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Matthew Apps, University of Oxford Narender Ramnani, Royal Holloway
University of London

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The anterior cingulate gyrus signals the net-value of others' rewards

Short Title: The ACC and others' net-value

Matthew A. J. Apps^{1,2,3} & Narender Ramnani¹

¹ Department of Psychology, Royal Holloway, University of London.

² Nuffield Department of Clinical Neuroscience, University of Oxford.

³ Department of Experimental Psychology, University of Oxford.

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Corresponding Author: Matthew Apps, PhD., Nuffield Department of Clinical Neurosciences. Level 6,
West Wing, John Radcliffe Hospital, University of Oxford, Oxford OX3 9DU, tel: +44 (0) 1865 234534;
Email: matthew.apps@ndcn.ox.ac.uk

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23 **Abstract**

24 Evaluating the costs and benefits of our own choices is central to most forms of decision-making and
25 its mechanisms in the brain are becoming increasingly well understood. To interact successfully in
26 social environments it is also essential to monitor the rewards that others receive. Previous studies
27 in non-human primates have found neurons in the Anterior Cingulate Cortex (ACC) that signal the
28 net-value (benefit minus cost) of rewards that will be received oneself, and also neurons that signal
29 when a reward will be received by someone else. However, little is understood about the way in
30 which the human brain engages in cost-benefit analyses during social interactions. Does the ACC
31 signal the net-value (the benefits minus the costs) of rewards that others will receive? Here, using
32 fMRI we examined activity time-locked to cues that signalled the anticipated reward magnitude
33 (benefit) to be gained and the level of effort (cost) to be incurred either by a subject themselves or
34 by a social confederate. We investigated whether activity in the ACC covaries with the net-value of
35 rewards that someone else will receive when that person is required to exert effort for the reward.
36 We show that while activation in the sulcus of the Anterior Cingulate Cortex (ACC_s) signalled the
37 costs on all trials, gyral ACC (ACC_g) activity varied parametrically only with the net-value of rewards
38 gained by others. These results suggest that the ACC_g plays an important role in signalling cost-
39 benefit information, by signalling the value of others' rewards during social interactions.

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47 Theories of decision-making highlight that choices are made by weighing up rewarding benefits
48 against the costs incurred to receive desired outcomes (Bautista et al., 1998; Phillips et al., 2007).
49 Such cost-benefit analyses underpin decision-making in many species, including humans (Charnov,
50 1976; Kagel and Levin, 1986; Bautista et al., 2001). However, it has often been overlooked that such
51 decisions are not made in a social vacuum (Walton and Baudonnat, 2012). Our decisions are
52 influenced by cost-benefit analyses that we apply to understand others' rewarding outcomes. We
53 investigate the neural processes that are involved in evaluating the costs and benefits of rewards
54 received oneself self *and* by others.

55 The Anterior Cingulate Cortex (ACC) is engaged when processing information about rewards (Rogers
56 et al., 2004; Sallet et al., 2007) and there is evidence that it plays an important role in cost-benefit
57 evaluation (Phillips et al., 2007; Walton and Baudonnat, 2012). Neurons in the ACC encode the net-
58 value of rewards (benefit – cost) at the time of cues that are instructive of how much effort is
59 required (cost) for primary reinforcement (benefit) (Kennerley et al., 2009; Kennerley et al., 2011;
60 Hillman and Bilkey, 2012). Neuroimaging studies have shown that activity in the ACC at the time of
61 such cues is a function of the magnitude of a secondary reinforcer and the anticipated amount of
62 effort (Botvinick et al., 2009; Croxson et al., 2009). This evidence suggests that the ACC signals the
63 net-value of rewards when they are to be received oneself.

64 The ACC is also implicated in the processing of social information (Behrens et al., 2009). Within the
65 ACC there is a dissociation between information processing in the sulcus (ACC_s) and the gyrus (ACC_g).
66 Lesions to the ACC_s, that leave the ACC_g intact, disrupt first-person decision-making (Kennerley et al.,
67 2006). In contrast, lesions to the ACC_g, that leave the ACC_s intact, disrupt social behaviour and the
68 processing of social stimuli (Rudebeck et al., 2006). However, there is evidence that the ACC_g and
69 ACC_s are both sensitive to reward-related information during decision-making (Behrens et al., 2009).
70 While the ACC_s processes information about one's own rewarding outcomes, the ACC_g is engaged
71 when monitoring choices others make to obtain rewarding outcomes (Behrens et al., 2008; Apps et

72 al., 2013b; Chang et al., 2013). This implicates the ACC_g as a candidate for processing the net-value
73 of rewards others will receive (Apps et al., 2013a). However, no previous study has investigated
74 activity in the brain when subjects weigh up the costs and benefits of rewards that others will
75 receive.

