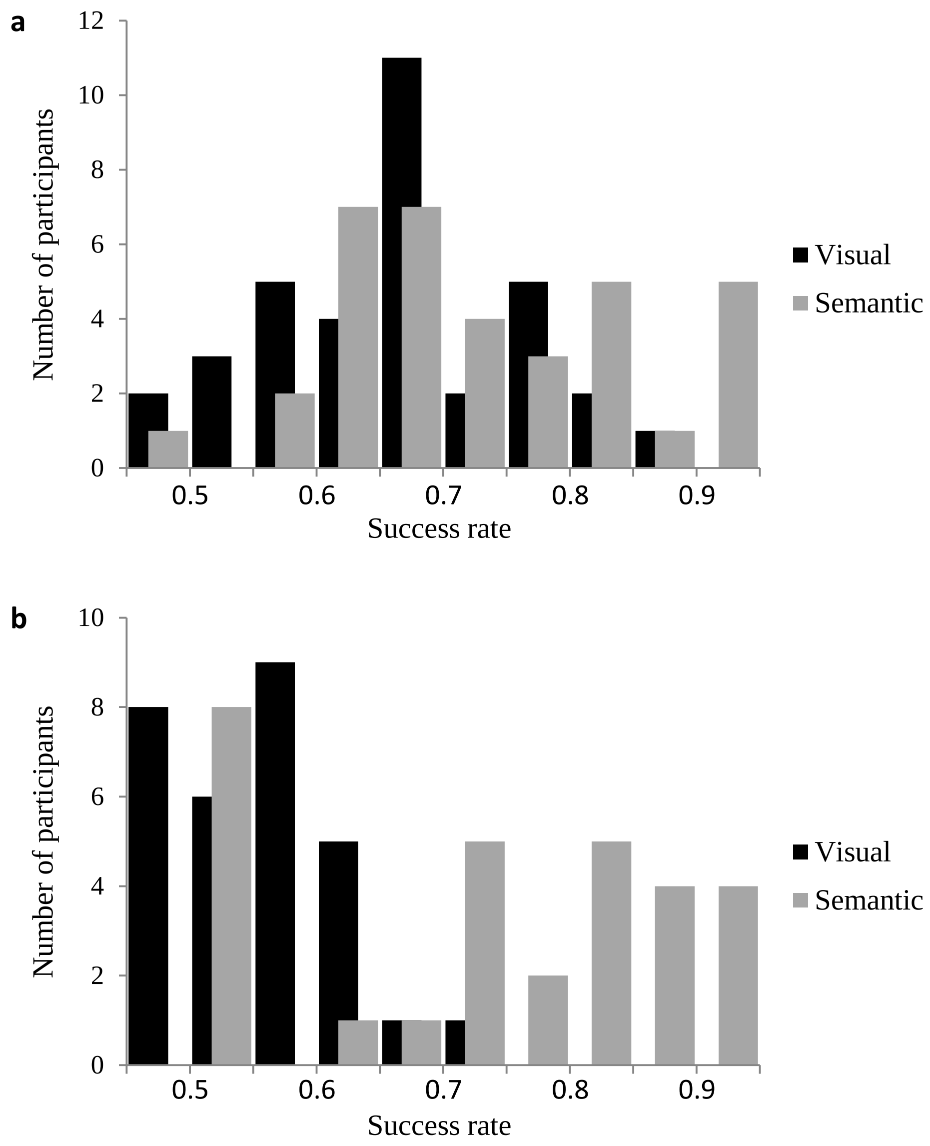
# Supplementary material

