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Supplementary Figures: 5

Supplementary Tables: 0

Supplementary Videos: 1

Reporting Checklist for Nature Neuroscience

This checklist is used to ensure good reporting standards and to improve the reproducibility of published results. For more information, please read Reporting Life Sciences Research.

Please note that in the event of publication, it is mandatory that authors include all relevant methodological and statistical information in the manuscript.

Statistics reporting, by figure

- Please specify the following information for each panel reporting quantitative data, and where each item is reported (section, e.g. Results, & paragraph number).
- Each figure legend should ideally contain an exact sample size (n) for each experimental group/condition, where n is an exact number and not a range, a clear definition of how n is defined (for example x cells from x slices from x animals from x litters, collected over x days), a description of the statistical test used, the results of the tests, any descriptive statistics and clearly defined error bars if applicable.
- For any experiments using custom statistics, please indicate the test used and stats obtained for each experiment.
- Each figure legend should include a statement of how many times the experiment shown was replicated in the lab; the details of sample collection should be sufficiently clear so that the replicability of the experiment is obvious to the reader.
- For experiments reported in the text but not in the figures, please use the paragraph number instead of the figure number.

Note: Mean and standard deviation are not appropriate on small samples, and plotting independent data points is usually more informative. When technical replicates are reported, error and significance measures reflect the experimental variability and not the variability of the biological process; it is misleading not to state this clearly.

		TEST USED		n			DESCRIPTIVE STATS (AVERAGE, VARIANCE)		P VALUE		DEGREES OF FREEDOM & F/t/z/R/ETC VALUE	
	FIGURE NUMBER	WHICH TEST?	SECTION & PARAGRAPH #	EXACT VALUE	DEFINED?	SECTION & PARAGRAPH #	REPORTED?	SECTION & PARAGRAPH #	EXACT VALUE	SECTION & PARAGRAPH #	VALUE	SECTION & PARAGRAPH #
example	1a	one-way ANOVA	Fig. legend	9, 9, 10, 15	mice from at least 3 litters/group	Methods para 8	error bars are mean +/- SEM	Fig. legend	p = 0.044	Fig. legend	F(3, 36) = 2.97	Fig. legend
example	results, para 6	unpaired t-test	Results para 6	15	slices from 10 mice	Results para 6	error bars are mean +/- SEM	Results para 6	p = 0.0006	Results para 6	t(28) = 2.808	Results para 6

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		TEST USED		n			DESCRIPTIVE STATS (AVERAGE, VARIANCE)		P VALUE		DEGREES OF FREEDOM & F/t/z/R/ETC VALUE	
	FIGURE NUMBER	WHICH TEST?	SECTION & PARAGRAPH #	EXACT VALUE	DEFINED?	SECTION & PARAGRAPH #	REPORTED?	SECTION & PARAGRAPH #	EXACT VALUE	SECTION & PARAGRAPH #	VALUE	SECTION & PARAGRAPH #
+ -	results, para 1	bootstrap across participants (overall decoding accuracy)	methods, para 8	32	all fMRI participants	methods, para 1	average, SEM	results, para 1	p < 0.00001 (0/100,000 bootstrap samples)	results, para 1	N/A	
+ -	2a; results, para 2	Spearman rank correlation (relationship between decoding and pre-training behavior)	methods, para 8	32	all fMRI participants	methods, para 1	N/A		p = 0.000008	results, para 2	r = 0.70	results, para 2
+ -	2b; results, para 2	bootstrap across participants (decoding accuracy before FA vs. CR)	methods, para 8	32	all fMRI participants	methods, para 1	average, SEM	results, para 2; methods, para 17	p < 0.00001 (0/100,000 bootstrap samples)	results, para 2; methods, para 17	N/A	
+ -	S2; results, para 2	bootstrap across participants (RT before FA vs CR)	methods, para 8	32	all fMRI participants	methods, para 1	average, SEM	methods, para 18	p < 0.00001 (0/100,000 bootstrap samples)	methods, para 18	N/A	
+ -	S3; results, para 2	bootstrap across participants (partial regression between decoding and behavioral accuracies)	methods, para 8	32	all fMRI participants	methods, para 1	average, SEM	methods, para 18	p < 0.00001 (0/100,000 bootstrap samples)	methods, para 18	N/A	
+ -	3; results, para 4	bootstrap across participants (change in A' for feedback group)	methods, para 8	16	fMRI participants in feedback group	results, para 4; methods, para 1	average, within-subject SEM	Fig. 3	p = 0.01	results, para 4	N/A	
+ -	results, para 4	Spearman rank correlation (relationship between average feedback value and change in A')	methods, para 8	16	fMRI participants in feedback group	results, para 4; methods, para 1	N/A		p = 0.002	results, para 4	r = .78	results, para 4

