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**Description of reinforcement learning task**

*Probabilistic reversal learning task*

The probabilistic reversal learning (PRL) task is a widely used paradigm to measure updating of value representations. In this paradigm, individuals choose between 2 stimuli (1 commonly and 1 rarely rewarded). Once the participant learns the more frequently rewarded stimulus, the reward contingencies reverse, and participants must modify their value representations through feedback (Culbreth et al., 2016; Schlagenhauf et al., 2014).

The outline of the classical PRL task experimental paradigm is shown in Figure S2 (Katthagen et al., 2020). Firstly, two abstract stimulus were presented simultaneously for 2500ms. Secondly, subjects were instructed to guess which pattern was most likely to yield reward, choose it by pressing buttons. Thirdly, they were given feedback (correct or incorrect) lasting 1500ms. In addition, participants were also told that occasionally the reward contingencies would reverse and the alternative stimulus would be associated with a high probability of reward, and their task is to maximize correct responses. The inter-stimulus interval was 1000ms–5000ms. When 8 of the previous 10 trials were answered correctly the reinforcement contingencies reversed.

*Probabilistic instrumental learning task*

The probabilistic instrumental learning task is a task to promote participants to build stimulus-response associations through feedback following their own choices. In this paradigm, individuals need to choose between two stimulus (one with high probability of rewards and one with low probability rewards), and to learn which stimulus was more likely to produce a reward by constant trials and errors (Ermakova et al., 2018).

The outline of the probabilistic instrumental learning task experimental paradigm is shown in Figure S2 (Hernaus et al., 2018; Reinen et al., 2016). To begin with, the participants were instructed to choose between two abstract visual stimuli displayed on a computer screen (3000ms). On each trial, the participant chose one of two stimuli, then feedback was provided (1000ms). From the feedback, the participant learnt which of the pictures were more likely to give a reward and their goals are to maximize obtained reward.

*Probabilistic trial and error learning task*

The outline of the probabilistic trial and error learning task experimental paradigm is shown in Figure S2 (Koch et al., 2010). The probabilistic trial and error learning task is an instrumental learning task that examines participants’ ability to learn from constant trials and errors.

Specifically, participants were presented a card with a geometrical figure on it (i.e. circle, cross, half-moon, triangle, square or pentagon), and they were told that each figure was associated with an unknown value ranging from 1 to 9. The participants were instructed to guess whether the figure on the card predicting a value higher or lower than the number five. Each correct guess was followed by a monetary reward, whereas each wrong guess was followed by a punishment. Participants were also instructed that each figure predicted the respective value (higher or lower than five) with a certain probability, and three conditions were employed (i.e. 50% , 81%, 100%, stimulus-outcome contingency). Participants were not informed about the predictive probabilities of the respective figures. Thus, they had to learn to improve their guesses based on the different prediction probabilities in the course of the experiment in order to maximize their gains.

**Supplementary Methods**

**Study search and selection**

We searched the PubMed, Web of Science, and ScienceDirect databases for relevant articles from January 2000 to March 2025 using the following terms: 1) “schizophrenia” OR “schizophrenic” OR “schizoaffective” OR “psychoses” OR “psychosis” OR “psychotic” OR “psychotic” OR “first episode psychosis” OR “FEP”; 2) “functional magnetic resonance imaging” OR “fMRI” OR “neuroimaging”; and 3) “reinforcement learning” OR “instrumental/operant learning” OR “reward learning”. Studies were also identified by consulting review articles and the references of retrieved articles. Details of the literature search and selection process are reported in Figure 1.

The included studies were selected on the basis of the following criteria: 1) studies involving human adult (age > 18) subjects diagnosed with schizophrenia, first-episode psychosis (FEP), schizoaffective or schizophreniform psychotic disorder, or other psychosis spectrum disorders based on the Diagnostic and Statistical Manual of Mental Disorders (DSM) or International Statistical Classification of Diseases (ICD) diagnostic criteria; 2) studies with group comparisons between SZ patients and HC participants; 3) studies using a standardized or modified instrumental learning task where subjects built A–O associations via their responses with subsequent feedback and repeated the same actions in the next trials to acquire more reward; and 4) studies in which peak activations were reported in the Montreal Neurological Institute (MNI) or Talairach Atlas (Tal) space.