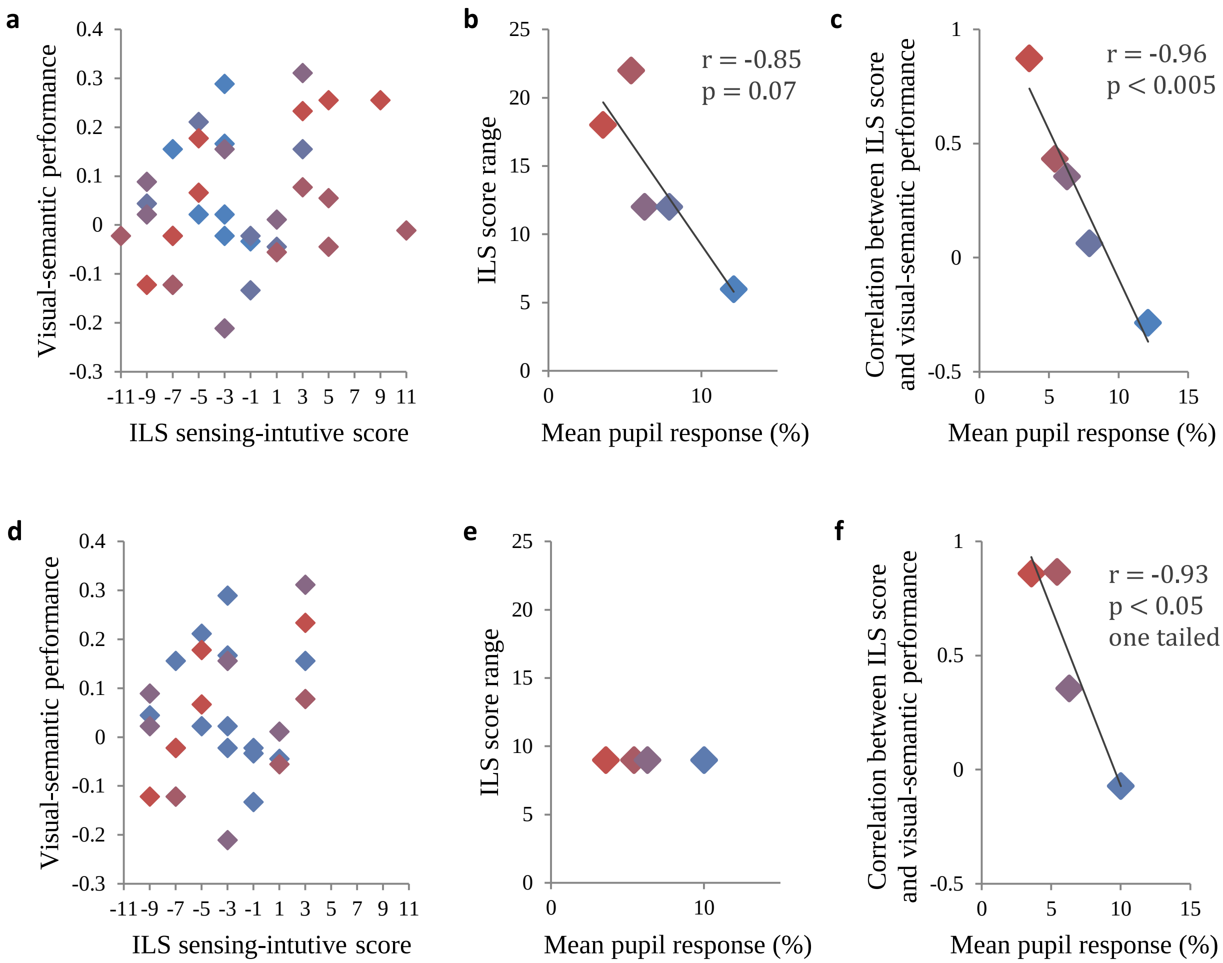
# The effects of neural gain on attention and learning