76 Using fMRI we examine activity time-locked to cues that signalled the level of economic reward
77 available, the cost incurred for receipt and also whether the rewards and costs pertained to the first-
78 person or to a third-person. We tested the hypothesis that ACC_g activity signals the anticipated net-
79 value of rewards to be received by a third-person when they are required to exert effort to gain
80 them, and that ACC_s activity signals net-value in relation to rewards gained oneself.

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94 Methods

95 *Subjects*

96 Subjects were sixteen, healthy right-handed participants screened for neurological disorders (aged
97 between 18 and 32; 13 female). Two subjects were excluded from the analyses. Both subjects failed
98 to maintain a belief in the deception and one of these subjects failed to perform the judgement task
99 (see below) better than chance (one male). All participants gave written informed consent. The
100 studies were approved by the Royal Holloway, University of London Psychology Department Ethics
101 Committee and conformed to the regulations set out in the CUBIC MRI rules of Operations. Subjects
102 were paired up with one of two confederate participants, who they believed were also naïve
103 participants. The subjects believed that they would be paid for their participation based on their
104 performance of the task during a scanning session (see below). They also believed that the
105 confederate would be paid based on their performance in the same manner.

106

107 *Apparatus*

108 Subjects lay supine in an MRI scanner with the fingers of the right hand positioned on an MRI-
109 compatible response box. Stimuli were projected onto a screen behind the subject and viewed in a
110 mirror positioned above the subjects face. Presentation software (Neurobehavioral Systems, Inc.,
111 USA) was used for experimental control (stimulus presentation and response collection). A custom-
112 built parallel port interface connected to the Presentation PC received transistor-transistor logic
113 (TTL) pulse inputs from the response keypad. It also received TTL pulses from the MRI scanner at the
114 onset of each volume acquisition, allowing events in the experiment to become precisely
115 synchronized with the onset of each scan. The timings of all events in the experiment were sampled
116 accurately, continuously and simultaneously (independently of Presentation) at a frequency of 1 kHz
117 using an A/D 1401 unit (Cambridge Electronic Design, UK). Spike2 software was used to create a

118 temporal record of these events. Reaction times were calculated off-line, and event timings were
119 prepared for subsequent general linear model (GLM) analysis of fMRI data (see below).

120

121 *Experimental Design*

122 The aim of this experiment was to examine the processing of cues that instructed a first-person and
123 a third-person as to how much reward they would receive following the exertion of differing levels
124 of effort. Subjects performed a task over two days with a training partner (confederate). On the first
125 day, the subject and the confederate learned the associations between a set of instruction cues, a
126 financial reward, and how much effort they were required to expend for its receipt. On the second
127 day, both agents continued to perform effortful actions to receive rewards. During this session, the
128 subject performed these trials whilst inside the MRI scanner, with the training partner situated in
129 the adjacent control room.

130 A 2x2x2 Factorial design was employed to examine activity time-locked to instruction cues (see
131 fig.1). The first factor was Agency. On each trial either the subject (first-person) or the confederate
132 (third-person) performed a series of cued button presses (or 'cancellations') on a keypad to receive a
133 reward. The second factor was the reward level that was obtainable on each trial. This could be
134 either high (HR), if 16 UK pence (p) was obtainable on the trial, or low (LR), if only 4p was obtainable.
135 The third factor was the level of effort. There were four levels of effort (two, three, eight or 12
136 responses), which corresponded to the number of cancellations (cued button presses) that were
137 required to receive the reward. These were collapsed into either low effort (LE; two or three
138 cancellations) or high effort (HE; 8 or 12 cancellations) conditions for the factorial design. All cues
139 were colour-coded on each trial, such that the first-person responded when stimuli were blue and
140 the third-person when stimuli were brown. On each trial, the instruction cues signalled the level of
141 reward available and effort required by either the first-person or the third-person. The instruction
142 cue stimuli were based around those used in previous studies (Knutson and Bossaerts, 2007;
143 Croxson et al., 2009) that investigated first-person reward prediction processing. The stimuli were

144 80mm diameter circles containing crosshairs. The position of the crosshairs indicated both the
145 amount of reward that was obtainable and the number of cancellations required to receive that
146 reward. Reward was represented vertically on the circle (16p was high on the circle, 4p was low).
147 Effort was represented horizontally with increasing levels of effort represented from left to right.
148 In total there were 16 different trial types dependent on the reward level, effort level and the agent
149 performing the cancellations. There were eight different trial types for each level of Agent (see fig.1).