The exclusion criteria were as follows: 1) studies involving tasks with simple probabilistic allocation of rewards or punishments, such as the monetary incentive delay (MID) task, or tasks with a more complex cognitive process to explore model-free and model-based learning systems of humans, such as two-stage tasks. The former was excluded because the experimental process is too simple to detect the ability of individuals to process rewards, integrate causality, and engage the related brain areas, while the latter was excluded because the focus on deeper cognitive processing problems, such as model-based and model-free learning, is inconsistent with the scope of our study; 2) studies whose experimental subjects were adolescents younger than 18 to avoid the influence of differences in learning and cognitive functions between adolescent and adult patients on the meta-analysis results; 3) animal studies, book chapters, reviews, or meta-analyses; 4) non-English articles; 5) studies focusing solely on one or more regions of interest (ROIs), as we aimed to examine differences between patients and healthy subjects at the whole-brain level; and 6) studies in which coordinates were not available, even after contacting the authors.

**Data extraction**

The following data were recorded from each article: sample size, mean age, duration of illness, personal and parental education levels, IQ score, percentage of males, severity of symptoms (Positive and Negative Syndrome Scale–Total (PANSS-T), PANSS-Positive (PANSS-P), and PANSS-Negative (PANSS-N)), proportion of SZ patients who had ever received first-generation antipsychotics (FGA)/second-generation antipsychotics (SGA), methodological details and dose equivalents, paradigms used in the studies and related behavioural indices (Table S3).

Our meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) (see Table S2). Two authors independently searched the literature and checked all the articles according to the criteria.

**Voxel-based meta-analysis**

The meta-analysis of instrumental learning brain activity differences between individuals with psychosis and HCs was performed via seed-based d mapping software (SDM, version 5.15, https://www.sdmproject.com), which has been widely applied in previous meta-analyses (Emch, von Bastian and Koch, 2019; Kolesar et al., 2019; Yang et al., 2016; Zeng et al., 2021). The main advantages of SDM are as follows: First, SDM uses only reported peak coordinates that remain significant at the whole-brain level to recreate maps of the signed volume differences between groups, which aims to avoid biases towards liberally thresholded brain regions. Second, both positive and negative coordinates are reconstructed in the same map to prevent a particular brain region from exhibiting increased and decreased activation simultaneously. Third, the map of the differences in brain activity is separately recreated for each study and weighted by the square root of the sample size of each study so that studies with large sample sizes contribute more (Radua and Mataix-Cols, 2009; Radua et al., 2010; Radua et al., 2011).

The meta-analysis was conducted via the following steps (Yang et al., 2022; Zeng et al., 2022): First, peak coordinates of activation differences between patients and controls and the activation of patients were extracted from each dataset. Studies reporting no group differences were also included. Second, the measurements (*z* scores and *p* values) were converted into t values and then input into the SDM software. Third, a standard MNI map representing the weighted mean functional differences was recreated separately for each study by means of a Gaussian kernel that assigns higher values to the voxels closer to peaks. Statistical significance was assessed by permutation testing (Radua et al., 2012). The statistical significance of each voxel was determined via a standard randomization test in SDM. The default kernel size and statistical thresholds were as follows: full width at half maximum = 20 mm, P = 0.005, peak height threshold = 1, and extent threshold = 10 (Radua et al., 2014).

In addition, complementary analyses, such as jackknife, subgroup and meta-regression analyses, were conducted to assess the robustness and heterogeneity of the results. The jackknife sensitivity analysis is used to assess the reproducibility of the results; we conducted it by repeating the main analysis n-1 (n = the number of datasets included) times, discarding one study each time. If a region disappears as soon as one study is removed from the analysis, this indicates a lack of interstudy consistency (Radua and Mataix-Cols, 2009; Radua et al., 2012). Subgroup analyses were performed to control for the possible heterogeneity caused by different clinical and imaging methodological variables during the meta-analysis (Kolesar et al., 2019). Finally, to examine the potential confounding effects of several relevant sociodemographic and clinical variables, we also conducted meta-regression analyses. The simple linear regression, weighted by the square root of the sample size and restricted to predict only the possible SDM values, was used to investigate the potential effects of the variables above. The threshold for the meta-regression analysis was set at p < 0.0005, and findings in regions other than those detected in the main analyses were discarded (Emch, von Bastian and Koch, 2019; Radua et al., 2011). More details are as follows:

***Sensitivity analysis***

To assess the reproducibility of the results, we conducted a jack-knife sensitivity by repeating the main statistical analysis for n-1(n = number of datasets included) times, but discarding one study each time (Radua and Mataix-Cols, 2012). If a brain region remains significant in many different combinations of studies, it could be regarded as highly replicable, nevertheless, a region disappears as soon as one study is removed from the analysis, indicating a lack of interstudy consistency.