Eran Eldar, Jonathan D. Cohen, Yael Niv



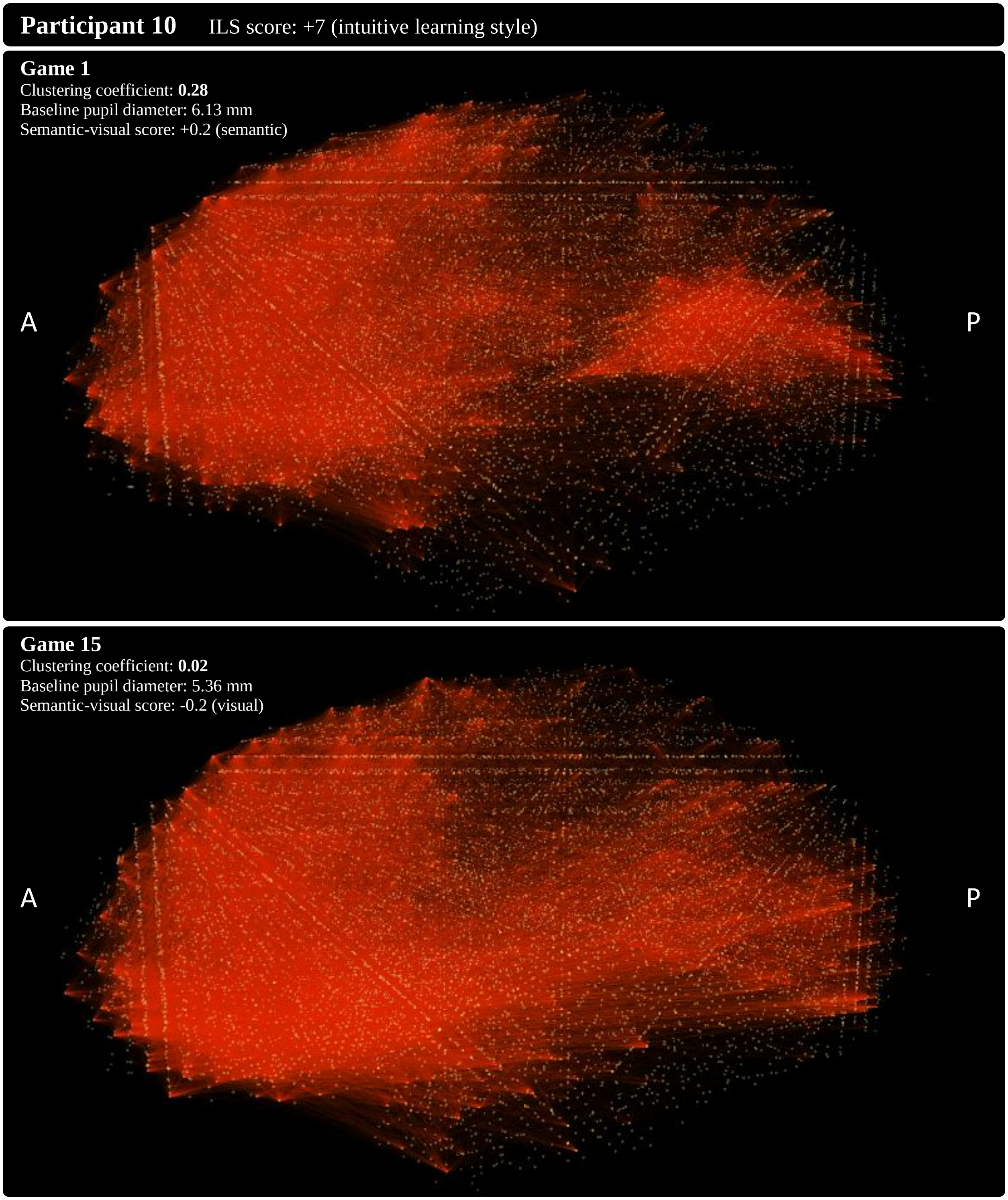

Supplementary Figure 1 Performance on visual and semantic trials. Chance performance level is 0.5. (**a**) Behavioral experiment. *n* = 35. (**b**) Imaging experiment. *n* = 30. Performance on visual trials was lower in the imaging experiment compared to the behavioral experiment, most probably due to a lower quality visual display, but it was still significantly above chance (mean 0.54, $t_{29} = 5.05$, $p < 10^{-5}$).