150 *Trial Structure*

151 Each trial (see fig.1) began with one of 16 different colour-coded instruction cues. These cues
152 indicated both the level of reward that was available on each trial and also the level of effort
153 required for its receipt. The colour of these cues also indicated who would have to perform the
154 cancellations on each trial (blue for the first-person, brown for the third-person). Following the
155 instruction cue there was an effort period, during which cued button presses were performed on a
156 keypad. During the effort period on the first-person trials, subjects were required to make a series of
157 cued button presses (cancellations). On the third-person's trials the cancellations were actually pre-
158 programmed computer controlled responses (see below for more details). At the end of the effort
159 period, a stimulus then displayed the number of cancellations that had been made during the effort
160 period. Following this stimulus, a trigger cue (three lines, with 16p over the left hand line, 4p over
161 the middle line and 0p over the right hand line) was presented on the screen, which cued the first-
162 person or the third-person to make a judgement of the amount of reward that would be received by
163 the other agent on that trial. Each line corresponded to one line on the keypad. Subjects had 750ms
164 to make their response. If they did not respond in this time window it was classified as an incorrect
165 response. Following this, a feedback cue indicated the accuracy of the judgement ("correct" if the
166 judgement was correct and "-10p" if incorrect) and then finally a feedback cue indicated the reward
167 received by the agent who performed the cancellations (16p, 4p or 0p). In total there were 192
168 trials, 96 first-person trials where the subject made cancellations and 96 where they monitored the
169 third-person's cancellations. Each instruction cue was presented on twelve trials.

170

171 *Task*

172 Subjects performed two tasks during scanning. On first-person trials subjects performed an 'effort
173 task' where cancellations were made in order to receive financial rewards. On the third-person's
174 trials subjects performed a judgement task, monitoring the third-person's performance of the effort
175 task and indicating the amount of reward they would receive.

176 *Effort Task*

177 During scanning, subjects performed trials where they were required to make the correct number of
178 cancellations to receive a financial reward. The 'effort task' required subjects to make a series of
179 cancellations during the effort period. Each cancellation was cued by the position of a square
180 stimulus above one of four lines on the screen. Each line on this cue corresponded to one button on
181 the keypad. The position of the square highlighted a target button. A cancellation constituted one
182 press of the target button i.e. one finger movement of one finger on the right hand. Once this target
183 button was pressed, the position of the square would move to highlight a new target button. Each
184 target button was always different to the previous. Subjects could make up to 14 of these
185 cancellations during the fixed time window of the effort period (6600ms). Subjects were only
186 rewarded on a trial if they performed exactly the number of cancellations specified by the cue. If
187 they performed more cancellations or fewer cancellations they would not obtain the rewarding
188 outcome. Using such an approach ensured that the level of effort expended by participants on the
189 task was closely matched to that specified by the cue. The order of cancellations was randomised
190 across the experiment and within each effort period. Subjects were therefore unable to make any
191 prediction about which button would be the next target. Subjects were instructed to make
192 cancellation responses as quickly and accurately as possible for every level of effort.

193 We used this cancellation task as a corollary of effortful exertion. A large number of previous studies
194 have shown that the number of actions that are performed is in index of effort. Such studies have
195 shown that the number of lever presses, or the number of actions or button presses modulates
196 reaction times and choice behaviour in rats, humans and monkeys. Reaction times to reward
197 predicting stimuli increase as the number of actions increases. Choices are made in favour of
198 rewards associated with fewer actions than the same magnitude of reward associated with more
199 actions (Walton et al., 2006; Phillips et al., 2007; Salamone et al., 2007; Floresco et al., 2008b;
200 Floresco et al., 2008a; Croxson et al., 2009; Floresco and Whelan, 2009; Kennerley et al., 2009;
201 Kennerley and Wallis, 2009; Walton et al., 2009; Day et al., 2010; Nunes et al., 2010). This supports
202 the argument that the number of actions that are to be performed modulates the value of the
203 rewarding outcome, as a result of the costly nature of increased effortful exertion. Thus, by using a
204 task where the number of actions was the index of effortful exertion, we have used a paradigm that
205 is well known to modulate reward desirability.

206

207 In our task we assumed that effort could be equated to the number of cancellations made, it was
208 therefore important that the number of required cancellations as specified in the instruction cue
209 was closely related to the actual amount of actions performed by the subjects. To do so, we first
210 ensured that the task was very simple and the subject and confederate were over-trained together
211 on the task before they entered the scanner during a training phase. As a result, subjects would not
212 press the incorrect target button for a cancellation on many trials. Thus, the number of cancellations
213 made would be very closely related to the number of button presses made and therefore the effort
214 expended. Furthermore the over-trained confederate was instructed to make very few mistakes in
215 terms of which button needed to be pressed. As a result, the subject had learnt to expect that the
216 confederate would make exactly the same number of button presses as required to make the
217 correct number of cancellations.

