Neural Correlates Of Decision-Making During A Bayesian Choice Task

By: Govinda R. Poudel, Anjan Bhattarai, **David L. Dickinson**, and Sean P.A. Drummond

Abstract

Many critical decisions require evaluation of accumulated previous information and/or newly acquired evidence. Although neural correlates of belief updating have been investigated, how these neural processes guide decisions involving Bayesian choice is less clear. Here, we used functional MRI to investigate neural activity during a Bayesian choice task involving two sources of information: base rate odds ('odds') and sample evidence ('evidence'). Thirty-seven healthy control individuals performed the Bayesian choice task in which they had to make probability judgements. Average functional MRI activity during the trials where choice was consistent with use of Odds, use of Evidence, and use of Both was compared. Decision-making consistent with odds, evidence and both each strongly activated the bilateral executive network encompassing the bilateral frontal, cingulate, posterior parietal and occipital cortices. The Evidence consistent, compared with Odds consistent, decisions showed greater activity in the bilateral middle and inferior frontal and right lateral occipital cortices. Decisions consistent with the use of Both strategies were associated with increased activity in the bilateral middle frontal and superior frontal cortices. These findings support the conclusion that both overlapping and distinct brain regions within the frontoparietal network underlie the incorporation of different types of information into a Bayesian decision.

Poudel, Govinda R.; Bhattarai, Anjan; **Dickinson, David L.**; Drummond, Sean P.A. Neural correlates of decision-making during a Bayesian choice task, NeuroReport: March 1, 2017 - Volume 28 - Issue 4 - p 193-199 doi: 10.1097/WNR.0000000000000730. Publisher version of record available at: https://journals.lww.com/neuroreport/Abstract/2017/03020/Neural_correlates_of_decision_making_during_a.3.aspx

Neural correlates of decision-making during a Bayesian choice task

Govinda R. Poudel[a,b], Anjan Bhattarai[a], David L. Dickinson[b,c,e] and Sean P.A. Drummond[a,d]

Many critical decisions require evaluation of accumulated previous information and/or newly acquired evidence. Although neural correlates of belief updating have been investigated, how these neural processes guide decisions involving Bayesian choice is less clear. Here, we used functional MRI to investigate neural activity during a Bayesian choice task involving two sources of information: base rate odds ('odds') and sample evidence ('evidence'). Thirty-seven healthy control individuals performed the Bayesian choice task in which they had to make probability judgements. Average functional MRI activity during the trials where choice was consistent with use of Odds, use of Evidence, and use of Both was compared. Decision-making consistent with odds, evidence and both each strongly activated the bilateral executive network encompassing the bilateral frontal, cingulate, posterior parietal and occipital cortices. The Evidence consistent, compared with Odds consistent, decisions showed greater activity in the bilateral middle and inferior frontal and right lateral occipital cortices. Decisions consistent with the use of Both strategies were associated with increased activity in the bilateral middle frontal and superior frontal cortices. These findings support the conclusion that both overlapping and distinct brain regions within the frontoparietal network underlie the incorporation of different types of information into a Bayesian decision. *NeuroReport* **28:193–199**

NeuroReport 2017, **28:**193–199

Keywords: Bayesian decision-making, decision-making, decision neuroscience, functional MRI, neuroimaging of decision-making

[a]School of Psychological Sciences, Monash Institute of Cognitive and Clinical Neurosciences, Monash University, Melbourne, Victoria, Australia, [b]Department of Economics and the CERPA (Center for Economic Research and Policy Analysis), Appalachian State University, Boone, North Carolina, [c]ESI (Economic Science Institute), Chapman University, Orange, [d]Department of Psychiatry, University of California San Diego, La Jolla, California, USA and [e]IZA (Institute for the Study of Labor), Bonn, Germany

Correspondence to Govinda R. Poudel, PhD, School of Psychological Sciences, Monash University, Clayton 3800, Victoria, Australia
Tel: +61 03 99024351; fax: +61 3 99053948;
e-mail: govinda.poudel@monash.edu

Received 10 November 2016 **accepted** 9 December 2016

Introduction

Everyday decisions range from simple perceptual selections (e.g. which shirt to wear) to complex social and financial decisions with potentially far-reaching consequences (e.g. mate selection or retirement account investment). Decision-making with unambiguous choices largely relies on cortical and subcortical networks involved in evaluating external sensory information and internal information such as preferences, beliefs and motivations [1–3]. However, in reality, complex decisions involving uncertainty often require probabilistic evaluations using both previous information (e.g. base rate odds) and newly acquired evidence in formulating decisions (referred to as Bayesian updating) [4–9]. An investigation of the neural basis of Bayesian updating is therefore fundamental for understanding decision-making in probabilistic environments.

