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Independent Neural Computation of Value from Other People's Confidence

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Abstract

Expectation of reward can be shaped by the observation of actions and expressions of other people in one's environment. A person's apparent confidence in the likely reward of an action, for instance, makes qualities of their evidence, not observed directly, socially accessible. This strategy is computationally distinguished from associative learning methods that rely on direct observation, by its use of inference from indirect evidence. In twenty-three healthy human subjects, we isolated effects of first-hand experience, other people's choices, and the mediating effect of their confidence, on decision-making and neural correlates of value within ventromedial prefrontal cortex (vmPFC). Value derived from first-hand experience and other people's choices (irrespective of confidence) were indiscriminately represented across vmPFC. However, value computed from agent choices weighted by their associated confidence was represented with specificity for ventromedial area 10. This pattern corresponds to shifts of connectivity and overlapping cognitive processes along a posterior-anterior vmPFC axis. Task behavior and self-reported self-reliance for decision-making in other social contexts correlated. The tendency to conform in other social contexts corresponded to increased activation in cortical regions previously shown to respond to social conflict in proportion to subsequent conformity (Campbell-Meiklejohn et al., 2010). The tendency to self-monitor predicted a selectively enhanced response to accordance with others in the right temporoparietal junction (rTPJ). The findings anatomically decompose vmPFC value representations according to computational requirements and provide biological insight into the social transmission of preference and reassurance gained from the confidence of others.

Significance Statement

Decades of research have provided evidence that ventromedial prefrontal cortex (vmPFC) signals the satisfaction we expect from imminent actions. Yet, we have a surprisingly modest understanding of the organization of value across this substantial and varied region. This study finds that using cues of the reliability of other peoples' knowledge to enhance expectation of personal success generates value correlates that are anatomically distinct from those concurrently computed from direct, personal experience. This suggests that representation of decision values in vmPFC is sub-organized according to the underlying computation, consistent with what we know about the anatomical heterogeneity of the region. These results also provide insight into the observational learning process by which someone else's confidence can sway and reassure our choices.

Introduction

The human brain can use a variety of learning strategies to better its situation. Unifying economic theories suggest that different decision processes converge to a single expectation of satisfaction (or ‘value’) that will be gained or lost from available actions – correlates of which are found in activity throughout ventromedial prefrontal cortex (Levy and Glimcher, 2012; Bartra et al., 2013), and guide decisions toward options of greater value. Whether this activity represents a single computation of value, a collection of distinct computations, or both, is not clear. But there are both computational and anatomical reasons to suspect sub-regional specialization.

Reward predictions from different types of information are computed differently. For instance, one can learn about an action's value by maintaining a running average of rewards received from performing it. However, some knowledge is only socially and/or inferentially accessible; if one observes someone else perform an action, one can recruit inferential strategies for a judgement of that action's value. For instance, people provide signals of high confidence when they have good knowledge of the likely outcomes to their actions (Patel et al., 2012). So, confident actions of others should have greater influence on our own appraisals (Thomas and Mcfadyen, 1995). So, if the other person appears to know what she is doing (and assuming her intentions are similar to mine), one can employ a rule of imitate-if-appears-confident, or more flexibly, one can infer what she knows from her actions and confidence, then combine this with knowledge inferred from other cues and personal experience. These and similar strategies, unlike directly sampling outcomes, may require steps of indirection and integration of multiple cues (e.g. of others' preference and confidence) but also enable us to compute value in the absence of first-hand experience with prior choice outcomes. We developed a task that provides different types of information for evaluating the value of the same choice: first-hand knowledge, choices of others, and their confidence. We then compared contributions of each information source to decision-making and neural representations of value across vmPFC.

We considered that different computations of value could make use of shifting connectivity, cytoarchitecture, and overlapping cognition toward the anterior of vmPFC (Kringelbach and Rolls, 2004). Cytoarchitecturally, laminar density and granular layer IV volume increase along a posterior to anterior axis (Ongur et al., 2003; Mackey and Petrides, 2010), indicative of increasing inter-area connectivity (Barbas, 2007). Local connectivity required for integrating value signals *in situ* dominates posterior vmPFC.

In contrast, anterior regions maintain a balance of local and distant connectivity that can *additionally* recruit higher-order input (Sepulcre et al., 2010). Correspondingly, moving anterior and dorsal from classical representations of value in area 25 (through areas labelled as area 14m (Mackie, 2010) or 10m and 10r (Ongur et al., 2003)) to medial area 10, known overlapping processes become more abstract, integrative, and inferential (Ramnani and Owen, 2004; Amodio and Frith, 2006; Burgess et al., 2007; Sescousse et al., 2013). Representations of value that require more inferential or integrative processes may map to distinct regions across this cortical landscape.

An anatomical distinction between value from first-hand knowledge and value from agents' confidence-weighted influence would exemplify the mapping of value to cortex as determined by its computational requirements. It would also provide the foundation for investigation of the neural mechanism by which the supporting confidence of others guides our actions. Based on changes of connectivity and overlapping function, value from confidence-weighted influence was predicted to preferentially recruit anterior regions of vmPFC while direct, personal sampling and the main effect of agents' choices (regardless of confidence) was not.

We linked individual differences of influence on task performance to sensitivity of neural responses to corresponding task stimuli. Finally, to establish the relevance of our task and findings to social environments we tested the relationship between observed effects (neural and behavioral) and influence of others on participant behavior (conformity and self-monitoring) outside the lab.

Materials and Methods

Participants

Participants were right-handed and had no history of brain injury or psychological disorder. Each gave informed consent. Inclusion criteria for fMRI analysis included at least some use of each information source during the behavioral task to enable contrasts between value-based activation derived from different sources (exclusions were indicated by near-perfect prediction of choice outcomes by only one or two influences, a simple rule-based strategy which precluded quantitative examination of behavior by leading to extremely large and unstable estimates of regression coefficients) (5 participants excluded). Head movements were required to be consistently smaller than a single voxel (2mm) (1 participant excluded). 23 participants (13 male, age: M 26 SD 3.6) met all requirements. Each received 110 Danish Krioner (kr) (20 USD) for time spent participating and 60 kr (10 USD) for winnings on tasks (all subjects were paid this same amount). The study was approved by Central Denmark Region ethics (No. 29718).

Task

The Urn Task (Figure 1) examines how participants make decisions when provided with different sources of information. It asks participants to infer the color of the next marble to be drawn (red or green) for each of a series of 160 mixed urns, with opportunities to do so by inferring other people's information about the likely outcome. Participants had the following information about each urn: a random sample of 8 marbles, four predictions described as being made by past participants (four "agents") based on their own samples from the same urns, and the confidence expressed by those agents. All samples were said to be replaced before the final marble was drawn.

Agents' faces were presented with neutral expressions. To ensure any effects were due to the use of agents' confidence, rather than its inference, we communicated confidence with an explicit cue described to subjects during training: the smug (confident cue) or perplexed (unconfident) animated smiley that appeared within the indicated choice (red or green marble) (See Figure 1). Agents' choices were also said to be presented in the time taken by the agent to make them. Confident response times were between 325 and 1000ms. Unconfident response times were between 1800ms to 2600ms. Once all agents' responses were made, participants had 1300ms to observe them before their own sample appeared. All information was available for 1250ms before a choice could be made, cued by presentation of choice options.

The participant never saw agent samples, and agents were said never to see the participant's sample. Agent choices were seen before personal samples because they were assumed to take longer to process. There was no time limit for participant decisions once the cue for a choice was presented. After a choice, confirmation of the choice was briefly shown and followed by a 1s inter-trial interval. The task took 23 minutes to completion, on average.

After instructions for the task, using visual displays, participants were quizzed by the experimenter on the meaning of each display item and asked what might be in the urn given various combinations of information. Instructions were repeated if necessary. It was critical before progression that participants understood that samples reflected 'randomly mixed' urn contents (the urn shook on arrival for emphasis) and were replaced. No trial outcome was provided to subjects, so participants could not learn to associate outcomes with colors or agents. They were required to make the best use of the information available, and told that a random urn would be selected and sampled to see if the subject was correct, with a potential reward of 30 Danish Kroner (DKK).

The experimenters actually programmed agents' choices, agents' confidences, and agents' deliberation times in a way that fully counterbalanced the factors of participants' samples, agents' choices, and the confidences of agents favoring either color. Agents were drawn with replacement from a set of 30 images from the Radboud face dataset, in sepia tone (Langner et al., 2010). The use of fictional agents' responses was necessary to achieve sufficient statistical power and ensure that each subject experienced each possible combination of agents' choice, agents' confidence and personal sample. This was explained to participants during debriefing.

The task was designed to study how participants decide across a range of combinations of sample, agents' choice and agents' confidence. Accordingly, trials were generated by creating every possible combination, across trials, of: the number of agents favoring red (vs. green), confidence for agents favoring red, confidence of agents favoring green, and participants' samples – all varying independently of one another. Thus there was no real-world optimal strategy (in the sense that the observations were not actually produced by simulating draws from an urn whose contents could then be predicted), and each participant was paid the maximum reward at the end of the study.

Confidence expressed by any agent was the same as confidence expressed by any other agent that predicted the same color. At the risk of this aspect appearing odd to participants, it enabled us to test our predictions with a clear choice x confidence factorial design that identified independent contributions of each information source to decisions and neural activity. It also kept the task length manageable for an fMRI study.