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+ -	results, para 4	bootstrap across matched participants (group difference in pre-training FA rate)	methods, para 8	16, 16	fMRI participants in feedback & control groups	results, para 4; methods, para 1	N/A		p = 0.72	results, para 4	N/A	
+ -	results, para 4	bootstrap across matched participants (group difference in pre-training A')	methods, para 8	16, 16	fMRI participants in feedback & control groups	results, para 4; methods, para 1	N/A		p = 0.90	results, para 4	N/A	
+ -	3; results, para 4	bootstrap across participants (change in A' for control group)	methods, para 8	16	fMRI participants in control group	results, para 4; methods, para 1	average, within-subject SEM	Fig. 3	p = 0.26	results, para 4	N/A	
+ -	results, para 4	bootstrap across matched participants (group x change interaction in A')	methods, para 8	16, 16	fMRI participants in feedback & control groups	results, para 4; methods, para 1	N/A		p = 0.04	results, para 4	N/A	
+ -	results, para 4	bootstrap across matched participants (group x change interaction in FA)	methods, para 8	16, 16	fMRI participants in feedback & control groups	results, para 4; methods, para 1	N/A		p = 0.007	results, para 4	N/A	
+ -	results, para 5	bootstrap across participants (change in A' for no-feedback group)	methods, para 8	16	behavioral participants in no-feedback group	results, para 5; methods, para 1, 23	N/A		p = 0.67	results, para 5	N/A	
+ -	results, para 5	bootstrap across matched participants (group x change interaction in A')	methods, para 8	16, 16	behavioral participants in RT-feedback and RT-control groups	results, para 5; methods, para 1, 24	N/A		p = 0.29	results, para 5	N/A	
+ -	results, para 7	bootstrap across matched participants (group x change interaction in whole-brain decoding accuracy)	methods, para 8, 19	16, 16	fMRI participants in feedback & control groups	methods, para 1	N/A		p = 0.01	results, para 7	N/A	

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+ -	results, para 7	bootstrap across matched participants (group x change interaction in lobe-specific decoding accuracy)	methods, para 8, 19	16, 16	fMRI participants in feedback & control groups	methods, para 1	N/A		frontal: p = 0.02 occipital: p = 0.04 temporal: p = 0.09 parietal: p = 0.08	results, para 7	N/A	
+ -	4; results, para 7	permutation across matched participants for each voxel (group x change interaction in decoding accuracy) with threshold-free cluster enhancement for multiple comparisons correction	methods, para 8, 19	16, 16	fMRI participants in feedback & control groups	methods, para 1	center-of-gravity MNI coordinates	Fig. 4 legend	all ps < 0.05, corrected	results, para 7; Fig. 4 legend	N/A	
+ -	results, para 9	bootstrap across participants (relationship between simulated feedback from FFA/PPA and multivariate whole-brain real-time feedback)	methods, para 8, 20	16	fMRI participants in feedback group	methods, para 1	average, SEM	results, para 9	p < 0.00001 (0/100,000 bootstrap samples)	results, para 9	N/A	
+ -	results, para 9	Spearman correlation (relationship between behavioral training effect and how correlated simulated feedback from FFA/PPA was to whole-brain multivariate feedback)	methods, para 8, 20	16	fMRI participants in feedback group	methods, para 1	N/A		p = 0.89	results, para 9	r = -0.04	results, para 9
+ -	results, para 10	bootstrap across participants (relationship between simulated feedback with network and whole-brain multivariate real-time feedback)	methods, para 8, 21	16	fMRI participants in feedback group	methods, para 1	average, SEM	results, para 10	occipitotemporal perceptual network: p < 0.00001 (0/100,000 bootstrap samples) frontoparietal attentional network: p < 0.00001 (0/100,000 bootstrap samples)	results, para 10	N/A	