***Subgroup analysis***

The subgroup analyses were performed to control the possible heterogeneity caused by different clinical and imaging methodological variables during the five meta-analysis. The subgroup analyses were repeated several times, including only homogeneous studies each time. Specifically, we conducted subgroup analyses for those studies only including chronic SZ, for those including individuals with psychosis diagnosed by DSM, for those including SZ patients receiving medication treatment, for those using a 3-T MRI scanner, for those using SPM software and for those using non money stimulus.

***Meta-regression analysis***

In order to examine the potential confounding effect of several relevant sociodemographic and clinical variables, we also conducted the meta-regression analyses. The simple linear regression weighted by the squared root of the sample size and restricted to predict only the possible SDM values, was used to investigate the potential effects of variable above. The threshold for meta-regression analysis was set at p < 0.0005, and findings in regions other than those detected in the main analyses were discarded. Several relevant factors were included: the mean age, the percentage of males, the duration of illness, the Positive and Negative Syndrome Scale (PANSS) scores (PANSS-T; PANSS-P; PANSS-N), the percentage of first-generation antipsychotic (FGA) and second-generation antipsychotic (SGA) users.

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**Table S1. Instrumental (Operant) Learning Task.**

|  |
| --- |
| Instrumental (Operant) Learning Task |
|  | Free Operant | Discriminated Operant |
| Terms | Action–outcome | Stimulus–action–outcome |
| Abbreviations | A–O | S–A–O |
| Acquisitions | Action increases | Action occurs in S |
| Examples | Action declines when A occurs without O | Action occurrence in S declines when it repeatedly occurs in S without O |

**Notes:** In free instrumental learning tasks, participants act first and obtain a good outcome, and they perform the same actions in subsequent trials. This task is typically used in animal experiments, such as Skinner boxes. In discriminated instrumental learning tasks, participants respond when a stimulus occurs and obtain a good outcome, and they repeat the responses when the stimulus occurs in the next trial. In other words, once participants acquire rewards via their correct action, they will repeat it in subsequent trials to obtain more rewards.