Decision-making recruits cortical and subcortical regions involved in executive control, rewards and motivation, and emotions depending on the task and the context [10]. Decision-making under uncertainty, in particular, recruits executive processes required for the evaluation of uncertain selections, which is supported by the dorsolateral prefrontal cortex (DLPFC) and the posterior parietal cortex (PPC) [8,11]. Decisions requiring belief updating recruit prefrontal, PPC and anterior cingulate cortices, which interact with each other, providing continuous updates on new and accumulated information [12–14]. Although these studies provide a comprehensive map of brain structures involved in the decision-making process, how these brain structures support decision-making process during a probabilistic Bayesian choice task remains unclear.

Here, we used functional MRI (fMRI) to examine brain regions underpinning decision-making during a Bayesian choice task. We report neural activity during decisions when participants placed weight on either or both of the two information sources presented: the base rate (Odds) and the sample draw (Evidence). We investigated whether the patterns of neural activity during decision-making using these two types of information are distinct or similar.

Patients and methods

Participants

Forty-two healthy and young participants were enrolled in the study. The participants had an average education

0959-4965 DOI: 10.1097/WNR.0000000000000730

level of 15.7 ± 2.2 (range: 12–20) years and numeracy measure of 9.3 ± 1.8 (range: 4–11). Numeracy was defined as the ability to process basic probability and numerical concepts. An minimum education of 12 years was used to screen the participants. Five participants were excluded because of excessive movement in the fMRI data and 37 participants (20 female; age = 24.5 ± 4.7 years) were included in the present analysis. The study was approved by the UCSD human research ethics committee and participants provided written informed consent.

The Bayesian choice decision-making task

The Bayesian choice task used has been described previously [9]. Participants were presented with an image containing: (a) two boxes filled with black and white balls; (b) the odds each box would be used to randomly draw, with replacement, five balls; and (c) the result of the draw (Fig. 1). Their task was to indicate the box from which the balls were drawn. The left box always contained two black/one white ball and the right box always contained two white/one black ball. Thus, participants had two sources of information, base rate probabilities (odds) and sample evidence (evidence), that they could use to perform an assessment of the box utilized.

In each trial, participants had 6 s to make a choice on the box used for the draws, and then a new stimulus would appear. Stimuli differed by base rate odds and sample evidence. The odds for each box varied from 0/6 to 6/6 across trials and the evidence could contain any combination of black and white balls. Each participant saw a total of 48 trials; 16 of these checked comprehension by using odds of 0/6 for one of the boxes. The remaining 32 stimuli were divided into 16 'Easy' and 16 'Hard' trials. Easy trials were defined as those where the posterior probability of the more likely box, which can be calculated by Bayes' rule, was 80–90%. Hard trails had Bayesian odds of the more likely box of 50–71%. Participants were not provided feedback on the accuracy of any trial until the end of the experiment, when one trial was randomly picked and participants earned $12 if they made a Bayesian accurate choice on that trial (vs. $2 if inaccurate).

MRI acquisition

Brain images were acquired using a GE Signa EXCITE 3T whole-body scanner. BOLD EPI covering the entire brain (TR = 2000 ms, TE = 30 ms, FA = 90°, FOV = 192 mm, matrix size 64 × 64, 44 transaxial slices, slice thickness 3 mm, 240 representatives) and a T1-weighted three-dimensional FSPGR sequence (TR = 1680 ms, TE = 2.13 ms, FA = 9°, matrix size = 240 × 240, voxel size = 0.9 × 0.9 × 0.9, 256 slices) were acquired. Image acquisition was interleaved.