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+ -	results, para 10	bootstrap across participants (difference between perceptual network-to-whole brain and attentional network-to-whole brain relationships)	methods, para 8, 21	16	fMRI participants in feedback group	methods, para 1	N/A		p = 0.04	results, para 10	N/A	
+ -	5; results, para 11	Spearman correlation (relationship between behavioral training effect and how correlated simulated feedback from the network was with the whole-brain multivariate real-time feedback)	methods, para 8, 21	16	fMRI participants in feedback group	methods, para 1	N/A		occipitotemporal perceptual network: p = 0.27 frontoparietal attentional network: p = 0.02	results, para 11	occipitotemporal perceptual network: r = 0.29 frontoparietal attentional network: r = 0.60	results, para 11; Fig. 5
+ -	methods, para 14	bootstrap across participants (relationship between yoked neurofeedback that control participants received and decoding from their brains)	methods, para 8	16	fMRI participants in control group	methods, para 1, 14	average, SEM	methods, para 14	p < 0.00001 (0/100,000 bootstrap samples)	methods, para 14	N/A	

Representative figures

1. Are any representative images shown (including Western blots and immunohistochemistry/staining) in the paper?

   If so, what figure(s)?

   No

2. For each representative image, is there a clear statement of how many times this experiment was successfully repeated and a discussion of any limitations in repeatability?

   If so, where is this reported (section, paragraph #)?

   N/A

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Statistics and general methods

1. Is there a justification of the sample size? If so, how was it justified? Where (section, paragraph #)? Even if no sample size calculation was performed, authors should report why the sample size is adequate to measure their effect size.	No, the effect size was not known in advance. For an fMRI study, 16 participants per group (32 total) is fairly common (especially with multiple sessions). For the behavioral control experiments, sample sizes were matched to the fMRI study. methods, para 1
2. Are statistical tests justified as appropriate for every figure? Where (section, paragraph #)?	Yes methods, para 8
a. If there is a section summarizing the statistical methods in the methods, is the statistical test for each experiment clearly defined?	Yes
b. Do the data meet the assumptions of the specific statistical test you chose (e.g. normality for a parametric test)? Where is this described (section, paragraph #)?	Non-parametric tests were used throughout to avoid assumptions of parametric tests. methods, para 8
c. Is there any estimate of variance within each group of data? Is the variance similar between groups that are being statistically compared? Where is this described (section, paragraph #)?	Yes, error bars reflecting within-subject SEM are provided in the figures and SEM is reported for every mean in the text.
d. Are tests specified as one- or two-sided?	All directional tests were one-sided and non-directional tests were two-sided.
e. Are there adjustments for multiple comparisons?	Yes, threshold-free cluster enhancement was used for voxelwise statistical tests.
3. Are criteria for excluding data points reported? Was this criterion established prior to data collection? Where is this described (section, paragraph #)?	Participants were excluded if they did not complete the study or for low behavioral performance in pre-training (> 3 SDs below mean). methods, para 1
4. Define the method of randomization used to assign subjects (or samples) to the experimental groups and to collect and process data. If no randomization was used, state so. Where does this appear (section, paragraph #)?	Participants in the fMRI experimental group were recruited based on age (18-35), normal or corrected-to-normal vision, and MRI compatibility. Each fMRI control participant was chosen to match one of the fMRI experimental participants. Behavioral control participants were also chosen to match one of the fMRI experimental participants, but were then randomly assigned to one of the three behavioral experiments. methods, para 1, 22, 24