During debriefing, no participant expressed doubt in the authenticity of the agents' responses.

There were 160 trials in the scanned task. For each number of agents choosing red (0 to 4), there were 32 trials. Sets of 32 were made up of 7 sample distributions (1-7 reds in the participant sample; samples with 4 reds were presented twice as often as the other combinations) evenly distributed over each available combination of agents' confidence. When 1 to 3 agents chose red, there were 4 confident/unconfident combinations. When 0 or 4 agents chose red there were two options (high and low confidence in the agents' chosen color).

Procedure

Prior to scanning, outside the scanner, the participants guessed the next marble from a series of 28 urns *and* indicated confidence in these predictions, based only on a sample of 8 marbles from each (no agents' choices). Participants were told that their own predictions during this task would be used for the Urn Task of future participants. This provided participants with the agents' perspective. Participants were also given a 30 DKK 'prize' for this task. Next, after receiving instructions, the participant practiced for 20 trials before beginning the task in the scanner. Finally, after scanning, the participant filled in questionnaires measuring self-monitoring and the tendency to conform outside the lab before being debriefed.

Behavior Analysis

We performed a factorial, mixed effects logistic regression, which we refer to as the *Component Value Behavioral Model*, to analyze participant choices (dependent variable: per trial choice of red, vs green) as a function of a number of candidate explanatory factors and their interactions. Choices were analyzed in R (v. 3.2.3, R development Core Team RRID:SCR_001905) using the lme4 package (v. 1.1.12). The model allows for the measurement of influence of multiple sources of information on the probability of choosing red. This includes added value of a confident agent's choice over an unconfident one. The following predictors of participant choice of red (described below) were added to the regression:

S: proportion of marbles in participant's sample that were red.

O: proportion of agents choosing red.

C_R: confidence of agents choosing red (-0.5 low, 0.5 high)

C_G: confidence of agents choosing green (-0.5 low, 0.5 high)

O_RC_R: proportion of agents choosing red x their confidence

O_GC_G: proportion of agents choosing green x their confidence

Each predictor was scaled to a range for 0 to 1 and centered around its mean, for each subject. Common scaling allows for the estimated coefficients to be comparable, across predictors, with each expressed in units of change in log odds of choice corresponding to a change from the minimal to the maximal value. Centering is recommended (Cohen, 2003) because it allows main effects to be interpreted as effects when all other effect variables are at their mean, without affecting interaction terms. Interaction terms were calculated from the product of the scaled and centered predictors. **C_R** and **C_G** had no meaning when no agents chose that color and so these variables were set to their mean (i.e. 0) in these instances, giving them no statistical effect.

The rationale and interpretation of these variables is as follows. **S** and **O** are two independent sources of information about the urn in the design; our major question is whether the confidence $\mathbf{C_R}$ & $\mathbf{C_G}$ modulates the effect of **O**. **S** codes the relative proportion of red (vs green) marbles in the agent's own sample, and a positive regression coefficient for it captures an increasing tendency to choose red when more red marbles are observed. Since the fraction of green marbles is equal to **1 - S**, a model with predictors for both effects (and an intercept) would be rank-deficient; however, following mean centering, **S** codes the difference in red vs green marbles sampled (with a positive value indicating a preponderance of red and negative values the opposite), capturing both effects symmetrically. The same point holds for **O**. The effect of **O** captures an increasing tendency to choose red when the relative proportion of agents choosing red (minus those choosing green) is larger. Following mean centering, $\mathbf{O} = \mathbf{-O_G}$ (proportion choosing green). So interactions $\mathbf{O_R C_R}$ and $\mathbf{O_G C_G}$ capture the difference of this effect for red and green choices (respectively) between confident vs. unconfident agents. The main effects of confidence, $\mathbf{C_R}$ and $\mathbf{C_G}$, capture the baseline effect of confident votes when the votes are evenly split, and control for any overall change in choice tendency when red, or green, votes are confident, independent of the number of votes.

Each effect contained both a fixed and a random effect term, i.e. a mean slope at the group level, an error term allowing that slope to vary from subject to subject, and a full covariance matrix among the random slopes. We verified that all these effects should be included in several ways. First, the significant tests for all regression coefficients (save the intercept) in Table 1 reject the null hypotheses corresponding to the nested models with any one effect being zero. We also present AIC comparisons for the full model against a set of submodels, each omitting one effect. Conversely, we also tested for progressive improvement in model fit to behavior (by AIC and a likelihood ratio test (χ^2 P < 0.05)) (Vazquez et al., 2010) as effects were added incrementally (in the order: intercept, **S**, **O**, $\mathbf{C_R}$ and $\mathbf{C_G}$, $\mathbf{O_R C_R}$ and $\mathbf{O_G C_G}$. Each significantly improved the model fit to behavior (detailed results not reported). An additional interaction term between **S** and **O** did not improve the fit.

Component Value Behavioral Model:

$$logit(P)_{ij} = \beta_0 + \beta_1 S_{ij} + \beta_2 O_{ij} + \beta_3 C_{R\,ij} + \beta_4 C_{G\,ij} + \beta_5 O_R C_{R\,ij} + \beta_6 O_G C_{G\,ij} + \epsilon$$

where *P* is the probability choosing red for the i^{th} trial for subject j, β represents regression coefficients including random effects for all coefficients and ϵ is error.

Individual Difference Measures

Task Behavior: To measure individual differences of information influence, we measured the effect of each information source on the likelihood of each participant's decisions. Using the fixed and random effects of the *Component Value Behavioral Model*, we calculated the fit (via negative log likelihood) of this model to choices of individual participants. We then calculated the fit of four other models (using the same fitted parameters as the full model): one without **S**, one without **O**, one without both $\mathbf{C_R}$ or $\mathbf{C_G}$ and one without both $\mathbf{O_R C_R}$ and $\mathbf{O_G C_G}$. The effect of each model reduction on behavior likelihood (smaller model – full model) represented the impact of the subtracted variable(s) for that participant: **S** effect, **O** effect, **C** effect and **OC** effect, respectively (Hampton et al., 2008). (The intent of this procedure was to measure the effect of each variable in each subject, but using units of differential log likelihood, analogous to variance explained, rather than estimated regression coefficients. This is because the scaling of the latter can be erratic from subject to subject). These effects were entered as covariates in a separate group level fMRI analyzes and tested for relation to behavior outside the lab.

Choices in Other Contexts: This study was agnostic to whether findings are unique to social environments, but it was imperative to test the relevance of the results to social behavior outside the lab, given their social context. To test the relevance of task behavior, we used a self-report 'conformity scale' (Mehrabian and Stefl, 1995). The Conformity Scale assesses weight placed on other people's choices relative to one's own information in a variety social contexts. It requires participants to rate agreement or disagreement (on a scale from -4 to 4) with 11 statements referring to reliance on others for decisions. Higher scores mean greater reliance on others. The scale does not assess the use of the others' confidence, so to test its relationship to task behavior we created a simplified model that contained only **S** and **O** (removing confidence from the model). Then, similar to above, we calculated the effects of **S** and **O** on model fit. We then tested the correlation between these effects (and difference between them) and conformity scale scores. Self-monitoring (Snyder, 1974) was also assessed measuring the tendency to adapt behavior in response to cues from an audience, but no effect was hypothesized given that there was no audience in this task.

Neuroimaging

fMRI Procedure

Participants were instructed and given time to practice until the task was understood and responses could be made in less than 4 seconds. The task was presented with Presentation v.12 software (Neurobehavioral Systems Inc. RRID:SCR_002521). Scanning took place at the Danish Neuroscience Centre, Aarhus, Denmark on a 3 Tesla Siemens Trio Scanner (Siemens Medical Solutions, Erlangen, Germany) fitted with a 32-channel head coil. The Urn Task displays were back-projected and observed via a mirror and responses were collected from the right-hand using a fibre-optic button box.

Image Acquisition

Functional (Echo Planer Images, EPI) data was collected as T2-weighted echo planar images (EPI) in an interleaved slice acquisition order. Each EPI volume contained 52 slices with the following parameters: voxel size 2x2x2 mm, TE 27 ms, TR 2800ms, Flip Angle: 90°. The small 2mm voxel size efficiently reduced orbitofrontal cortex dropout and distortion. 176-slice 1mm voxel whole-brain anatomical scans were also acquired for co-registration with the EPI data using an MPRAGE sequence on a 256x256x176 grid with the following parameters: TE: 3.7ms, Inversion Time: 900ms, TR: 2420ms, Flip angle: 9°.

First Level fMRI Analysis

All image analysis was carried out with tools of FMRIB's Software Library (FSL RRID:SCR_002823) version 5.0.6 (Smith et al., 2004). Preparation of the EPI data used FSL defaults (FEAT 6.0). Volumes acquired during significant (>1mm) head movements were replaced with neighboring volumes and events with modelled responses occurring during these acquisitions were removed from all models. Independent Component Analysis was used to visually identify and remove remaining artefacts in the data using MELODIC (Beckmann and Smith, 2004). General linear models were fit in pre-whitened data space for each individual participant. Regressors and temporal derivatives were convolved with the default FSL haemodynamic response function (gamma function, delay: 6s, standard deviation: 3s), and filtered by the same high pass filter as the data. Single-participant results were transformed using nonlinear deformation algorithms into standard space (Montreal Neurological Institute, MNI152).