Nature Neuroscience: doi:10.1038/nn.3428

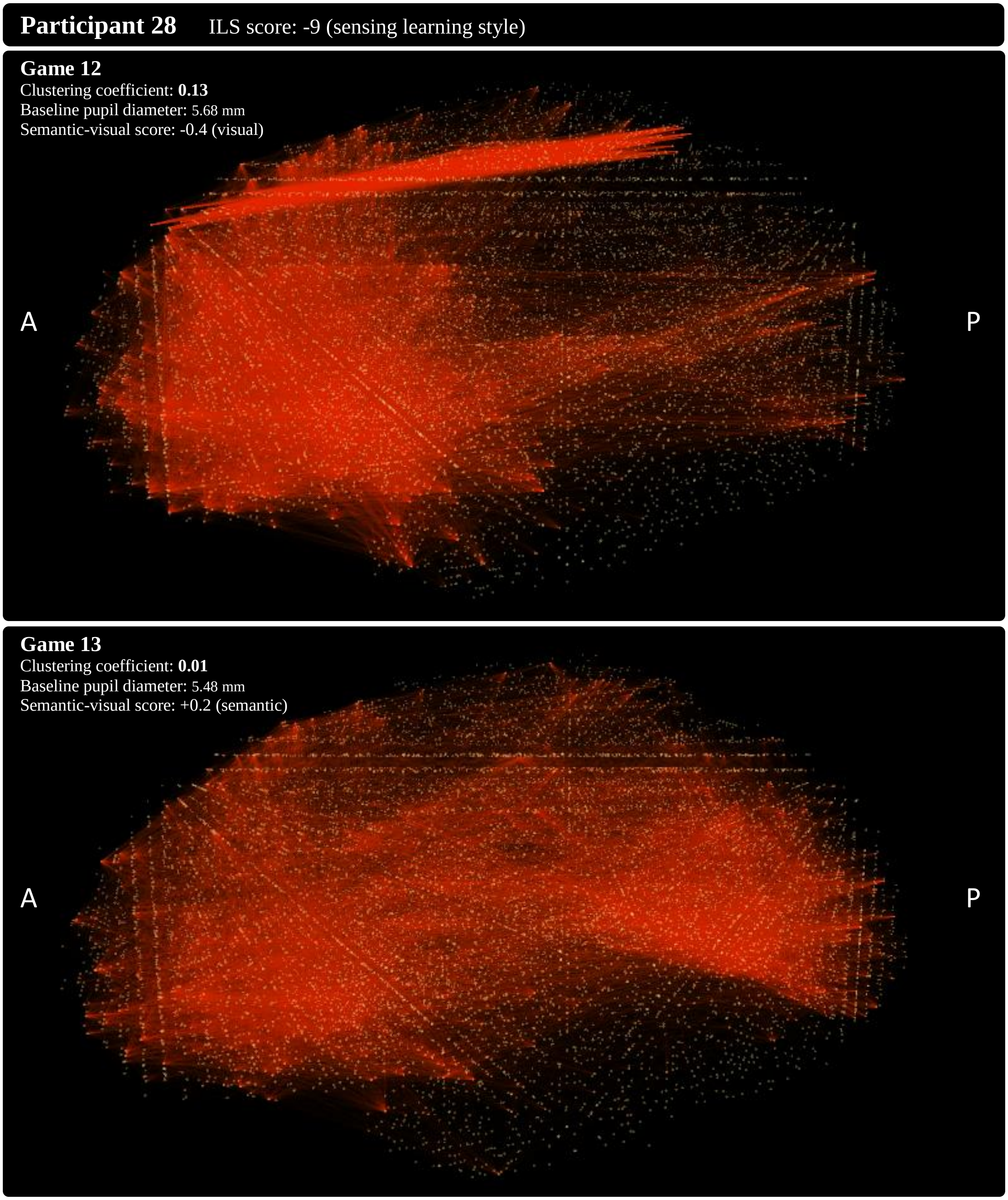



Supplementary Figure 2 ILS score range and the relationship between ILS score and task performance. In the first (behavioral) experiment, high mean pupil response was associated not only with a decrease in correlation between ILS scores and task performance (**a**,**c**; $r$ = -0.96, $p < 0.005$), but also with a decrease in the range of ILS scores (**b**; $r$ = -0.85, $p$ = 0.07). Decrease in range may thus serve as an alternative explanation for the decrease in correlation. However, in the second (imaging) experiment the range of ILS scores did not vary with mean pupil response ($r$ = -0.03, $p$ = 0.97), while the decrease in correlation between ILS scores and task performance recurred ($r$ = -0.93, $p < 0.01$; Fig. 2e). Furthermore, equating the range of ILS scores between the different groups of participants of the first experiment (**d**, **e**), did not eliminate the decrease in correlation between ILS scores and task performance that was observed in the first experiment (**f**). Thus, we can conclude that low mean pupil response was associated with a decrease in correlation between ILS scores and task performance irrespective of ILS score range.