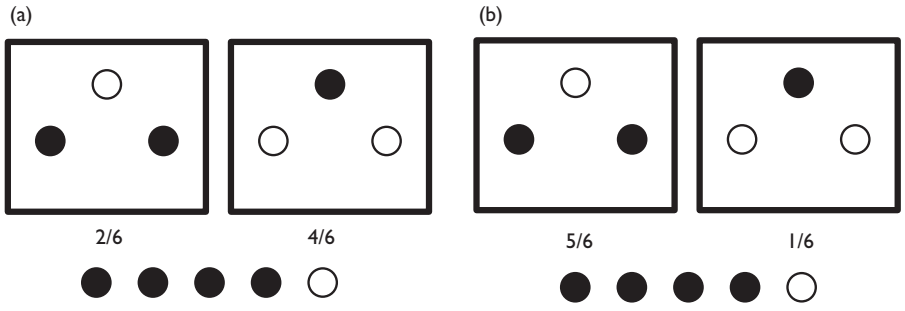
MRI preprocessing

fMRI data were analysed using FSL (*https://www.fmrib.ox.ac.uk/fsl*, version 5.0.7) in the multi-modal Australian Sciences Imaging and Visualisation Environment [15]. The neck was manually cropped before structural brain images were processed (BET 2). Functional images were spatially realigned to the structural image (linear full search, 6 *d.f.*), slice-time corrected and normalized to the standard space of the Montreal Neurological Institute brain (nonlinear full search, 12 *d.f.*). McFlirt motion correction and spatial smoothing was performed with an isotropic three-dimensional Gaussian filter with full width at half maximum is equal to 6 mm. A high-pass filter was implemented using a cutoff period of 128 s to remove low-frequency drift from the time series.

Statistical analysis of functional MRI data

Trials were divided into nine types for analysis. Trails were segregated by stimulus type: Baseline (i.e. odds of 0/6 and 6/6 for the boxes), Easy or Hard and by the participant's response. For the latter, nonbaseline trial responses were identified as being consistent with the Odds only (box selected was the one with greater odds), Evidence only (if there were more black balls in the