Component Value fMRI Model

In the *Component Value Behavioral Model* of choices, the dependent variable was choice of red (vs green), and variables were constructed as they related to the evidence in favor of choosing either color. In the fMRI analysis, the dependent measures were neural activity during these choices. However, rather than covarying with the tendency to choose options on the basis of a dimension like color, BOLD activity is widely reported to vary along the dimension of the chosen vs. unchosen option, with larger responses in medial PFC when the chosen (or about to be chosen) option is more likely to be correct, carries more reward, or is otherwise more strongly preferred (Tanaka et al., 2004; Daw et al., 2006; Kim et al., 2006; O'Doherty et al., 2007; Behrens et al., 2008; Wunderlich et al., 2010). Therefore, to test for analogous neural effects as on the behavior, we model the BOLD data using precisely the same set of explanatory variables as the behavioral analysis, but expressed with respect to evidence supporting the chosen vs. unchosen options on each trial, rather than the red vs. green options. So when *red* is chosen, $\mathbf{S_A}$ and $\mathbf{O_A}$ (for evidence in “accordance” with the choice) are defined in terms of *red* samples and choices. When green is chosen, they are defined in terms of green samples and choices. In keeping with the literature on neural correlates of decision variables, we refer to activity correlated with these variables as reflecting their influence as components of “chosen value,” meaning the overall supporting evidence that the subject’s choice was correct. However, we stress that given the symmetry of our task (where choices are mutually exclusive, and evidence supporting red opposes green), such activity can be understood as reflecting relative (chosen minus unchosen) value, as indeed has been reported for medial PFC (Boorman et al, 2009).

So the set of variables in the fMRI analysis track those from the behavioral analysis, but coded in terms of accordance of an information source with the subject's choice. Each variable had a parametric weight of accordance that varied trial-by-trial. As in the behavioral model, variables were scaled to a range of 1 and mean centered (orthogonal to a constant term). Like the behavioral model, interaction regressors were calculated by multiplying respective main effect regressors after scaling and mean centering.

The *Component Value fMRI Model* contained the following variables:

$\mathbf{S_A}$: proportion of marbles in sample in accord with participant's choice

$\mathbf{O_A}$: proportion of agents' choices in accord with participant's choice

$\mathbf{C_A}$: confidence of accordant agents (-0.5 or 0.5)

$\mathbf{C_D}$: confidence of discordant agents (-0.5 or 0.5)

$\mathbf{O_A C_A}$: accordant agents' choices x their confidence

$\mathbf{O_D C_D}$: discordant agents' choices x their confidence

plus intercept.

'A' and 'D' subscripts represent accordance or discordance of the information source with the choice. Just as in the behavioral analysis, following mean centering $\mathbf{S_A}$ codes the relative proportion of accordant (minus discordant) marbles; $\mathbf{O_A}$ codes the relative proportion of accordant (minus discordant) other agents' choices; hence $\mathbf{S_D}$ (=-$\mathbf{S_A}$) and $\mathbf{O_D}$ (=-$\mathbf{O_A}$) are redundant. Also as for behavior, $\mathbf{C_A}$ and $\mathbf{C_D}$ are mutually independent, and their interactions with $\mathbf{O_A}$ (and $\mathbf{O_D}$=-$\mathbf{O_A}$) capture the difference of effect on BOLD from other agents' accordant (vs discordant) choices, when those agents are confident compared to when they are unconfident. Also, as with behavior $\mathbf{C_A}$ and $\mathbf{C_D}$ had no meaning (and were not presented) when no agents chose the color and so these variable were set to the mean (i.e. 0) in these instances, having no statistical effect.

Integrated Value fMRI Model

Preceding the full model fit described above, which aimed to decompose the influence of different sources of information on value-related BOLD correlates, we wished to verify the presence of activity related to overall value. To define this, we extracted the likelihood assigned by the *Component Value Behavioral Model* to each chosen option of each subject, and took this choice probability as our estimate of the integrated chosen value. Such probabilities reflect the transform of the weighted sum of evidences, through the logistic softmax so as to range from 0 to 1, which provides a well normalized summary of the overall evidence in favor of a red vs green choice, or chosen minus unchosen value, which has been shown to track medial PFC activity (e.g., (Daw and Doya, 2006)).

Accordingly, the fitted model to each subject was:

$$\boldsymbol{Y_i = \beta_0 + \beta_1 S_i + \beta_2 O_i + \beta_3 C_{R\,i} + \beta_4 C_{G\,i} + \beta_5 O_R C_{R\,i} + \beta_6 O_G C_{G\,i} + \epsilon}$$

for each i[th] trial, where $\boldsymbol{\beta}$ represents fitted mixed and random effect parameters and ϵ is error. If participant chooses red, choice likelihood is $\frac{e^{Y_{ij}}}{1+e^{Y_{ij}}}$. If participant chooses green, choice likelihood is $1 - \frac{e^{Y_{ij}}}{1+e^{Y_{ij}}}$. This vector of likelihoods was entered, along with a constant, to predict the neural correlates of integrated value (Figure 3A).

Timing

The modelled fMRI event, for all regressors, was a 1250 ms period when agents' choices and personal samples were concurrently available, before a choice could be made. During this period, both vmPFC sample-driven activation and agent-driven activation were at peak levels (Figure 4). A temporal derivative of each event was added to the model to control for slight errors of fit to the haemodynamic response. The interval between modelled events varied as determined by participant reaction time (M 1.2s, SD 1.6s) and variable time taken for choices of agents to appear (range 0.32 to 2.7s). 80% of participant reaction times were under 1.7s and 90% under 3s. This resulted in a positively skewed distribution of periods between modelled events (M 8.6s, SD 1.7s).

The Spatial Linear Parametric Analysis

To characterize anatomical patterns of activation associated with estimated value from S_A (first-hand experience of sample), O_A (agents' choices alone), and O_AC_A (interaction effect of agents' confidence and agents' choices) we generated five anatomically defined spheres of 10mm diameter linearly traversing an anatomical axis (Nicolle et al., 2012; Sul et al., 2015). This axis spanned the superior medial gyrus, dorsal to the gyrus rectus. It began in area 10m/14m (Ongur et al., 2003; Mackey and Petrides, 2010),at MNI coordinates [0mm, 32mm, -16mm], within a region defined by metanalysis as associated with choice value (Levy and Glimcher, 2012; Bartra et al., 2013). It ended to the frontal pole at the approximate center of ventromedial area 10 (MNI coordinates 0mm, 64mm, 8mm), a region associated with abstract reasoning about mental states (Amodio and Frith, 2006) (Figure 4). Mean percent signal change as extracted from each sphere, for each variable. Percent signal change in response to S, O and OC variables, as well as the contrasts of OC – S and OC – O (to test how the difference of responses to different information change along this axis) was examined by mixed effect linear regressions (lme4 with Kenward-Roger approximation of dof).

Fixed impulse response (FIR) sets were then fitted to each regressor in the *Component Value fMRI Model*. These sets spanned a period of 19.6s divided into 7 time bins, each the length of a TR (2.8s). This period began at the point that agents' responses began to appear on the screen. Mean parameter estimates for each of S_A, O_A and O_AC_A were extracted in each sphere and plotted in Figure 4. To investigate the nature of the interaction between of agents' choice and confidence, we did the same for a second GLM that included separate regressors for confident and unconfident agents supporting the participant's choice. Remaining regressors of the *Component Value fMRI Model* were included as covariates ($\mathbf{S_A}$, $\mathbf{C_D}$ and $\mathbf{O_DC_D}$). We plotted the time courses of the effects of confident agents and unconfident agents in Figure 5.

Group Level fMRI Analysis

Both group models were fitted to parameter estimates from each lower level analysis, using mixed effects in FSL. All group-level Z (Gaussianised T/F) statistical images represent whole-brain searches using cluster corrected statistics (FMRIB's Local Analysis of Mixed Effects (FLAME) 1+2) (Woolrich et al., 2004) ($Z > 3.0$ voxel threshold, $P < 0.05$ cluster significance threshold) shown to be robust against false positives (Eklund et al., 2016), using automatic outlier deweighting (Woolrich, 2008).

Individual Differences (Group Level)

Individuals vary on their reliance on others for decision-making, and this is a reasonably stable trait (McGuire, 1967). We harnessed these differences to test relationships between behavioral influence of specific types of information, their effects neural correlates of value, and social influence on choice in other contexts.

Neural Effects x Behavior: The four measured influences on individual participant behavior (S effect, O effect, C effect and OC effect) were added, mean-centered, as between-participant covariates in a new group-level *Component Value fMRI Model* analysis. We asked if the behavioral O effect, S effect, their difference, and the OC effect predicted the sensitivity of the brain to these influences, highlighted by fMRI effects of $\mathbf{O_A}$, $\mathbf{S_A}$, and $\mathbf{O_A C_A}$. This analysis employed small volume correction within our *a-priori* anatomical region of interest, the vmPFC. This mask was created as the conjunction of all Harvard-Oxford Atlas regions falling within vmPFC with a range along the x axis of -18mm to +18mm and maximum height level of 18mm to cover, with some room for error. regions anatomically specified as vmPFC in prior studies (Mackey and Petrides, 2010).