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5. Is a statement of the extent to which investigator knew the group allocation during the experiment and in assessing outcome included? If no blinding was done, state so. Where (section, paragraph #)?	The investigator for the fMRI study was not blinded because of the complexity of data acquisition and analysis, especially the need to ensure that the real-time classification and feedback system was functioning. For the RT-feedback behavioral study, the investigator was blinded. This was not possible for the no-feedback behavioral study because the instructions were different. methods, para 1, 22, 24
6. For experiments in live vertebrates, is a statement of compliance with ethical guidelines/regulations included? Where (section, paragraph #)?	N/A
7. Is the species of the animals used reported? Where (section, paragraph #)?	N/A
8. Is the strain of the animals (including background strains of KO/ transgenic animals used) reported? Where (section, paragraph #)?	N/A
9. Is the sex of the animals/subjects used reported? Where (section, paragraph #)?	Yes, 45 females and 35 males participated in the study. methods, para 1
10. Is the age of the animals/subjects reported? Where (section, paragraph #)?	Yes, the average age of the participants was 20.3 years. methods, para 1
11. For animals housed in a vivarium, is the light/dark cycle reported? Where (section, paragraph #)?	N/A
12. For animals housed in a vivarium, is the housing group (i.e. number of animals per cage) reported? Where (section, paragraph #)?	N/A
13. For behavioral experiments, is the time of day reported (e.g. light or dark cycle)? Where (section, paragraph #)?	N/A
14. Is the previous history of the animals/subjects (e.g. prior drug administration, surgery, behavioral testing) reported? Where (section, paragraph #)?	No, this information was not collected other than ensuring that the fMRI participants were MRI compatible.
a. If multiple behavioral tests were conducted in the same group of animals, is this reported? Where (section, paragraph #)?	Yes methods, para 4

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15. If any animals/subjects were excluded from analysis, is this reported?

    Where (section, paragraph #)?

    Yes

    methods, para 1

    a. How were the criteria for exclusion defined?

       Where is this described (section, paragraph #)?

       Participants were excluded if they did not complete the study or for low behavioral performance in pre-training (> 3 SDs below mean).

       methods, para 1

    b. Specify reasons for any discrepancy between the number of animals at the beginning and end of the study.

       Where is this described (section, paragraph #)?

       N/A

Reagents

1. Have antibodies been validated for use in the system under study (assay and species)?

   N/A

   a. Is antibody catalog number given?

      Where does this appear (section, paragraph #)?

   b. Where were the validation data reported (citation, supplementary information, Antibodypedia)?

      Where does this appear (section, paragraph #)?

2. If cell lines were used to reflect the properties of a particular tissue or disease state, is their source identified?

   Where (section, paragraph #)?

   N/A

   a. Were they recently authenticated?

      Where is this information reported (section, paragraph #)?

Data deposition

Data deposition in a public repository is mandatory for:

a. Protein, DNA and RNA sequences
b. Macromolecular structures
c. Crystallographic data for small molecules
d. Microarray data

Deposition is strongly recommended for many other datasets for which structured public repositories exist; more details on our data policy are available here. We encourage the provision of other source data in supplementary information or in unstructured repositories such as Figshare and Dryad.

We encourage publication of Data Descriptors (see Scientific Data) to maximize data reuse.

1. Are accession codes for deposit dates provided?

   Where (section, paragraph #)?

   N/A

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Computer code/software

Any custom algorithm/software that is central to the methods must be supplied by the authors in a usable and readable form for readers at the time of publication. However, referees may ask for this information at any time during the review process.

1. Identify all custom software or scripts that were required to conduct the study and where in the procedures each was used.

N/A

2. If computer code was used to generate results that are central to the paper's conclusions, include a statement in the Methods section under "**Code availability**" to indicate whether and how the code can be accessed. Include version information as necessary and any restrictions on availability.

N/A

Human subjects

1. Which IRB approved the protocol?

   Where is this stated (section, paragraph #)?

Princeton University Institutional Review Board.

methods, para 1

2. Is demographic information on all subjects provided?

   Where (section, paragraph #)?

Yes, summary demographic information is provided.

methods, para 1

3. Is the number of human subjects, their age and sex clearly defined?

   Where (section, paragraph #)?

Yes

methods, para 1

4. Are the inclusion and exclusion criteria (if any) clearly specified?

   Where (section, paragraph #)?

Yes

methods, para 1

5. How well were the groups matched?

   Where is this information described (section, paragraph #)?