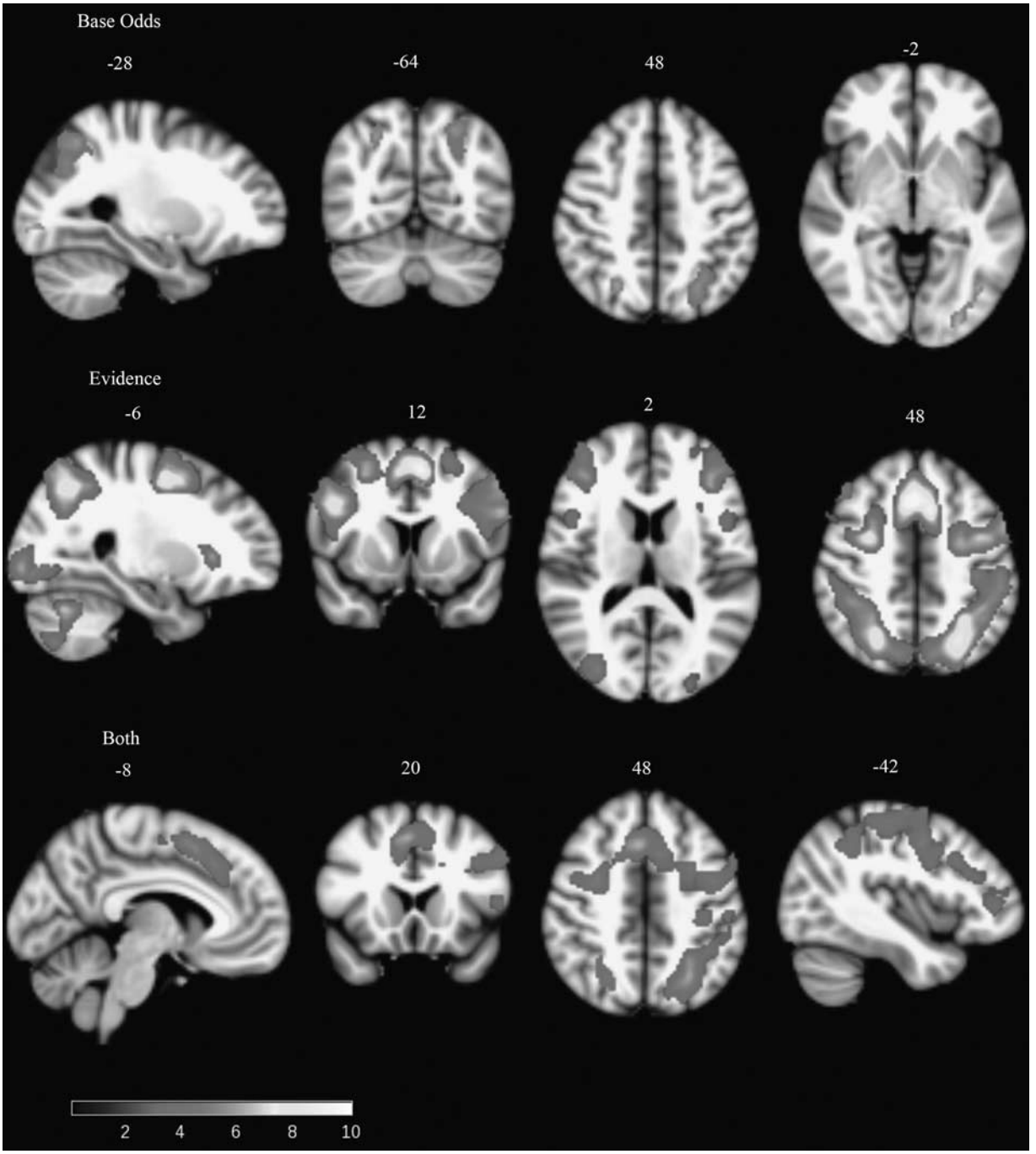
Fig. 1



Two examples of the Bayes' choice task. Participants indicated from which box they thought balls were drawn. Participants are shown the contents of each box, fractions below each box indicate base rate odds for that box being used for the draw and the set of coloured balls (the evidence) is the result of drawing five balls with replacement from the selected box. There is no feedback on accuracy between trials. (a) Is an example of an Easy choice; (b) is an example of a Hard choice.

evidence and the box with more black balls was selected, or similar for white balls), Both (response consistent with both odds and evidence) or Neither. For each participant, preprocessed fMRI data were analysed using first-level general linear models. The linear models included separate regressors for each of the nine trials (Baseline, Odds Easy, Odds Hard, Evidence Easy, Evidence Hard, Neither Easy, Neither Hard, Both Easy, Both Hard) and standard motion parameters (six regressors). Regressors were convolved with a double-gamma haemodynamic response function before estimation of the first-level model. Contrast parameter estimates measuring the

Fig. 2



Spatial maps of activation during Odds, Evidence, Both trials in a Bayesian choice task.'Both' trials are where responses are consistent with both the odds and the evidence. Activation maps are overlaid on a standard MNI template and shown in radiological orientation. The greyscale bar represents *Z*-values. MNI, Montreal Neurological Institute.

Table 1 Brain regions showing significantly increased activity during odds, evidence, and both trials compared with baseline trials

Brain regions	Volume (mm^3)	*t*-statistic	*x*	*y*	*z*
Odds trials vs. Baseline					
L. superior lateral occipital cortex	552	5.64	−30	−60	50
L. superior parietal lobule	–	5.04	−30	−54	44
R. superior lateral occipital cortex	70	5.97	26	−64	44
L. inferior lateral occipital cortex	47	6.55	−28	−92	−4
R. frontal Pole	29	5.6	46	42	28
L. inferior lateral occipital cortex	23	6.13	−40	−68	−4
Evidence trials vs. Baseline					
R. insular cortex	39 979	11.9	32	26	0
R. paracingulate gyrus	–	11.6	4	20	48
L. paracingulate gyrus	–	10.7	−6	12	50
L. supplementary motor area	–	10.6	−4	6	56
L. middle frontal gyrus	–	10.6	−30	−4	54
Both trials vs. Baseline					
R. precentral gyrus	9917	6.4	46	4	28
L. superior lateral occipital cortex	–	6.4	−28	−62	48
R. paracingulate gyrus	–	6.33	4	20	46
L. superior parietal lobule	–	6.07	−26	−54	42
R. superior lateral occipital cortex	273	4.56	24	−64	44
R. supramarginal gyrus	–	4.3	24	−68	34
L. inferior frontal gyrus	42	3.62	−52	18	8

Coordinates for local maxima within the significant clusters are reported in MNI. Brain regions were identified using the Hard–Oxford atlas.
L., left; MNI, Montreal Neurological Institute; R., right.

level of BOLD fMRI activity during each trial type were estimated for each participant and used in a group-level analysis (except neither as there were too few).