Conformity and Self-Monitoring: To test the relationship of neural activity during the task to real-world behavior, we tested whether sensitivity to different sources of information during task execution ($\mathbf{S_A}$ and $\mathbf{O_A}$) related to self-reported self-reliance for decision-making (Conformity scale) and self–monitoring behavior by adding these as covariates in a separate group level analysis of the *Component Value fMRI Model*. Age and gender were also added as covariates.

vmPFC effects were insensitive to individual differences, so we explored outside this region. For the conformity comparison, we used small volume correction within regions identified to respond more to social conflict in proportion to individual differences of subsequent conformity in an independent study (Campbell-Meiklejohn et al., 2010). Social conflict being a driver of conformity in the brain {Wu}, it was predicted that those rating high on self-reported conformity would experience greater neural responses to conflict with agents.

While self-monitoring would not affect behavior in our task (with no live audience), individuals high in self-monitoring behavior might react differently social cues. With no *a priori* region of interest for this contrast, we used a whole-brain cluster-corrected analysis.

Results

While scanned with fMRI, participants repeatedly predicted the color of marbles to be drawn from an urn by balancing several sources of evidence: their own sample of marbles from the urn, predictions described as made by four other agents based on their private samples from the same urn, and those agents' confidences. We sought to measure subjects' reliance on the subject's sample vs. agents' choices, and particularly to examine the extent to which the influence of the agents' choices was modulated by their confidence. The latter is a key measure in this setting, for distinguishing behavior from simpler heuristics like imitation. This is because an agent's confidence implies the quality of the agent's knowledge informing the choice, and therefore the extent to which their opinion should be trusted. Indeed, a differential effect of confident agents can be captured in a Bayesian ideal-observer model (simulations not shown), which infers the proportion of marbles in the urn from the different sources of evidence, by inferring and marginalizing over the agents' private samples, with confidence as a signal of more decisive evidence.

Behavior

We used a multi-level mixed logistic regression to estimate parameters reflecting how the tendency to predict red was influenced by each information source that should monotonically affect it.

Each variable was established as a distinct contribution to choice behavior (Table 1, Figure 2). At the group level, participants were more likely to predict red following samples with more red (vs. green) marbles (**S**), more agents choosing red (vs. green) (**O**), higher confidence of agents associated with red ($\mathbf{C_R}$) (regardless of how many agents chose that color), and lower confidence for green ($\mathbf{C_G}$). The magnitude of the coefficients for **S** and **O** indicates that four agents (at average confidence) were relied on roughly the same amount as the sample of eight marbles, meaning each of the agents' choices had impact approximately twice that of observing a single marble in terms of information on this task. Table 1 additionally presents the different variables effects in terms of AIC and variance explained according to McFadden's (1974) pseudo-R^2.

Our key question concerned the interaction, which measures whether agents' choices have a differential effect when they are confident. Here, as hypothesized, we found that effect of each agent's choice on participant decisions was greater when that agent was confident (O_RC_R, O_GC_G).

Conformity and Self-Monitoring Scales

We next considered whether individual differences in this relatively stylized laboratory task tracked an index of real-world social behavior. Greater reliance on personal samples during the Urn Task corresponded greater self-reliance for decision-making in other social contexts ($r = -.461$, $P = .013$, Mean Conformity Scale Score -3.7 SD 11.4)

(Figure 7A). Controlling for gender and age, the effect remained significant ($r = -.37$, $P = .049$). There was no relationship between the conformity scale and the effect of agents on behavior ($P > .4$) most likely due to the complication of agent confidence. In contrast, self-monitoring relates specifically to behavioral adjustments to social cues to enhance reputation, would not be expected to show an effect in the absence of a live audience and this was confirmed by the data.

Neuroimaging

We pursued a parallel strategy in the brain to distinguish influence of each information type on neural correlates of estimated value in vmPFC. As vmPFC activity is well known to track the degree to which the chosen option is correct or likely to be rewarded (“chosen value”, often relative to the unchosen option) (Tanaka et al., 2004; Daw et al., 2006; Kim et al., 2006; O'Doherty et al., 2007; Behrens et al., 2008; Wunderlich et al., 2010), we redefined all of our explanatory variables in terms of information indicating the chosen (vs unchosen) option will be correct, rather than red vs. green. Therefore, neural results are described with respect to ‘accordance’ (evidence indicating that the subject’s chosen option will be correct) vs ‘discordance’ (evidence indicating that the subject’s choice will be incorrect). (Note that these are symmetric: evidence that the subjects’ choice is correct is, equivalently evidence that the other is incorrect.)

Neuroimaging findings are reported as group-level cluster-corrected statistics with a cluster-forming voxel threshold of $Z > 3$ and cluster significance level of $P < 0.05$. Results are described in format: [peak location in MNI coordinates (mm)], Z score of peak voxel, P value of cluster, size of cluster in voxels (and minimum cluster size at $P < 0.05$). Scaling of variables should be considered when interpreting the results (i.e.

a change from 0 to 4 agents' choices is scaled the same as a change from 0 to 8 marbles in a sample). All observed effects relate to when all other variables are at their mean. Mean effect contrasts all endured whole-brain cluster correction. Only activations within the medial prefrontal cortex (mPFC) reported, as this is the focus of our study. Between-subject analysis employed small volume correction using independent masks of regions of interest (detailed in methods).

Integrated Value fMRI Model

Neural correlates of overall chosen value from all information sources were found in central vmPFC ([-8 50 -8], Z_{max} = 4.08, P < .001, 410 voxels (min 76)). Negative correlations (higher activity when evidence favors the unchosen option more) correlated with dmPFC activity ([0 26 48], Z_{max} = 4.82, P < .001, 1345 voxels (min 76). See Figure 3A).

Component Value fMRI Model

We then tested whether these correlates of integrated value could decomposed according to the contribution of the different information sources (Figure 3B). For this we examined the effects of the same explanatory variables as the behavioral model, but expressed in terms of accordance vs. discordance with the subject's choice. Sample accordance ($\mathbf{S_A}$) predicted central vmPFC activity ([2 38 -8], Z_{max} = 4.12, P < 001, 446 voxels (min 76). Sample discordance (a negative effect of S_A) increased dmPFC activity ([4 30 44], Z_{max} = 4.1, P < .001, 276 voxels (min 76)). Accordance of agents' choices ($\mathbf{O_A}$) similarly increased central vmPFC activity (peaks: [-2 22 -12] and [-10 44 -12], Z_{max} = 4.19, P < .001, 679 voxels (min 77)), while discordance of agents' choices (the negative effect of O_A) increased dmPFC activation ([-2 20 46], Z_{max} = 6.03, P<0.01, 797 voxels (min 77)). The conditional main effect of agent confidence (of accordant or discordant choices) did not produce activation in MFPC at this threshold.

As with behavior, the key question concerned activity corresponding to the differential impact of agents' choices when they are confident vs. unconfident, captured by the interaction ($\mathbf{O_A C_A}$). Such an interaction was observed for BOLD activity only in anterior mPFC (amPFC), primarily occupying ventromedial area 10, with a small extension through anterior 14m (Mackey and Petrides) (peaks [8 58 6] and [4 62 2]], Z_{max}= 3.78, 85 voxels (min 79). This was the only activation for this contrast in the brain. Within this region, unconfident agent choices did little to influence the representation of value, while confident choices had a clear effect (see Figure 5).

The Spatial Linear Parametric Effect

Next, in order to formally examine the impression of spatial separation between the effects of the different information sources, we statistically compared spatial profiles of key effects of Component Value fMRI Model analysis ($\mathbf{S_A}$, $\mathbf{O_A}$, $\mathbf{O_A C_A}$) along an anatomically defined axis from vmPFC to amPFC (Figure 4A). Only $\mathbf{O_A C_A}$ increased its effect (in percent signal change) along this axis (β = .03, SE = .01, P= 0.04). ($\mathbf{S_A}$ and $\mathbf{O_A}$ Ps > .27), and the difference of response between these variables also varied along the axis: $\mathbf{O_A C_A}$ - $\mathbf{S_A}$ (β = .03, SE = .01, P= 0.045) and $\mathbf{O_A C_A}$ - $\mathbf{O_A}$ (β = .03, SE = .02, P= 0.026). This rejected the null hypothesis that value-based activity relying on different information sources has a common spatial profile.

Peristimulus plots along this axis reveal that, moving anteriorly, regions of vmPFC respond with increasing selectivity for value derived from confident agents. Neither effects of agents' accordant choices (independent of confidence) nor of accordant samples shared this anatomical specificity. See Figures 4 and 5.

Individual Differences

<u>Neural Effects x Behavior:</u> We next tested whether component neural correlates predict component influence on decision-making behavior, using a between-subject analysis. At the group level, the effects of different information sources on choices, as estimated from behavior for each individual, were added as covariates to the *Component Value fMRI Model*. Contrasts were made between them. Within a mask of vmPFC and at a conservative cluster forming threshold (Z > 3), we found that weight placed on personal samples (S effect) predicted a greater neural response to personal sample accordance with choice (S_A) ([-6 54 -4], Z_{max} = 3.83, P = 0.03, 32 voxels (min 28). Dorsal and anterior to this, relatively more weight placed on the choices of agents (O effect – S effect) predicted a greater neural response to agents ($\mathbf{O_A}$) ([-4 60 10], Z_{max} = 4.02, P = 0.05, 28 voxels (min 28). See Figure 6.