(**a**) Visual-semantic performance difference on the behavioral task as a function of sensing-intuitive score on the ILS questionnaire. Negative values indicate better visual performance (Y axis) and a ‘sensing’ learning style (X axis), while positive values indicate better semantic performance and an ‘intuitive’ learning style. Color indicates binning according to mean pupil response, with a redder color indicating lower pupil response. $n$ = 35. (**b**) Range of ILS sensing-intuitive scores for each group of participants. Participants were divided into 5 groups according to mean pupil response. Each data point represents a group of 7 participants. (**c**) Correlation between ILS sensing-intuitive score and visual-semantic performance difference in the task, as a function of mean pupil response. (**d**,**e**,**f**) ILS score range was equated for all groups by discarding the data of 6 participants whose score was lower than -9 or larger than 3, and merging the two groups whose mean pupil response was lowest.




Supplementary Figure 3 Connectivity graphs from participant 10 in two different games. This participant's baseline pupil diameter was highest in game 1 and lowest in game 15. In line with our hypothesis, the clustering coefficient was higher in game 1 (0.28) than in game 15 (0.02). As can be seen, connectivity formed two disparate clusters in game 1, whereas in game 15 it was more globally distributed. Also note that this subject had an intuitive learning style, and accordingly, task performance in game 1 was biased towards the semantic features, as compared to game 15. A – anterior, P – posterior. For the purpose of visual rendering only, connectivity graphs were compressed to a size of 10,000 vertices using a k-means clustering algorithm, merging together vertices whose voxels' MNI coordinates are closest. The correlation values of merged vertices were averaged, and the strongest 0.05% of the resulting correlations were displayed as edges.




Supplementary Figure 4 Connectivity graphs from participant 28 in two different games. The clustering coefficient was highest for this participant in game 12 and lowest in game 13. As shown, functional connections were mostly clustered in fontal cortex in game 12, whereas in game 13 they were distributed over most of the brain. Indeed, the participant's baseline pupil diameter was higher in game 12 (5.68) than in game 13 (5.48). This subject had a sensing learning style, and accordingly, task performance in game 12 was biased more towards the visual dimensions, as compared to game 13. A – anterior, P – posterior. For the purpose of visual rendering only, connectivity graphs were compressed to a size of 10,000 vertices using a k-means clustering algorithm, merging together vertices whose voxels' MNI coordinates are closest. The correlation values of merged vertices were averaged, and the strongest 0.05% of the resulting correlations were displayed as edges.