A 3 × 2 analysis of variance (Odds, Evidence, Both × Easy, Hard) analysis showed no significant effect of task difficulty. Hence, difficulty level was excluded from further analysis of imaging data. We ran six sets of whole-brain a-priori comparisons using paired *t*-tests for trial comparisons: Evidence versus Baseline, Odds versus Baseline, Both versus Baseline, Odds versus Evidence, Odds versus Both and Evidence versus Both. Group-level statistical significance was tested using a nonparametric permutation method implemented using the randomise tool available in FSL (5000 permutations) and thresholded at *P*-value less than 0.05, family-wise error correction for multiple comparison using threshold-free cluster enhancement. Parameter estimates from significant regions were extracted for visualization purposes. Harvard–Oxford cortical and subcortical atlas was used to label the brain regions showing significant activations.

Results

Task-related activity compared with baseline

The brain regions showing task-related activity during the three trial types compared with Baseline trials are shown in Fig. 2 and Table 1. Odds trials were associated with significant clusters of activity in the bilateral PPC and lateral occipital cortices and the frontal pole. Evidence trials activated a large cluster encompassing the brain regions bilaterally in the superior parietal lobule, middle frontal gyrus, anterior cingulate/paracingulate gyus and insula, as well as clusters in the brain-stem and cerebellar areas. During Both trials, significant activity was observed bilaterally in the precentral, PPC and anterior cingulate cortices and in left DLPFC.

Comparison between evidence and odds based decision-making

Comparison of Evidence trials with Odds trials showed significantly increased activity in the right DLPFC, bilateral precentral and right lateral occipital cortex for Evidence trails (Fig. 3 and Table 2). There was no significantly greater activity during 'Odds' compared with 'Evidence'.

Comparison between 'both' and 'odds' and 'evidence' based decision-making

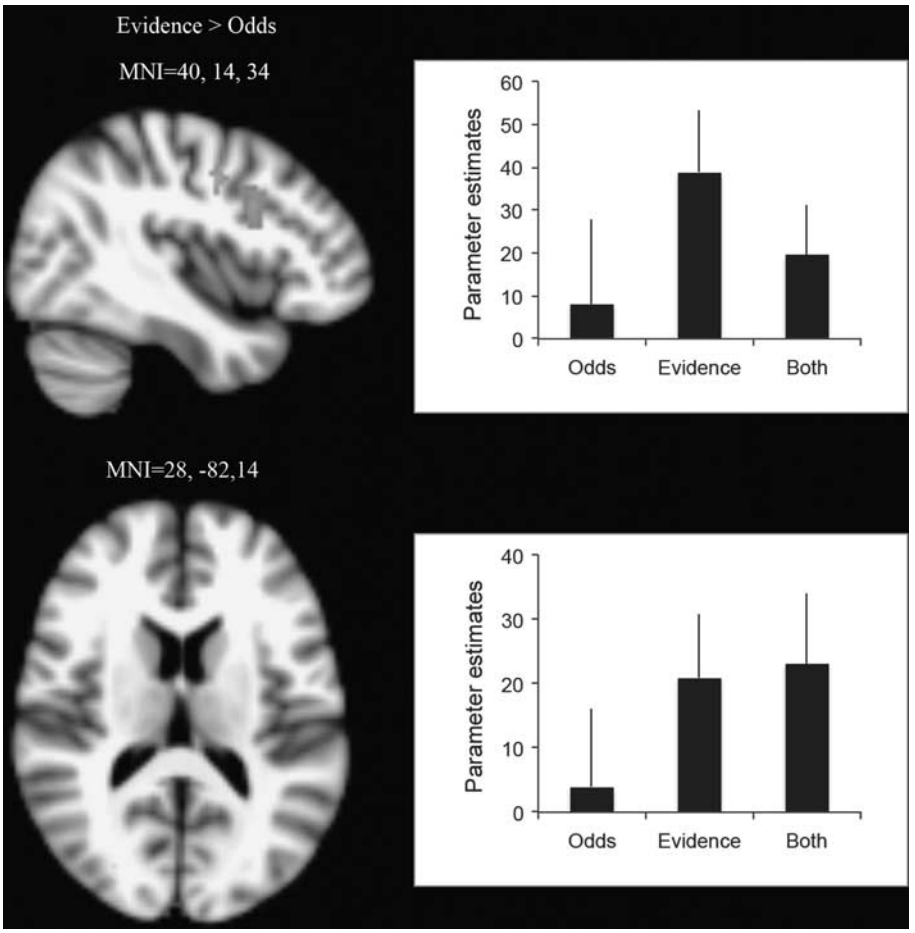
Group-level pairwise comparison of Both with Odds trials showed significantly increased activity in the bilateral precentral, supplementary motor, middle frontal, and postcentral cortices and left superior parietal cortex (Fig. 4 and Table 3). A similar pattern of increased activity was observed when Both trials were compared against Evidence trials.