**Table S2.** **PRISMA 2020 checklist.**

| **Section and topic** | **Item #** | **Checklist item** | **Location where item is reported** |
| --- | --- | --- | --- |
| **Title** |  |  |  |
| Title | 1 | Identify the report as a systematic review. | p.1 |
| **Abstract** |  |  |  |
| Abstract | 2 | See the PRISMA 2020 for Abstracts checklist  | p.2-3 |
| **Introduction** |  |  |  |
| Rationale | 3 | Describe the rationale for the review in the context of existing knowledge. | p.4-5 |
| Objectives | 4 | Provide an explicit statement of the objective(s) or question(s) the review addresses. | p.6-7 |
| **Methods** |  |  |  |
| Eligibility criteria | 5 | Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses. | Supplementary information |
| Information sources | 6 | Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted. | Supplementary information |
| Search strategy | 7 | Present the full search strategies for all databases, registers and websites, including any filters and limits used. | Supplementary information |
| Selection process | 8 | Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process. | Supplementary information |
| Data collection process | 9 | Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process. | Supplementary information |
| Data items | 10a | List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect. | Supplementary information |
| 10b | List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information. | Supplementary information |
| Study risk of bias assessment | 11 | Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process. | Supplementary information |
| Effect measures | 12 | Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results. | Supplementary information |
| Synthesis methods | 13a | Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)). | Supplementary information |
| 13b | Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions. | Supplementary information |
| 13c | Describe any methods used to tabulate or visually display results of individual studies and syntheses. | Supplementary information |
| 13d | Describe any methods used to synthesise results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used. | Supplementary information |
| 13e | Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression). | Supplementary information |
| 13f | Describe any sensitivity analyses conducted to assess robustness of the synthesised results. | Supplementary information |
| Reporting bias assessment | 14 | Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases). | Supplementary information |
| Certainty assessment | 15 | Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome. | NA |
| **Results** |  |  |  |
| Study selection | 16a | Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram. | p.8 & Figure1 |
| 16b | Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded. | Supplementary information |
| Study characteristics | 17 | Cite each included study and present its characteristics. | p.8 & Table 1 |
| Risk of bias in studies | 18 | Present assessments of risk of bias for each included study. | p.10 & Table S4 |
| Results of individual studies | 19 | For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots. | p.8 &Table S2 |
| Results of syntheses | 20a | For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies. | p.10-11 |
| 20b | Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect. | Table 2 |
| 20c | Present results of all investigations of possible causes of heterogeneity among study results. | p.10-11 |
| 20d | Present results of all sensitivity analyses conducted to assess the robustness of the synthesised results. | p.10-11 |
| Reporting biases | 21 | Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed. | p.10-11 |
| Certainty of evidence | 22 | Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed. | NA |
| **Discussion** |  |  |  |
| Discussion | 23a | Provide a general interpretation of the results in the context of other evidence. | p.11-23 |
| 23b | Discuss any limitations of the evidence included in the review. | p.22-23 |
| 23c | Discuss any limitations of the review processes used. | p.22-23 |
| 23d | Discuss implications of the results for practice, policy, and future research. | p.22-23 |
| **Other information** |  |  |
| Registration and protocol | 24a | Provide registration information for the review, including register name and registration number, or state that the review was not registered. | NA |
| 24b | Indicate where the review protocol can be accessed, or state that a protocol was not prepared. | NA |
| 24c | Describe and explain any amendments to information provided at registration or in the protocol. | NA |
| Support | 25 | Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review. | p.24-25 |
| Competing interests | 26 | Declare any competing interests of review authors. | p.25 |
| Availability of data, code, and other materials | 27 | Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review. | NA |

**Table S3. Instrumental learning-related behavioral indicators of the studies included in the meta-analysis.**

|  |  |  |
| --- | --- | --- |
| **Studies** | **Healthy Controls** | **Psychosis** |
| **Reversals** | **Win-stay** | **Lose-shift** | **Correct Choice** | **Total Reward** | **Learning Rate** | **Reversals** | **Win-stay** | **Lose-shift** | **Correct Choice** | **Total Reward** | **Learning Rate** |
| **Probabilistic reversal learning task** |
| Culbreth2016b | 13 | 80% | 40% | 43% |  |  | 9.1 | 20% | 10% | 36.8% |  |  |
| Culbreth2016a | 7.3 |  |  |  |  |  | 4.5 |  |  |  |  |  |
| Katthagen2020 |  | 91.9% | 40.7% |  |  |  |  | 78% | 49.7% |  |  |  |
| Schlagenhauf2014 | 9.9 |  |  | 75% |  |  | 6.1 |  |  | 64.3% |  |  |
| Waltz2013 | 14.2 |  |  |  |  |  | 7.8 |  |  |  |  |  |
| **Probabilistic instrumental learning task** |
| Deserno2020 |  |  |  | 77% |  | 0.44 |  |  |  | 69% |  | 0.118 |
| Dowd2016 |  |  |  | 82% |  | 0.277 |  |  |  | 70% |  | 0.194 |
| Ermakova2018 |  | 84.35% | 23.94% |  |  |  |  | 74.77% | 48.61% |  |  | 0.37 |
| Gradin2011 |  |  |  |  | 51 | 0.49 |  |  |  |  | 38 | 0.35 |
| Hernaus2018 | 6.82 | 60.57% | 23.07% |  | 8.47 |  | 6.19 | 57.72% | 24.59% |  | 8.10 |  |
| Lee2019 |  |  |  | 68% |  |  |  |  |  | 63% |  |  |
| Murray2008 |  |  |  | 64% |  | 0.18 |  |  |  | 53% |  | 0.14 |
| Reinen2016 |  |  |  |  | 19.4 |  |  |  |  |  | 18.7 |  |
| Segarra2016 |  |  |  |  | 67.0 |  |  |  |  |  | 48.3 |  |
| Vanes2018 |  |  |  | 63% |  |  |  |  |  | 57% |  |  |
| Waltz2017 |  | 78.4% | 27.7% |  |  | 0.2245 |  | 69.9% | 34.3% |  |  | 0.1835 |
| White2015 |  |  |  |  | 12.41 |  |  |  |  |  | 11.71 |  |
| **Probabilistic trial and error learning** |
| Koch2010 |  |  |  |  |  | 0.88 |  |  |  |  |  | 0.67 |