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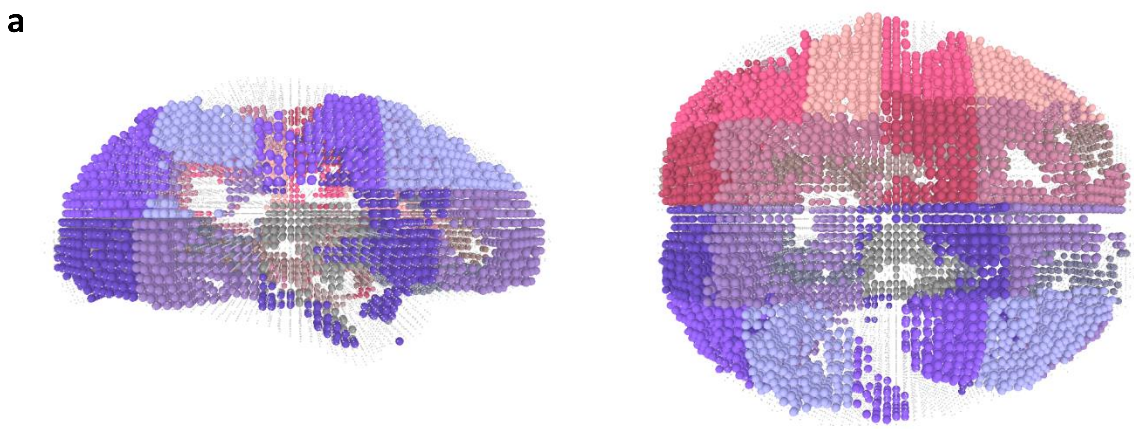