Discussion

We sought to characterize the neural correlates of decision-making during a Bayesian choice task. Our study used a unique Bayesian choice task to uncover the neural correlates underpinning the use of previous information (e.g. base rate odds) and newly acquired evidence in formulating subjective decisions. We found a robust pattern of fMRI activity in the bilateral frontal, parietal, motor and somatosensory and visual areas when making decisions consistent with the use of Evidence-only and decisions consistent with the use of both Evidence and Odds (Both trials). Decisions consistent with the use of Odds-only activated the bilateral PPC and frontal pole. Evidence-only decisions involved the most widespread spatial area of neural activity among the three trial types. There was a greater recruitment of the right middle prefrontal cortex during decisions consistent with the use of Evidence compared with the decisions consistent with use of Odds. These findings suggest that both overlapping and distinct regions in the executive network drive decisions during a Bayesian choice task depending on the source of information used to make the decision. Understanding the neural correlates of Bayesian updating, as uncovered in our study, is fundamental for understanding how the brain makes decisions in probabilistic environments that also involves processing updated information augmenting the probabilities.

Frontal and parietal cortical brain regions play an important role in attending, processing and storing

Fig. 3



Brain regions showing greater activity during Evidence compared with Odds trials. Bar diagram shows parameter estimates for each trial type. MNI, Montreal Neurological Institute.

Table 2 Bain regions showing significantly increased activity during evidence compared with Odds trials

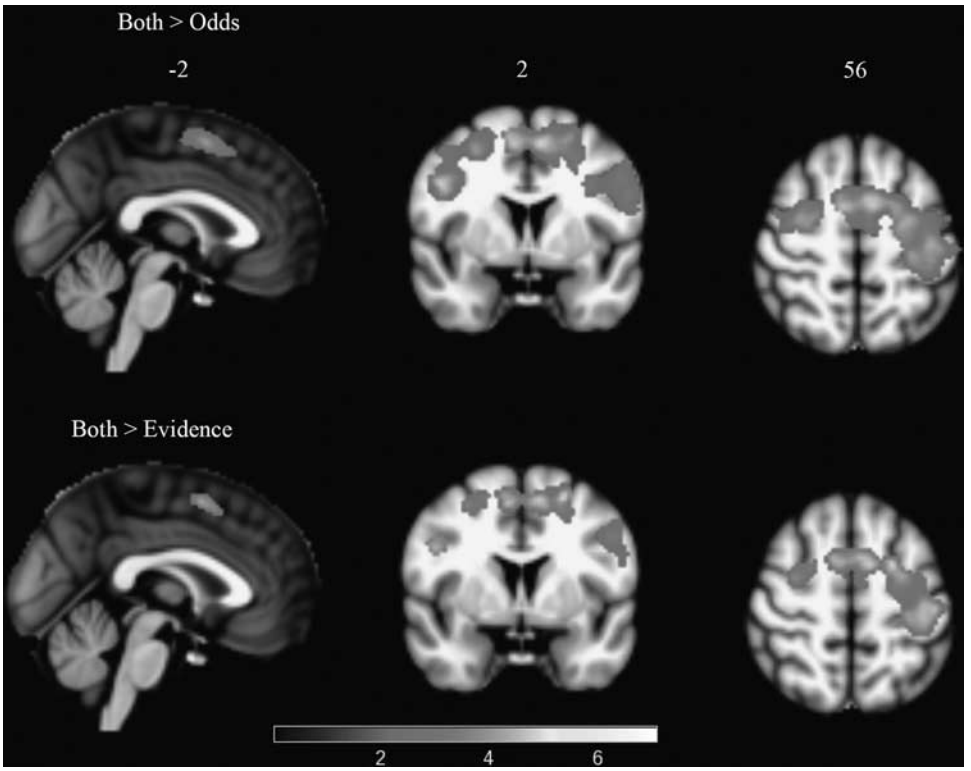
Brain regions	Volume (mm^3)	*t*-statistic	*x*	*y*	*z*
L. precentral gyrus	194	3.21	−40	−6	62
R. middle frontal gyrus	129	2.91	40	14	34
R. precentral gyrus	47	3.04	42	−4	40
R. lateral occipital cortex	16	4.09	28	−82	14
R. lateral occipital cortex	4	3.36	30	−70	20