**Notes**: During instrumental learning task, “Reversals” refers to the times of reward contingencies reversing during PRL task; “Win-stay” is the percentage of trials in which participant select the rewarded stimuli in last trial, similarly, “Lose-shift” is the percentage of trials in which participants avoid selecting the unrewarded stimuli in last time. What’s more, “Correct Choice” refers to the percentage of trials in which participants choose the high-probability stimuli; “Total reward” means the total money or scores that participants obtained in the whole task; and “Learning Rate” is an important parameter in RL models to assess the individual learning capability. During Pavlovian learning task, “Correct Report” refers to average percentage of correctly reported stimulus-outcome associations; “SCR” refers to the skin conductance responses, which is one of fearing conditioned responses; and “CR” refers to conditioned responses. “CS+” is the conditioned stimulus which follow unconditioned stimulus, and “CS-” is the conditioned stimulus which don’t.

**Table S4. Subgroup analyses and sensitivity analysis in the study of brain activity difference between psychosis and HC in instrumental Learning.**

|  |  |  |
| --- | --- | --- |
| **Study** | **Activation** | **Deactivation** |
| **L MOG** | **L****insula** | **L ING** | **L PoCG** | **R SPG** | **L cerebellum** | **R** **striatum** | **R PCC&MCC** | **R IFG&insula** | **R IFG** | **R MFG** | **L** **mPFC** | **R ITG** | **R** **dlPFC** | **R OFC**  | **R thalamus**  |
| **Subgroup analyses** |
| Studies including chronic SZ patients only (n=15) | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Studies including patients receiving medication treatment (n=14) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes |
| Studies using money stimulus (n=16) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Studies including SZ patients diagnosed by DSM (n=11) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Studies using a 3.0-T MR scanner (n=16) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Studies including English-speaking individuals only(n=16) | Yes | No | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| **Sensitivity analysis** |
| Culbreth2016b | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Culbreth2016a | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Deserno2020 | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Dowd2016 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Ermakova2018 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Gradin2011 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Hernaus2018 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Katthagen2020 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Koch2010 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Lee2019 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Murray2008 | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Reinen2016 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Schlagenhauf2014 | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Segarra2016 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Vanes2018 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Waltz2013 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Waltz2017 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| White2015 | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

Notes: DSM = diagnostic and statistical manual of mental disorders; MOG = middle occipital gyrus; ING = lingual gyrus; PoCG = postcentral gyrus; ANG =

angular gyrus; PCC = posterior cingulate cortex; IFG = inferior frontal gyrus; CAL = calcarine fissure / surrounding cortex; MFG = middle frontal gyrus; mPFC = medial prefrontal cortex; ITG = inferior temporal gyrus; dlPFC = dorsolateral prefrontal cortex; OFC = orbital prefrontal cortex; L = left; R = right.

**Figure S1. Structure of instrumental learning tasks.**



Notes: **a,** Probabilistic reversal learning task. The green smiley face stands for positive feedback, and the red frowny face stands for negative feedback. The reward probability for triangles is initially set to 80%, while the probability for squares is 20%. After reversal, the reward probabilities for triangles and squares are 20% and 80%, respectively. **b,** Probabilistic instrumental learning task. Every trial, subjects had to choose one out of 2 figures in order to receive either a win or a loss. The cue-outcome contingencies were perfectly anti-correlated (0.8/0.2 rewards), and the reward probabilities for triangles and squares are 20% and 80%, respectively. **c,** Probabilistic trial and error task. In this trial, the square is associated with the value of 7, and the selection “>5” is correct. In different conditions, the stimulus-outcome contingency was set at 50%, 100% and 81%.