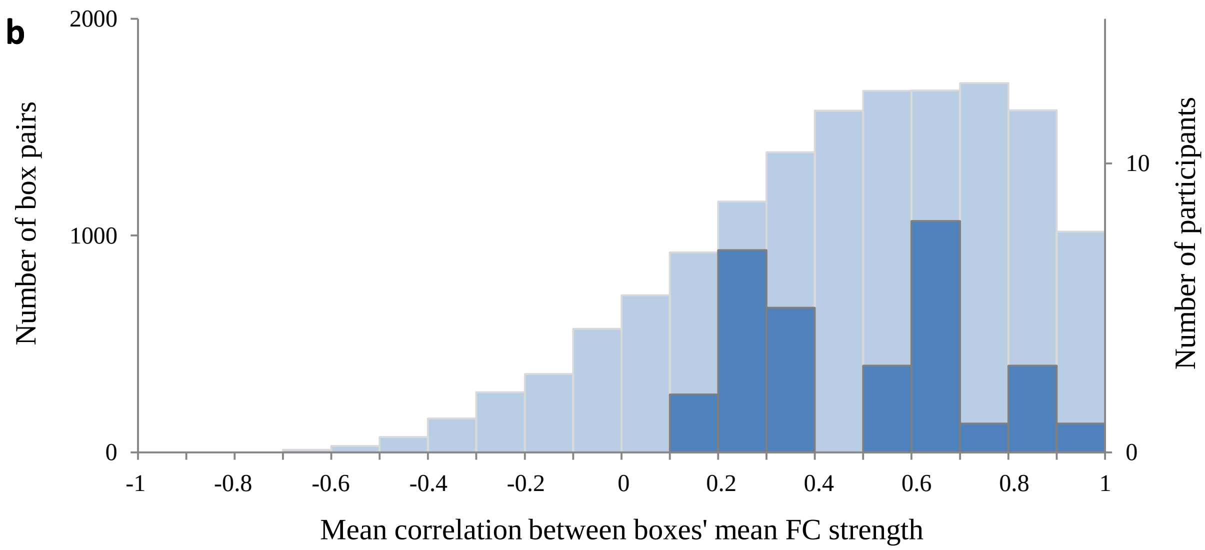
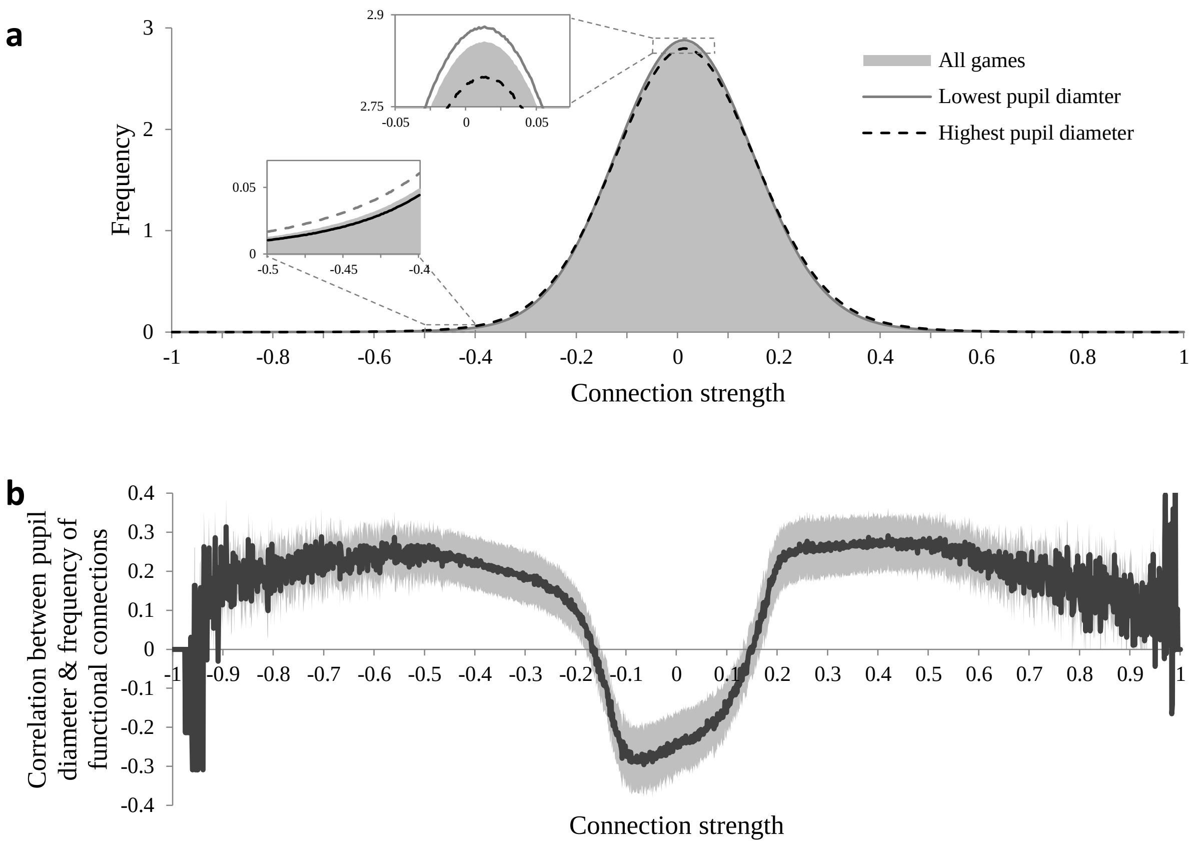
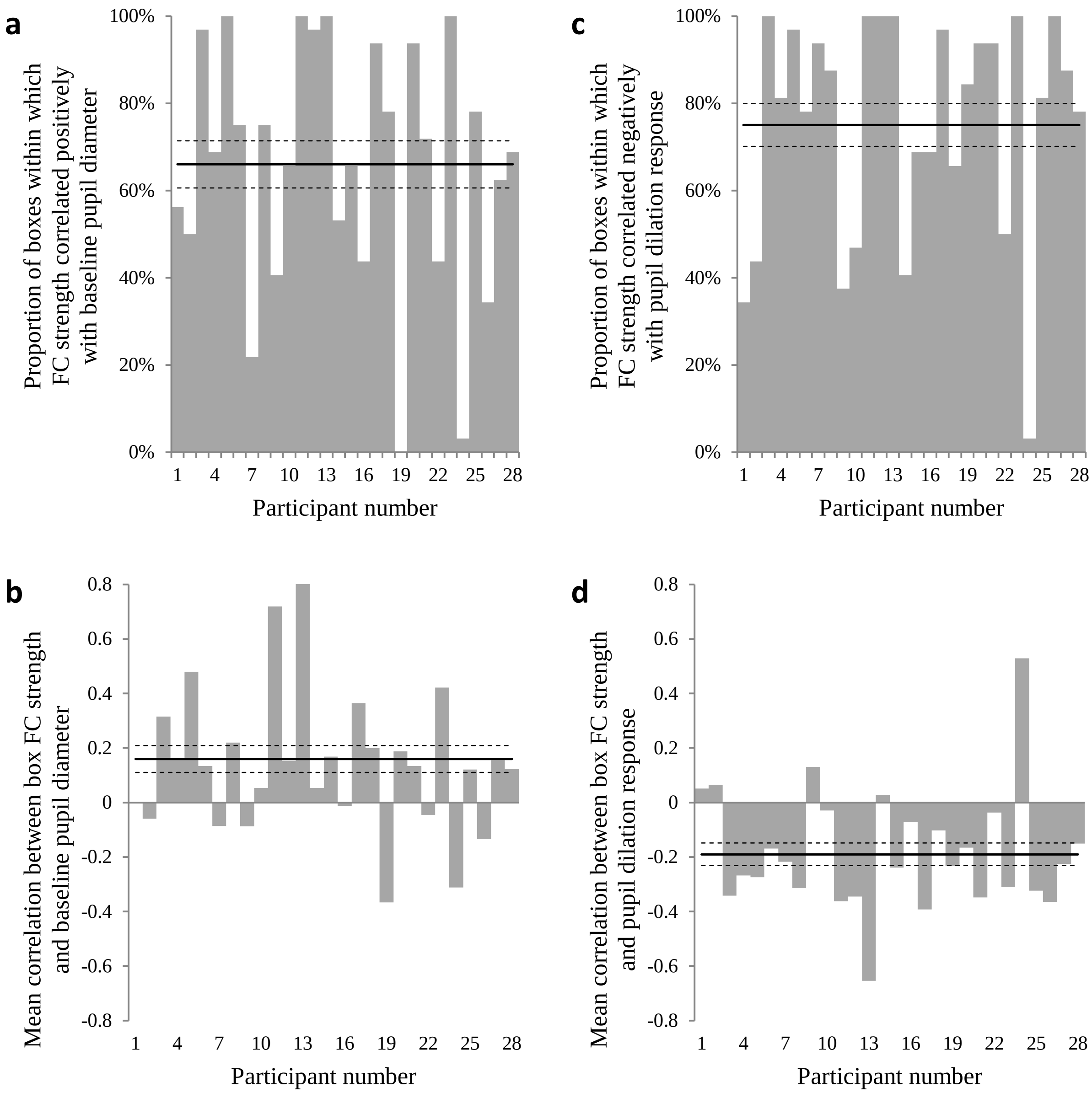