Coordinates are reported in MNI, and brain regions identified using the Hard–Oxford atlas.
L., left; MNI, Montreal Neurological Institute; R., right.

information [16]. Hence, common recruitment of the frontal and parietal regions in decision-making consistent with the use of Odds, Evidence and Both may indicate the recruitment of general attention and working memory processes used to sustain stimuli representations for decision processing. Previous studies have also implicated these brain structures in decision-making processes under uncertainty [11]. For example, activity in the bilateral insula and prefrontal and parietal cortices increased with increasing uncertainty during a probabilistic decision-making task [17]. Furthermore, the PPC, which was shown to be one of the strongly activated regions during Odds-based decisions, may generate critical inputs about probability and value as it is the primary site for calculation and estimation [18,19]. The present results further extend our understanding of this system in Bayesian decision-making by showing that irrespective of the type of decision encoding, the role of the frontoparietal system is paramount.

The greater engagement of the middle frontal gyrus for decisions consistent with use of Evidence compared with the decision consistent with the use of Odds is also in line with previous neuroimaging studies. The middle and inferior frontal areas have been implicated previously in decision-making tasks requiring storage and manipulation of new information [11,20]. During complex decisions, the middle frontal cortex and in, particular, DLPFC can influence decisions by modulating the computation of stimulus values in the orbitofrontal cortex

Fig. 4



Spatial maps of activation during Both compared with Odds and Evidence trials. Activation maps are overlaid on a standard MNI template and shown in radiological orientation. The greyscale bar represents *Z*-values. MNI, Montreal Neurological Institute.

Table 3 Brain regions showing significantly increased activity during odds, evidence, and both trials compared with Baseline trials

Brain regions	Volume (mm^3)	*t*-statistic	*x*	*y*	*z*
Both trials vs. Odds					
R. precentral gyrus	12 052	5.08	52	8	22
L. superior parietal lobule	–	4.73	−28	−58	50
L. postcentral gyrus	–	4.59	−46	−22	52
R. superior parietal lobule	–	5.17	26	−52	48
R. superior parietal lobule	401	3.42	30	−40	44
R. precuneous	–	4.47	24	−62	24
R. superior lateral occipital cortex	178	4.39	28	−74	16
R. postcentral gyrus	–	4.49	46	−30	46
R. supramarginal gyrus	82	4	38	−34	40
Both trials vs. Evidence					
R. precentral gyrus	7634	6.79	48	4	28
L. supplementary motor area	–	6.07	−6	6	54
R. supplementary motor area	–	6.01	6	4	54
L. paracingulate gyrus	–	5.97	−8	12	50
R. paracingulate gyrus	–	5.66	10	16	46
L. superior parietal lobule	633	4.43	−28	−58	50
L. superior lateral occipital cortex	–	4.03	−22	−66	30

Coordinates for local maxima within the significant clusters are reported in MNI, and brain regions identified using the Hard–Oxford atlas.
L., left; MNI, Montreal Neurological Institute; R., right.

[21,22]. More importantly, and relevant to our findings, the DLPFC implements specific neural processes for manipulating cognitive representations in the spatial domain and enables goal-directed behaviour and adaptive decision-making [1,12,21]. To our knowledge, this is the first study to show that right prefrontal activity is involved in the decision-making process requiring the evaluation of new information in a Bayesian choice.

In considering limitations, it is important to note that we utilized a retrospective rule-based approach, using both behavioural response and the trial types, to identify the trials consistent with the use of Odds or Evidence in making decisions. It is possible that our logic may not perfectly reflect a participant's choice process, although our categorization of trial types is conceptually consistent with the behavioural model estimated in our previous research [9]. The behaviour-driven nature of our trial categorization also implies different numbers of each trial type across participants, which could have affected the level of average fMRI activity detected for each trial type and their comparisons at the group level.

In summary, our experiment identifies the large-scale networks involved in making decisions using different strategies in a Bayesian choice task. Decisions using new information, in particular, recruit executive control processes required for evaluation and manipulation of information, which is supported by increased activity in the right middle frontal cortex. These findings suggest

that frontoparietal brain network can shape decision outcomes when making probability judgements in a Bayesian choice environment.

Acknowledgements

This study was funded by the US National Science Foundation (award #0729021 to SPAD, award # SES-0727794 to DLD). Govinda R. Poudel is supported by the Hereditary Disease Foundation Fellowship in USA and Corporative Research Centre for Alertness, Monash University, Australia.