<u>*Conformity and Self-Monitoring Scales:*</u> Finally, we sought to test to test whether neural effects during the experiment reflect real-world behavior. Conformity scale scores predicted greater dmPFC activation when going with one's own sample [0 26 38], Z_{max} = 5.02, P = 0.006, 50 voxels (min 25), and activation just anterior to rTPJ (supramarginal gyrus) in response to conflict with others choices [66 -28 26], Z_{max} = 4.38, P = 0.01, 40 voxels (min 25) (Figure 7B). Self-Monitoring, which reflects the tendency to alter behavior in in response to social cues from an audience, predicted a greater response to increasing accordance with agents in activity extending into rTPJ (peak [62 -28 36] Z_{max} = 4.45 with subpeak (Z = 4.08) [56 -36 28], P = 0.003, 120 voxels (min 74). This indicated differential treatment of social agreement with greater self-monitoring, even without a live audience (Figure 7C).

Discussion

This study identified distinct behavioral and neural effects of distinct types of evidence used for making predictions. Behaviorally, each information type influenced decisions in a sensible direction. Confident agents had a greater influence on choices of participants – the hypothesized signature of complex, integrative use of information to evaluate options.

Collectively, increased reward expectancy from all evidence was tracked indiscriminately across a posterior to anterior axis in vmPFC, confirming earlier findings (e.g. Daw et al., 2006; Kim et al., 2006; Behrens et al., 2008; Wunderlich et al., 2010). However, this signal could also be decomposed according to the contribution of distinct components. Increased reward expectancy due to accordant samples and accordant agents' choices (irrespective of confidence) increased activity across vmPFC. In contrast, value that varied with accordant agents' choices but conditional on their confidence was preferentially represented in ventromedial regions of area 10. This is a distinct neurobiological marker of assurance from another person's confidence.

Segregation of value representations over regions of systematically varying cytoarchitecture is consistent with heterogeneity of their computation. The anatomical locations of confidence-based value processes are likely the resolution of computational requirements and connectivity of supporting anatomy. The cytoarchitecture and connectivity of amPFC suggests that value estimates from confident agents specifically involve a form of higher-order cognition (Ongur et al., 2003; Mackey and Petrides, 2010; Sepulcre et al., 2010). While influences of agents in the task can be modelled (as in our regression) simply as the counting of agents' choices weighted by their confidence – the weighting itself is a signature of the variable's metacognitive treatment.

The nature of this treatment, and how it relates to anterior vmPFC is not yet known. One possibility is the use of inference. The Urn Task can be solved by using statistical inference to infer the contents of the urn given the observed evidence. This requires marginalizing agents' private samples, whose quality is inferred from an interaction of agents' choice and confidence. In principle, Bayes' rule can be invoked to infer (and then marginalize out) the probable state of the agents' samples. This could involve inferences of agents' knowledge from their behavior which would account for BA 10 involvement (Frith and Frith, 2012). Such computations are likely part of a broader class of inferential influences on choice (Tolman, 1948; Hampton et al., 2006, 2008; Daw et al., 2011; Solway and Botvinick, 2012). Additionally, BA 10 involvement could relate the confluence of cognitive processes (Ramnani and Owen, 2004; Zaki, 2013), such as the integration of observed and non-observable information (Burgess et al., 2007).

Both inferential and integrative processes are useful because they flexibly allow a naïve observer to make decisions in new environments. In social contexts, they allow for adaptable valuation using shifting combinations of inferred knowledge, intentions, impulsivity, and optimism of others before deciding how to use their choices to inform one's own. From this perspective, our findings support a theory that the evolution of area 10 could relate to cognitive specialization that optimizes decision-making in human cultures with the complexity of human expression (Povinelli and Preuss, 1995; Dunbar and Shultz, 2007).

It less likely that differences between neural correlates of value relate to a difference of mathematic heuristics: these regions do not come up in fMRI contrasts of counting methods, addition or multiplication (Piazza et al., 2002; Kawashima et al., 2004). Similarly, while previous studies have examined associative learning in social contexts (Behrens et al., 2008; Hampton et al., 2008; Burke et al., 2010), associative learning was precluded in the present study by the omission of trial outcomes and infrequent repetition of agents.

Previously, however, neuroscience has highlighted the relationship between mPFC and associative learning about the reliability of others. For example, Behrens et al (2008) showed that mPFC is recruited to update beliefs about the accuracy of advice. Meshi et al (2012) and Boorman et al (2013) found that mPFC is related to using and evaluating the another's expertise. It will be interesting to explore how inferential and associative learning about the reliability of others relate.

Nicolle et al (2012) found that ventral-dorsal vmPFC axis delineates action-relevant from action-irrelevant preferences. Subsequent work has shown that individual differences of value representation along a (ventral-dorsal) vmPFC axis also distinguishes self- and other-regarding individuals (Sul et al., 2015). In the present study, we found that ventral area 10 does represent action-relevant preferences, but depending on the computations required. It may be the abstract nature of the calculation (counterfactual choice in the previous study, abstractly inferred or integrated information in the present) that determines amPFC involvement. Indeed, specificity across the posterior to anterior vmPFC axis, may relate to similar anatomical distinctions between primary and secondary rewards (McNamee et al., 2013; Sescousse et al., 2013; Clithero and Rangel, 2014; Li et al., 2015).

dmPFC activity was negatively correlated with estimated value from various sources of information. As in most decision tasks, the value of the action and uncertainty/conflict associated with that value are inversely correlated, though not perfectly coupled. This is because, for instance, it is more difficult to choose the correct option for choices with conflicting information. Given the literature on correlates of different decision variables in midline prefrontal cortex, the activity we observed in anterior cingulate may reflect a form of conflict (Botvinick et al., 2004) or a cost-benefit process that accounts for both conflict and reduced likelihood of reward (Rushworth et al., 2011).

If a participant was more likely to be influenced by the personal sample, BOLD activity in central vmPFC varied more with the accordance of the sample with their imminent choice. Similarly, if a participant was more likely to be influenced by the choices of agents (relative to the personal sample) BOLD activity in amPFC varied more with accordance of agents' choices with their imminent choice. This suggests that the tendency to be influenced by an information source can be tracked, to an extent, by the sensitivity of that individual to supporting information from that source, within specific mPFC anatomy.

Social behavior outside the lab (i.e. conformity) was inversely correlated with the influence of private evidence during the task. In vmPFC, conformity and self-monitoring in other contexts did predict activations. However, exploration outside of this region revealed a link between neural responses to task influences, and the tendency to be socially influenced in other contexts. The tendency to adopt the decisions of others outside the lab predicted increased supramarginal gyrus responses to conflict with agents, just anterior to rTPJ (Figure 7B). It also predicted increased dmPFC activity when going with one's own sample. These results replicate findings that the tendency to conform socially can be predicted by the neural response to social conflict in these regions (Campbell-Meiklejohn et al., 2010; for meta-analysis see Wu et al., 2016). Activity within rTPJ that correlates with reward expectancy from observing agent choices (Figure 7C), in high-self-monitors may relate to findings that reward expectancies from observing choices of others can recruit theory-of-mind-like processes (Bruguier et al., 2010; De Martino et al., 2013). This occurs in the absence of a live audience, suggesting that self-monitoring relates to cognitive processes that are somewhat independent of an action's immediate social consequences. Stimulation of the rTPJ region enhances the tendency to take another's perspective (Santiesteban et al., 2012) and its activity has been previously shown to increase when determining the relevance of someone else's behavior for one's decision-making (Carter et al., 2012). Although social interactions in the task were simulated and stylized, their relevance to real-world social settings is supported by these findings.

While results are relevant to real social contexts, we do not suggest that the highlighted processes are exclusive to the social domain. Indeed, the task's logic is based on comparing inferences from different sorts of information rather than social and non-social frames. This reflects the case for the coevolution of general cognitive faculties and social ability (Humphrey, 1976; Emery et al., 2007). Correspondingly, research has shown that the physiology of value representations in 'social' and 'non-social' contexts are similar, when similar processes are employed and similar models applied (Izuma et al., 2008; Zink et al., 2008; Takahashi et al., 2009; Campbell-Meiklejohn et al., 2010; Tricomi et al., 2010; Biele et al., 2011; Lin et al., 2011; Bartra et al., 2013; Boorman et al., 2013). The present results suggest that any differences between social and non-social valuation processes in vmPFC may be proportional to differential use of higher-order computation, and in future this may prove to be the most flexible definition of a 'social' reward.

Conclusions

The finding that decision-related signals in vmPFC are segmented by the unique cognitive requisites of their computation is an important step in our understanding of the representation of value in the brain. Concurrently, our findings provide new neurobiological insight into the transmission of value information between individuals and the mechanism by which confidence expressed by others assure or discourage us in our decisions. Looking to the future, the findings present new questions as to how distinct valuation processes with separate neural mechanisms can be independently altered by experience, damage, and treatment.