Supplementary Figure 5 Global fluctuations in local functional connectivity (replication of Fig. 5 with alternative preprocessing – see methods for details). (**a**) 3D rendering of one participant's gray-matter voxels divided into 32 boxes, viewed from the right and from above. Each sphere represents a voxel. Adjacent boxes are denoted in different colors. Voxel division is visualized using custom-made software created in the Processing programming environment[36]. (**b**) Histogram of between-box correlations of mean within-box functional connectivity strength (light blue, left Y axis), and of participants' mean correlation values (dark blue, right Y axis).




Supplementary Figure 6 Pupil diameter and whole-brain functional connectivity (replication of Fig. 6 with alternative preprocessing – see methods for details). (**a**) Distribution of functional connections by connection strength (*n* = 28). The distribution is shown separately for all games (gray shading), for the third of each participant's games in which the participant's baseline pupil diameter was lowest (solid line), and for the third of games in which pupil diameter was highest (dashed line). Insets: magnification of boxed areas to show differences between lowest and highest pupil diameter games. (**b**) Game-by-game correlation between baseline pupil diameter and frequency of functional connectivity measurements as a function of functional connectivity value (*n* = 28). The Y axis indicates whether large pupil diameter was associated with more (positive values) or fewer (negative values) voxel pairs for which functional connectivity strength is indicated on the X axis. For each participant, we computed the distribution of functional connections during each game, and then computed the correlation across games between baseline pupil diameter and the number of voxel pairs in each bin of the distribution. The curve shows the correlations averaged over participants with s.e.m. indicated by the lighter shading. Larger pupil diameter was associated with more strong functional connectivity measurements (absolute strength > 0.17) and fewer weak functional connectivity measurements (between -0.17 and +0.15).




Supplementary Figure 7 Pupil diameter and local functional connectivity (replication of Fig. 7 with alternative preprocessing – see methods for details). (**a**, **c**) Proportion of boxes within which mean FC strength was positively correlated with baseline pupil diameter (**a**) or negatively correlated with pupil dilation response (**c**) for each participant. (**b**, **d**) Mean correlation between within-box FC strength and baseline pupil diameter (**b**) or pupil dilation response (**d**) for each participant. Solid horizontal line: group means, dashed horizontal lines: s.e.m.

| **Correlation with mean pupil response** | **Behavioral Experiment (*n* = 35)** | **Imaging Experiment (*n* = 29)** |
|---|---|---|
| Interest | *r* = 0.26, *p* = 0.14 | *r* = -0.39, *p* = 0.038 |
| Motivation | *r* = 0.23, *p* = 0.19 | *r* = -0.45, *p* = 0.013 |
| Difficulty to maintain attention | | *r* = 0.21, *p* = 0.27 |

| **Correlation with match between task performance and ILS score (i.e., adherence to predispodition)** | **Behavioral Experiment (*n* = 5 groups of 7)** | **Imaging Experiment (*n* = 29) (*n* = 5 groups of 6)** |
|---|---|---|
| Interest | *r* = -0.46, *p* = 0.44 | *r = 0.43, p = 0.47* |
| Motivation | *r* = -0.20, *p* = 0.75 | *r = 0.72, p = 0.17* |
| Difficulty to maintain attention | | *r = -0.33, p = 0.58* |

Supplementary Table 1 Post-experiment ratings, pupil response and task performance. Relationship of post-experiment ratings of interest, motivation and difficulty to maintain attention, with pupil diameter (top) and adherence to predispositions in the task (bottom). Following the experiment, participants were asked to rate between 1 to 5 how interesting they found the experiment (Interest), how motivated they were to earn as much money as possible (Motivation), and, in the imaging experiment, how difficult it was for them to maintain attention (Difficulty to maintain attention). One participant in the imaging experiment did not fill out the debriefing questionnaire. Thus, in the group-based analysis (bottom panel), the group with the lowest ratings consists of 5 participants only.