Conflicts of interest

There are no conflicts of interest.

References

1 Heekeren HR, Marrett S, Ungerleider LG. The neural systems that mediate human perceptual decision making. *Nat Rev Neurosci* 2008; **9**:467–479.
2 Philiastides MG, Sajda P. Temporal characterization of the neural correlates of perceptual decision making in the human brain. *Cerebral cortex* 2006; **16**:509–518.
3 Binder JR, Liebenthal E, Possing ET, Medler DA, Ward BD. Neural correlates of sensory and decision processes in auditory object identification. *Nat Neurosci* 2004; **7**:295–301.
4 Lee D, Seo H. Neural basis of strategic decision making. *Trends Neurosci* 2016; **39**:40–48.
5 Achtziger A, Alos-Ferrer C, Hugelschafer S, Steinhauser M. The neural basis of belief updating and rational decision making. *Soc Cogn Affect Neurosci* 2014; **9**:55–62.
6 Gold JI, Shadlen MN. The neural basis of decision making. *Annu Rev Neurosci* 2007; **30**:535–574.
7 Tom SM, Fox CR, Trepel C, Poldrack RA. The neural basis of loss aversion in decision-making under risk. *Science* 2007; **315**:515–518.
8 Sanfey AG, Rilling JK, Aronson JA, Nystrom LE, Cohen JD. The neural basis of economic decision-making in the Ultimatum Game. *Science* 2003; **300**:1755–1758.
9 Dickinson DL, Drummond SP, Dyche J. Voluntary sleep choice and its effects on Bayesian decisions. *Behav Sleep Med* 2015. 1–13.
10 Platt ML, Huettel SA. Risky business: the neuroeconomics of decision making under uncertainty. *Nat Neurosci* 2008; **11**:398–403.
11 Paulus MP, Hozack N, Zauscher B, McDowell JE, Frank L, Brown GG, *et al.* Prefrontal, parietal, and temporal cortex networks underlie decision-making in the presence of uncertainty. *NeuroImage* 2001; **13**:91–100.
12 Vossel S, Mathys C, Stephan KE, Friston KJ. Cortical coupling reflects Bayesian belief updating in the deployment of spatial attention. *J Neurosci* 2015; **35**:11532–11542.
13 Bennett D, Murawski C, Bode S. Single-trial event-related potential correlates of belief updating (1,2,3). *eNeuro* 2015; **2**.
14 O'Reilly JX, Schuffelgen U, Cuell SF, Behrens TE, Mars RB, Rushworth MF. Dissociable effects of surprise and model update in parietal and anterior cingulate cortex. *Proc Natl Acad Sci USA* 2013; **110**: E3660–E3669.
15 Goscinski WJ, McIntosh P, Felzmann U, Maksimenko A, Hall CJ, Gureyev T, *et al.* The multi-modal Australian ScienceS Imaging and Visualization Environment (MASSIVE) high performance computing infrastructure: applications in neuroscience and neuroinformatics research. *Front Neuroinform* 2014; **8**:30.
16 Keuken MC, Muller-Axt C, Langner R, Eickhoff SB, Forstmann BU, Neumann J. Brain networks of perceptual decision-making: an fMRI ALE meta-analysis. *Frontiers in human neuroscience* 2014; **8**:445.
17 Huettel SA, Song AW, McCarthy G. Decisions under uncertainty: probabilistic context influences activation of prefrontal and parietal cortices. *The Journal of neuroscience: the official journal of the Society for Neuroscience* 2005; **25**:3304–3311.
18 Dehaene S, Piazza M, Pinel P, Cohen L. Three parietal circuits for number processing. *Cogn Neuropsychol* 2003; **20**:487–506.
19 Drummond SPA, Brown GG, Stricker JL, Buxton RB, Wong EC, Gillin JC. Sleep deprivation induced reduction in cortical functional response to serial subtraction. *NeuroReport* 1999; **10**:3745–3748.
20 Donahue CH, Lee D. Dynamic routing of task-relevant signals for decision making in dorsolateral prefrontal cortex. *Nat Neurosci* 2015; **18**:295–301.
21 Rangel A, Hare T. Neural computations associated with goal-directed choice. *Curr Opin Neurobiol* 2010; **20**:262–270.
22 Barbey AK, Koenigs M, Grafman J. Dorsolateral prefrontal contributions to human working memory. *Cortex* 2013; **49**:1195–1205.