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Figure Legends

Figure 1. Urn Task. On each trial: (i) A new urn of randomly mixed marbles is presented. Contents are hidden. (ii) Animation of five hands individually reaching for five different samples from the urn occurs (parts i and ii last 1.5 to 2s). (iii) Predictions of the *next* marble drawn from the urn, and their associated confidence in those predictions of four agents shown. Agents were represented as sepia toned faces with neutral expression. Agents' predictions were expressed by the colour of the circle positioned next to their face. Confidence indicated as the expression within that circle and the speed at which the answer was shown (rapid + smug = high confidence). Agents' answers took between 300 and 2500ms to appear. Once agents' choices were in, they remained on the screen for 1250s. (iv) Next, the participant's own sample of marbles appeared from the bottom of the screen was displayed with all other information for a further 1250ms. The sample contained 8 marbles, with one to seven of them being red. This was the event modelled in the fMRI analysis. (v) Finally, the participant is asked to make a prediction (red or green). No choice feedback was provided.

Figure 2. Behavioural Effects. Probability (mean proportion) of choices for red as a function of: reds in sample, frequency and confidence of red choices by agents, and frequency and confidence of green choices by agents. Error bars are standard error.

Figure 3. Neural Representation of Value in vmPFC. Activations colour-coded with respect to amount of evidence supporting the likelihood of the participant's choice being correct (Clusters Defined by Z > 3.0, Cluster Sig P< 0.05) **A:** neural representation of value from the *Integrated Value fMRI Model* combining all available information. **B**: Distribution and overlap of activity correlating with increasing value computed from information sources of the *Component Value fMRI Model*. **C**:

Distribution and overlap of activity correlating with increasing value computed from information sources of the *Component Value fMRI Model*.

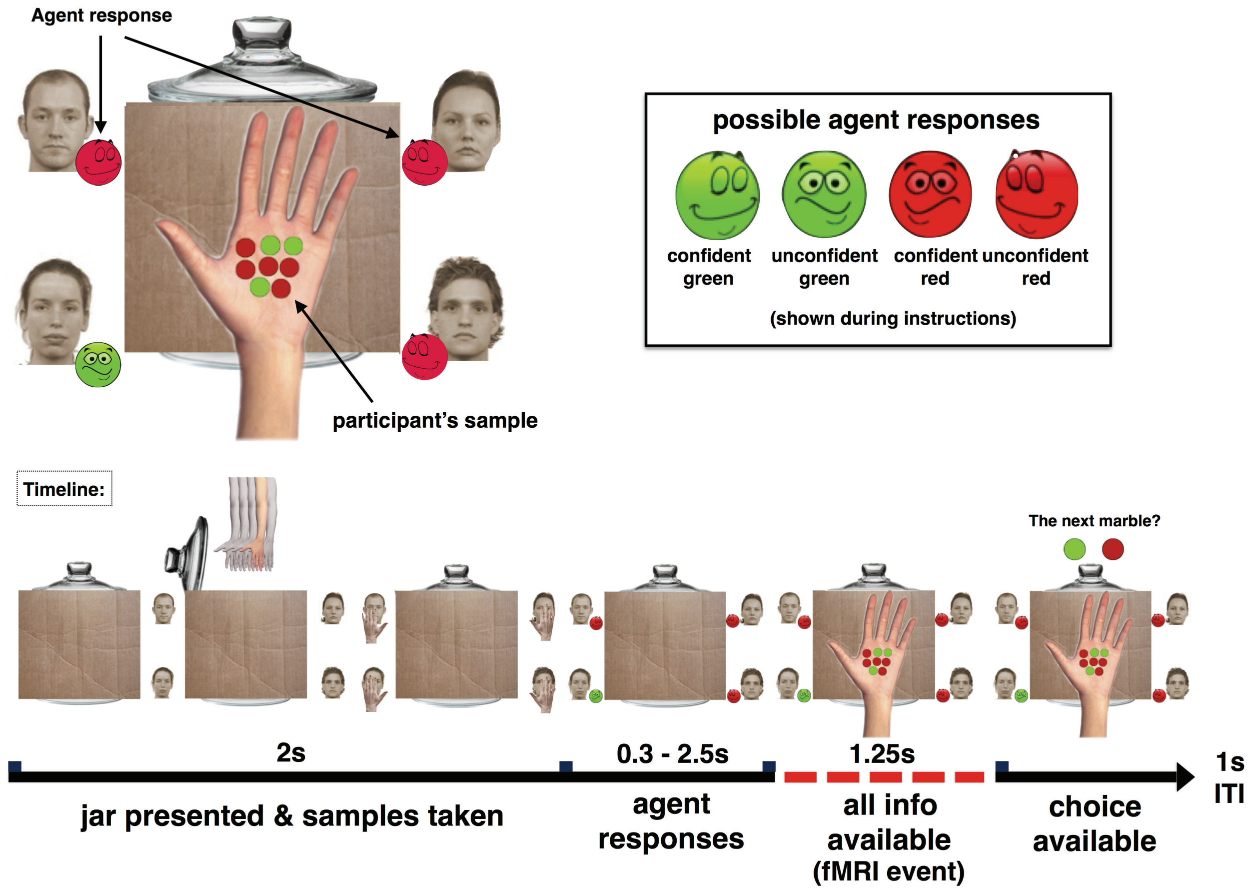
Figure 4. Effect Time-Courses Across vmPFC. A. Anatomically defined spherical regions of interest spanning the superior medial gyrus from area 14m (Mackey and Petrides, 2010) to ventromedial area 10. **B.** Plots of mean effects of interest within the *Component Value fMRI Model* across 5 Time bins are 2.8s (1 TR) beginning at the onset of agents' responses. Figure shows relative non-specificity of S_A and O_A across the region, the increasing specificity of O_AC_A toward dorsoanterior regions, and the sustained response to agents' choices O_A into the response window of S_A. Error bars are standard error.

Figure 5. Effects of Confident and Unconfident Agents across vmPFC. Mean effect of an adapted *Component Value fMRI Model* that separates effects of confident agents' choices from unconfident agents' choices across the 5 spheres and time bins of Figure 4. Figure shows the increasing specificity of socially-learned value that is contingent on agents' confidence toward dorsoanterior regions of vmPFC. Error bars are standard error.

Figure 6. Individual Differences of Task Behavior: Effects of information sources on choices, for each individual, were added as covariates to the *Component Value fMRI Model* analysis. vmPFC responses to S_A are predicted by the influence of samples on choice behavior. amPFC responses to O_A are predicted by the relative influence of agents (O effect – S effect) on choice behavior.

Figure 7. Social Influence in Other Situations. A. Scatterplot showing relationship between the use of one's own sample during the Urn Task (arbitrary units) and self-reported reliance on agents outside the lab. **B** Between-subjects those more likely to

conform in other social situations respond more to conflict with agents and less conflict with personal samples within regions previously shown predict conformity from social conflict responses (Campbell-Meiklejohn et al., 2010). **C**. Between subjects, rTPJ responds more to accordance of agents' choices in proportion to tendency to adapt behaviour to social cues in real-world situations (self-monitoring).


Agent response
participant's sample
possible agent responses
confident green
unconfident green
confident red
unconfident red
(shown during instructions)
Timeline:
The next marble?
2s
0.3 - 2.5s
1.25s
1s ITI
jar presented & samples taken
agent responses
all info available (fMRI event)
choice available