Each control (both fMRI and behavioral) participant was matched as closely as possible to the demographics of an fMRI experimental participant, in terms of age, gender, and handedness.

methods, para 1, 22

6. Is a statement included confirming that informed consent was obtained from all subjects?

   Where (section, paragraph #)?

Yes

methods, para 1

7. For publication of patient photos, is a statement included confirming that consent to publish was obtained?

   Where (section, paragraph #)?

N/A

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fMRI studies

For papers reporting functional imaging (fMRI) results please ensure that these minimal reporting guidelines are met and that all this information is clearly provided in the methods:

1. Were any subjects scanned but then rejected for the analysis after the data was collected?	Yes
a. If yes, is the number rejected and reasons for rejection described? Where (section, paragraph #)?	A total of four fMRI participants who were at least partially scanned were excluded due to technical problems or falling asleep. methods, para 1
2. Is the number of blocks, trials or experimental units per session and/or subjects specified? Where (section, paragraph #)?	Yes methods, para 4, 5
3. Is the length of each trial and interval between trials specified?	Yes
4. Is a blocked, event-related, or mixed design being used? If applicable, please specify the block length or how the event-related or mixed design was optimized.	A blocked design was used. Each block lasted 50s, was preceded by 2s of instructions, and followed by 4-6s of rest.
5. Is the task design clearly described? Where (section, paragraph #)?	Yes methods, para 4-6; Figure S1
6. How was behavioral performance measured?	Behavioral performance is measured using response time, false alarm rate, and sensitivity (A').
7. Is an ANOVA or factorial design being used?	No
8. For data acquisition, is a whole brain scan used? If not, state area of acquisition.	Yes
a. How was this region determined?	
9. Is the field strength (in Tesla) of the MRI system stated?	Yes
a. Is the pulse sequence type (gradient/spin echo, EPI/spiral) stated?	Yes
b. Are the field-of-view, matrix size, slice thickness, and TE/TR/flip angle clearly stated?	Yes
10. Are the software and specific parameters (model/functions, smoothing kernel size if applicable, etc.) used for data processing and pre-processing clearly stated?	Yes

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11. Is the coordinate space for the anatomical/functional imaging data clearly defined as subject/native space or standardized stereotaxic space, e.g., original Talairach, MNI305, ICBM152, etc? Where (section, paragraph #)?	Yes methods, para 15
12. If there was data normalization/standardization to a specific space template, are the type of transformation (linear vs. nonlinear) used and image types being transformed clearly described? Where (section, paragraph #)?	Yes methods, para 15
13. How were anatomical locations determined, e.g., via an automated labeling algorithm (AAL), standardized coordinate database (Talairach daemon), probabilistic atlases, etc.?	Anatomical locations were determined via probabilistic atlases.
14. Were any additional regressors (behavioral covariates, motion etc) used?	No
15. Is the contrast construction clearly defined?	Yes
16. Is a mixed/random effects or fixed inference used?	Random effects.
a. If fixed effects inference used, is this justified?	
17. Were repeated measures used (multiple measurements per subject)?	Yes, pre/post training design.
a. If so, are the method to account for within subject correlation and the assumptions made about variance clearly stated?	Comparisons were made within participants and between matched participants in the feedback and control groups. Non-parametric tests were used throughout to eliminate assumptions.
18. If the threshold used for inference and visualization in figures varies, is this clearly stated?	N/A
19. Are statistical inferences corrected for multiple comparisons?	Yes, threshold-free cluster enhancement (TFCE) was used for voxelwise analyses.
a. If not, is this labeled as uncorrected?	
20. Are the results based on an ROI (region of interest) analysis?	Some of the results.
a. If so, is the rationale clearly described?	Yes
b. How were the ROI's defined (functional vs anatomical localization)?	Anatomical masks of lobes were created using the MNI probabilistic structural atlas provided in FSL. FFA and PPA were defined functionally. Functional masks of the perceptual and attentional networks were created using neurosynth.org.
21. Is there correction for multiple comparisons within each voxel?	N/A
22. For cluster-wise significance, is the cluster-defining threshold and the corrected significance level defined?	There is no cluster-defining threshold in the TFCE method. The corrected significance level is defined as $p < 0.05$.

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Additional comments

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