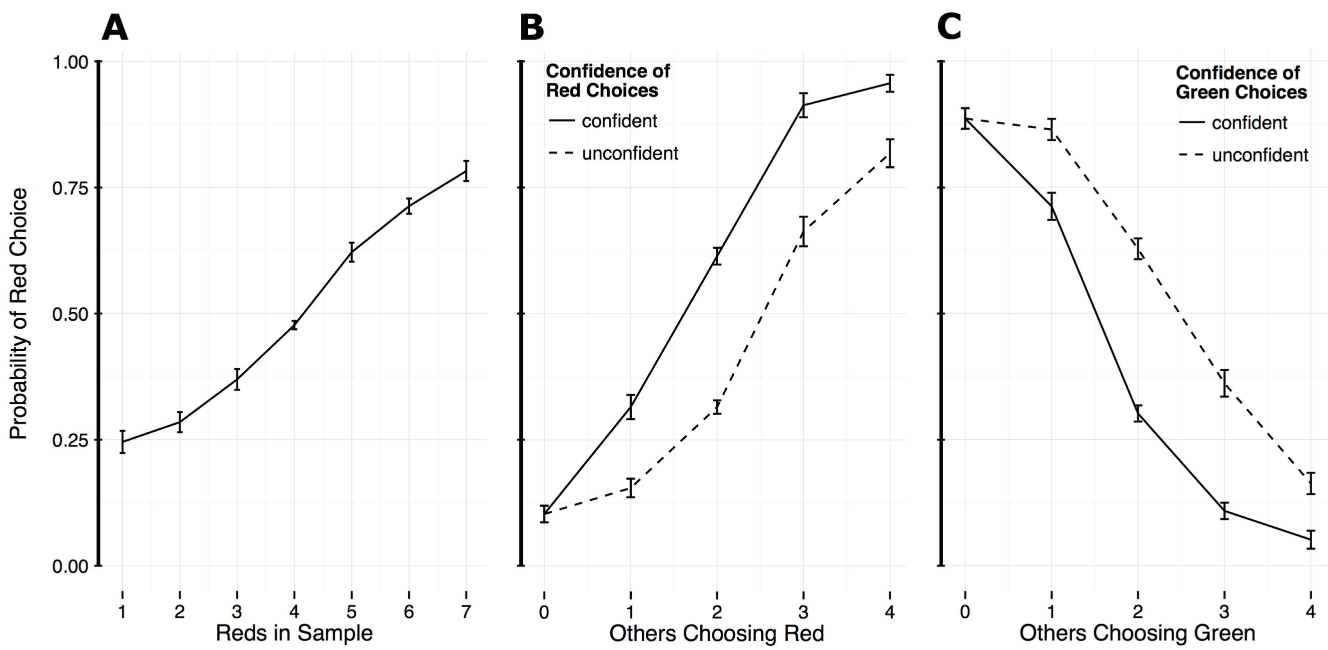
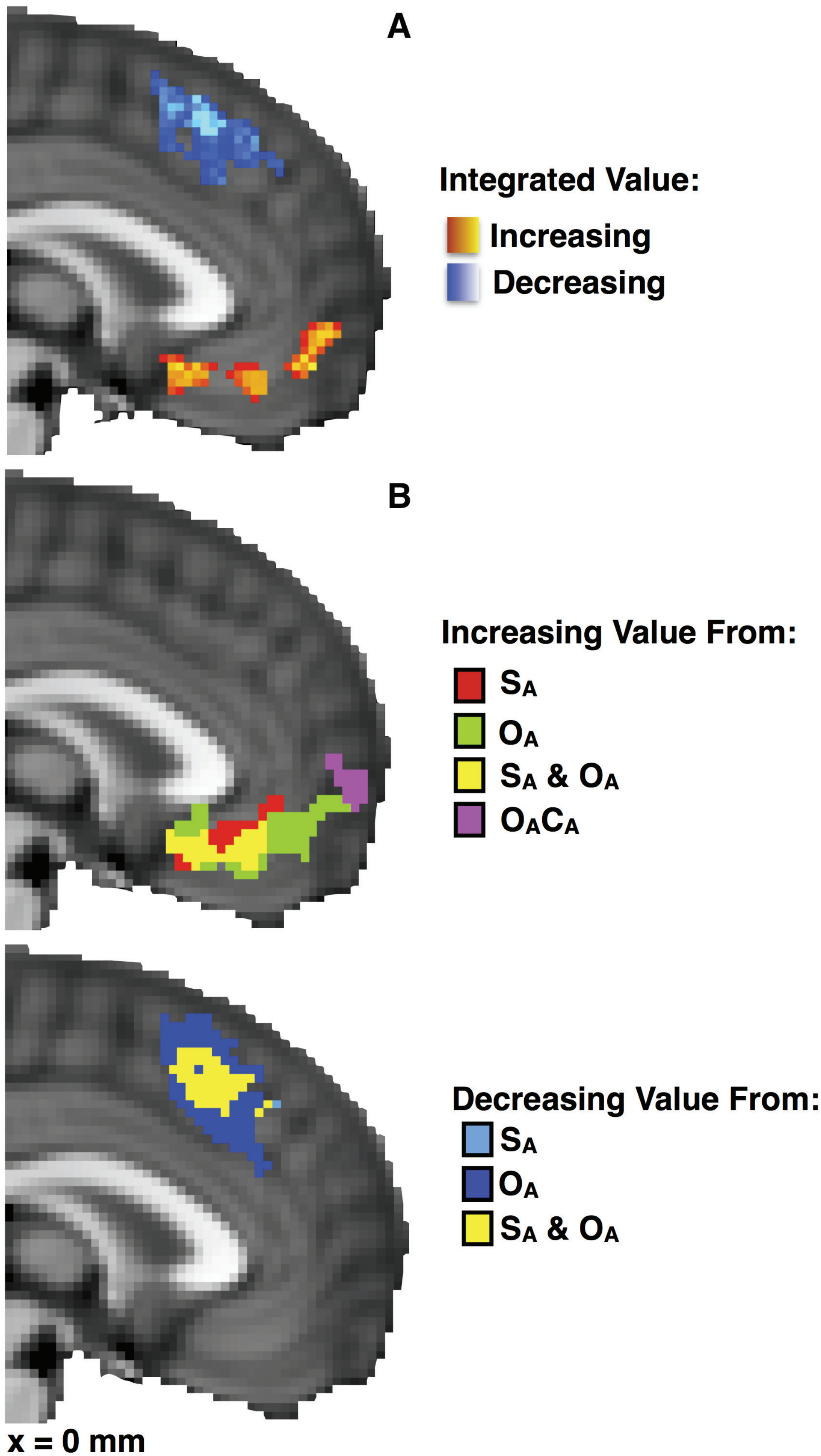

A
B
C
1.00
0.75
0.50
0.25
0.00
Probability of Red Choice
1 2 3 4 5 6 7
Reds in Sample
Confidence of
Red Choices
confident
unconfident
0 1 2 3 4
Others Choosing Red
Confidence of
Green Choices
confident
unconfident
0 1 2 3 4
Others Choosing Green

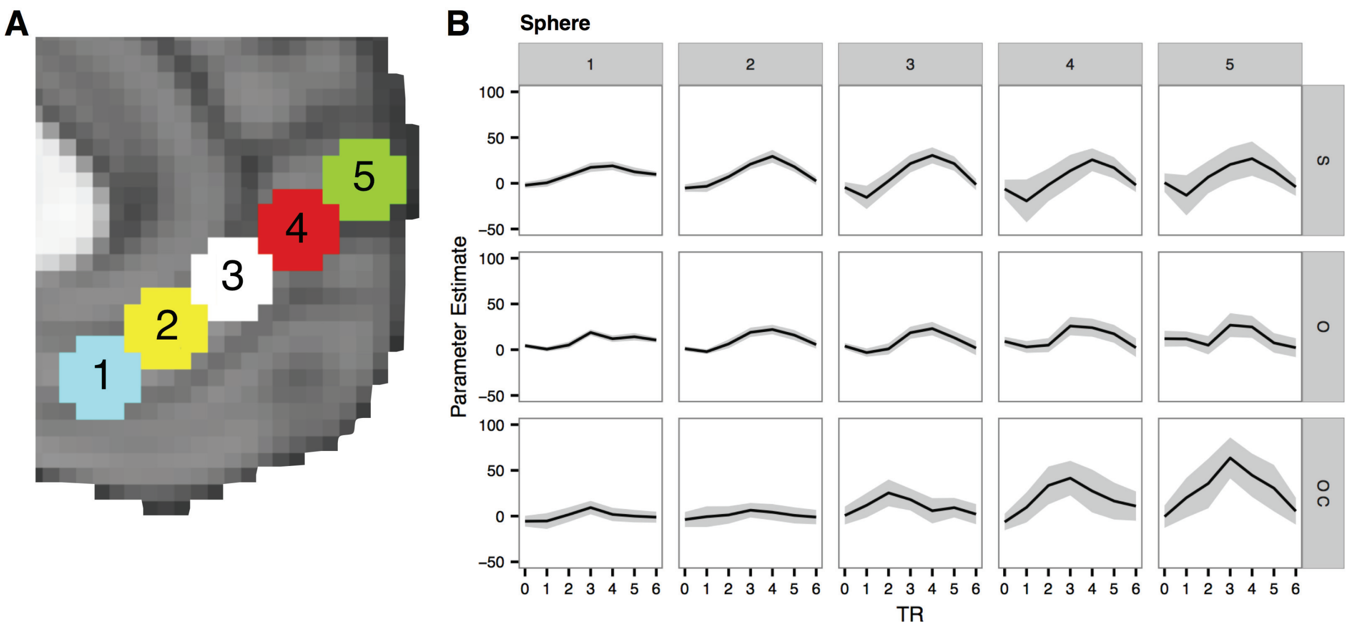
Table 1. Fixed Effects from Mixed Effects Logistic Regression of Each Variable's Effect on Choice of Red

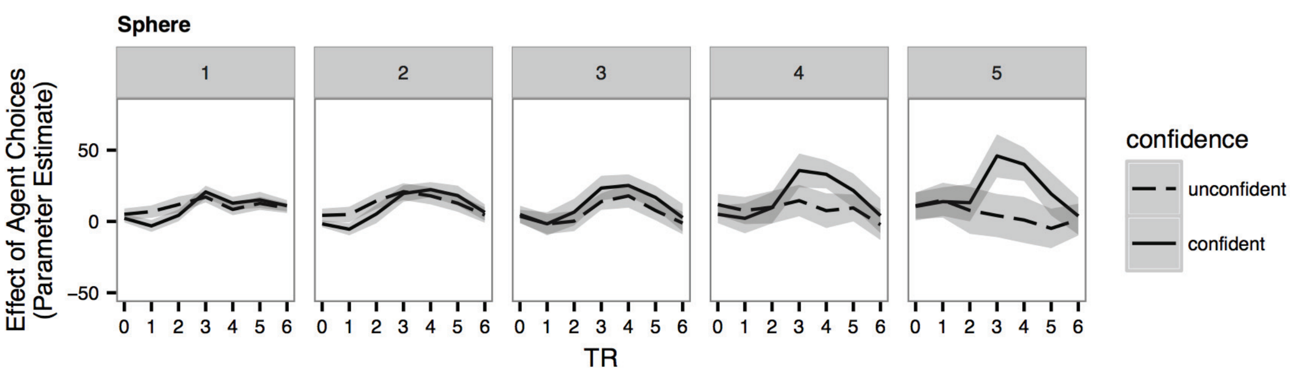
Variable	β	SE	P	Partial R2	Δ AIC
(Intercept)	-0.03	0.07	0.62		
Proportion of Sample That is Red (S)	10.26	0.87	<0.001	0.38	1160
Proportion of Agents Choosing Red (O)	9.96	0.75	<0.001	0.55	2297
Confidence of Agents Choosing Red (C_R)	2.57	0.30	<0.001	0.15	321
Confidence of Agents Choosing Green (C_G)	-2.61	0.30	<0.001	0.15	332
Proportion of Agents Choosing Red x Confidence (O_RC_R)	1.78	0.53	<0.001	0.01	8.2
Proportion of Agents Choosing Green x Confidence (O_GC_G)	-1.40	0.53	0.01	0.01	0.4

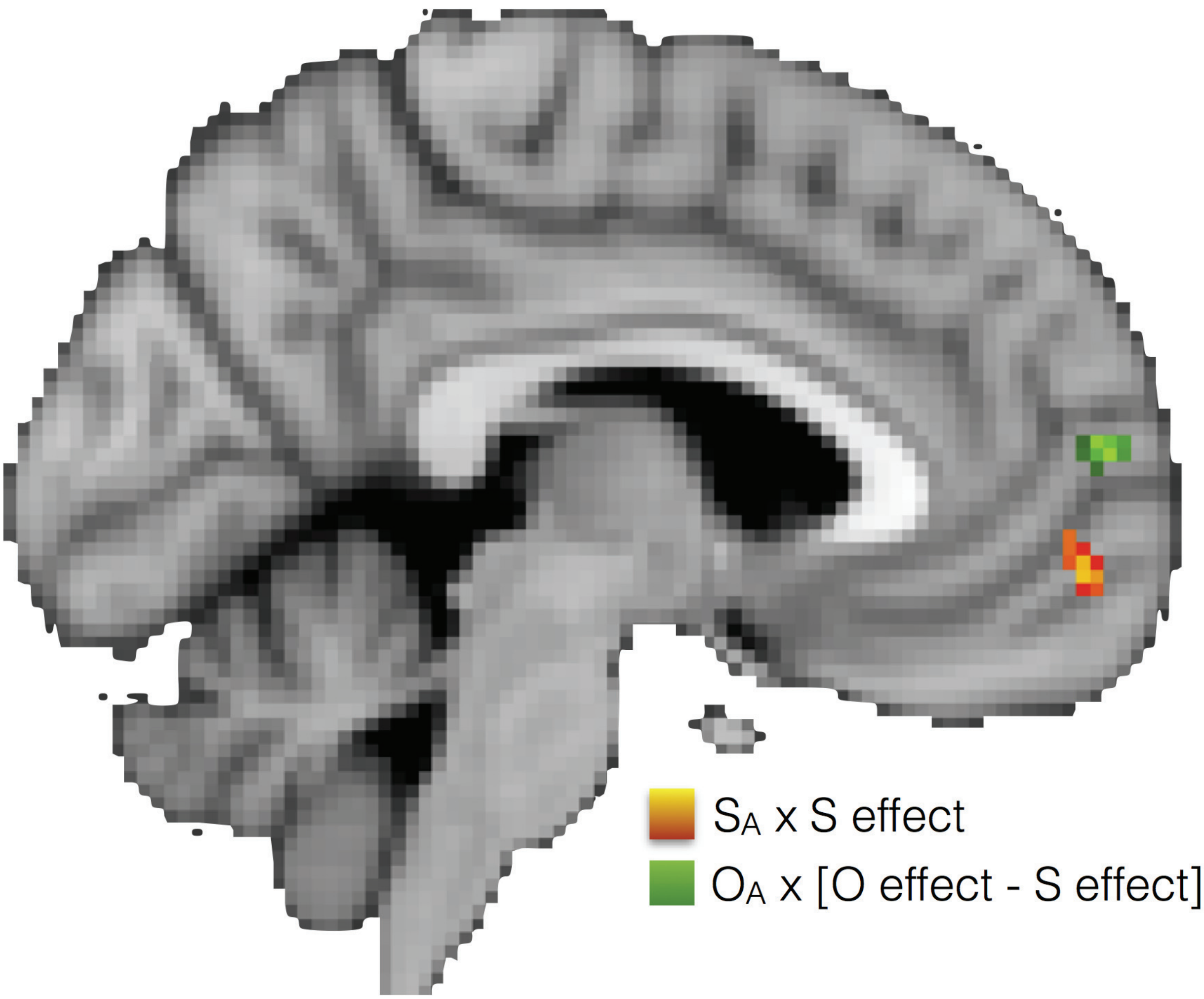
R^2 of full model is .68 (McFadden's Pseudo R^2)

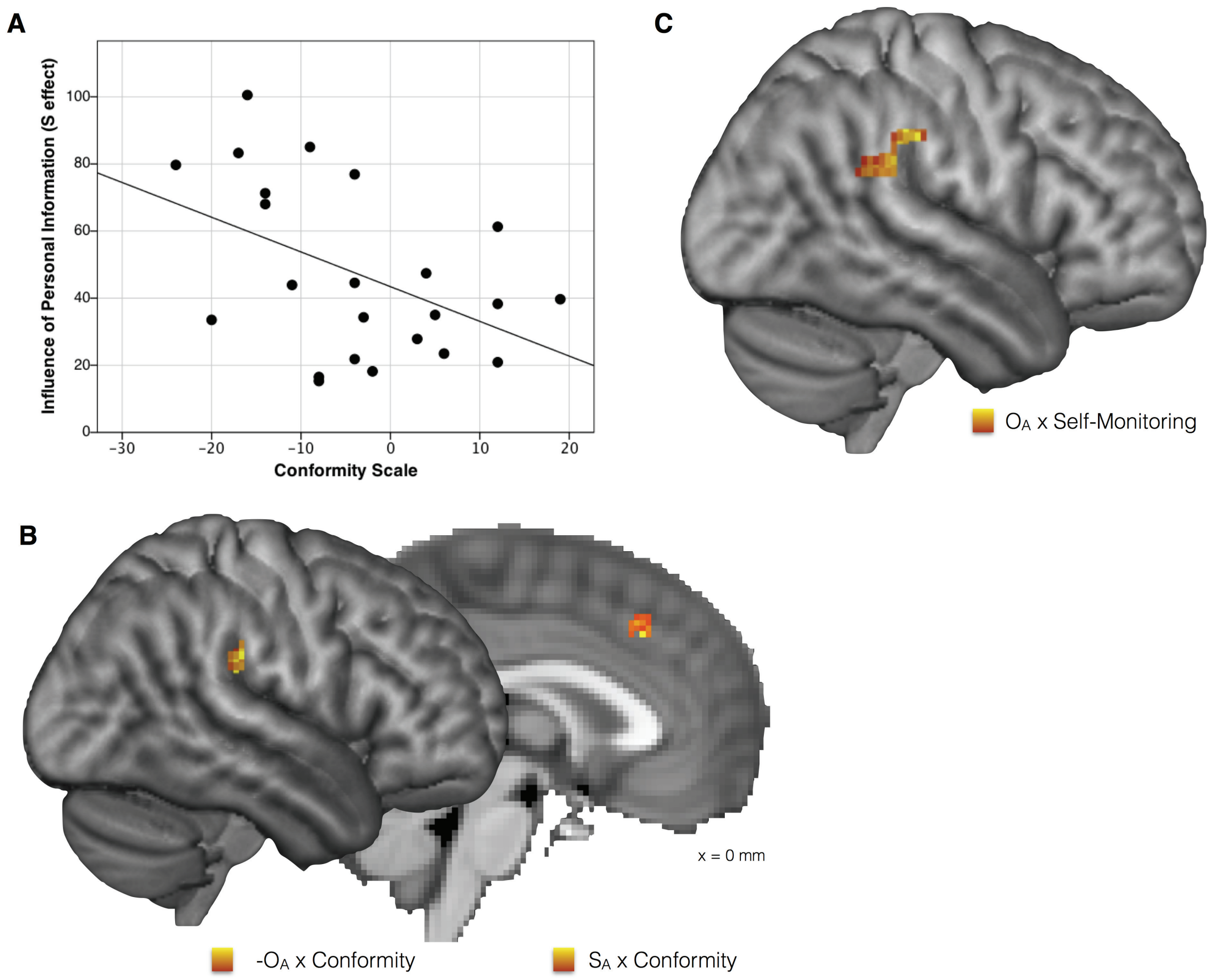
Partial R^2 calculated as 1 - (log likelihood of full model / log likelihood of model without designated predictor). Corresponding change in AIC value also provided.


A
Integrated Value:
Increasing
Decreasing
B
Increasing Value From:
S_A
O_A
S_A & O_A
O_AC_A
Decreasing Value From:
S_A
O_A
S_A & O_A
x = 0 mm


A
1
2
3
4
5
B
Sphere
1
2
3
4
5
S
O
OC
Parameter Estimate
100
50
0
−50
TR
0 1 2 3 4 5 6


Sphere
1
2
3
4
5
Effect of Agent Choices (Parameter Estimate)
50
0
-50
0 1 2 3 4 5 6
TR
confidence
unconfident
confident


S_A x S effect
O_A x [O effect - S effect]


A
Influence of Personal Information (S effect)
0
20
40
60
80
100
−30
−20
−10
0
10
20
Conformity Scale
C
OA x Self-Monitoring
B
x = 0 mm
-OA x Conformity
SA x Conformity