218 Second, in the cancellation task, the subject was required to perform the correct button press for a
219 new cancellation cue to be presented. If they pressed the incorrect button then the cancellation cue
220 would not move to a new location. Thus, the subject inside the scanner was able to monitor the
221 number of new targets presented to infer the number of correct button presses being made by the
222 confederate. These two features of the design ensured that the subject was able to know the
223 number of cancellations on every trial and also infer that this would be highly correlated with the
224 actual number of button presses and therefore the level of effortful exertion.

225

226 During scanning, subjects were told that they were accumulating monetary rewards for their
227 performance on this task. As such subjects believed that they were earning the reward available on
228 each first-person trial, if they performed the correct number of cancellations. Subjects were told that
229 if they performed every cancellation correctly they would accumulate £10 as payment for the
230 experiment. However, unbeknown to the subjects, they would be paid £10 for participation
231 regardless of their task performance.

232

233 *Judgement Task*

234 In addition to the effort task, subjects also performed a judgement task on the trials where the third-
235 person was performing the effort task. For this task the subjects were required to indicate the level
236 of reward that would be received by the third-person, which could be 16p or 4p for the correct
237 number of cancellations or 0p if the number of cancellations was incorrect. Subjects were required
238 to perform this judgement on every trial performed by the third-person. Subjects believed that they
239 were punished for each incorrect judgement (when the subject indicated that the amount of money
240 earned by the confederate on the third-person trials was different from the amount they would
241 actually earn) by 10p being removed from the money they were accruing on the effort task. A
242 correct judgement left the rewards accumulated during the effort task the same. Thus, subjects

243 believed that if they performed every set of cancellations correctly, but every judgement incorrectly,
244 they would receive no payment for the experiment. Therefore, subjects were motivated to perform
245 both tasks to the same degree of accuracy. This punishment ensured that subjects attended to the
246 rewarding value and the effort information contained in the instruction cues on the third-person's
247 trials. Importantly, the punishment used as the motivation for the subject on the third-person's
248 trials, was unrelated to the anticipated reward and effort level that would be processed at the time
249 of the instruction cues.

250

251 This task required subjects to monitor both the amount of effort and the reward magnitude in the
252 instruction cue, but also the number of cancellations performed. To perform this task correctly
253 subjects needed to monitor the cancellations made during the effort period. They could do so in two
254 ways. Firstly, subjects could monitor the number of times that cues disappeared during the effort
255 period. Secondly, subjects were explicitly instructed as to how many cancellations had been made by
256 the confederate at the end of the effort period by an additional cancellation cue. As a result,
257 subjects were able to monitor the number of cancellations made by the confederate without
258 difficulty.

259

260 To maintain experimental control, we deceived participants as to the nature of the third-person.
261 Whilst subjects believed they were performing the task with a real other person, the responses they
262 saw were computer-generated. This approach was necessary in order to maintain control over the
263 performance of the third-person. However, in order to ensure payment for the experiment was
264 ethical and not dependent on the third-person performance, all subjects were paid the same
265 amount for participation. Subjects were thoroughly debriefed using a standard set of questions as
266 used previously (Ramnani and Miall, 2004; Apps et al., 2012; Apps et al., 2013b). Only two
267 participants, who were excluded from the analysis, showed any awareness of the nature of the
268 deception.

269

270 The effort task used in this study is very similar to that employed by Croxson et al., (2009) that was
271 used to investigate first-person effort-discounting. Given this similarity, it is important to note the
272 differences between the task employed here and that used by Croxson et al., (2009). Croxson et al.,
273 (2009) used 8 different instruction cues in which crosshairs indicated the level of effort and the
274 amount of reward obtainable. There are two important differences between the effort task
275 employed in that study and that employed here. Firstly, unlike in this study, there were no
276 constraints placed upon the time which subjects had to make cancellations. Secondly, unlike in this
277 experiment, subjects were only presented with the correct number of targets to be cancelled.
278 However, these two aspects of their task were not suitable for the purposes of this study. A crucial
279 aspect of our design was that subjects were required to make a judgement on the reward to be
280 received by a third-person. This task ensured that subjects attended to the effort and reward levels
281 at the time of the instruction cues on the third-person's trials. Without a temporal constraint on the
282 effort period, there would be no possibility of making an incorrect number of cancellations, and
283 thus, the confederate would not make errors on the effort task. Without confederate errors, the
284 subject could perform the judgement task by attending to the level of reward at the time of the
285 instruction cues on the third-person's trials and not the level of effort. Thus, in this experiment, a
286 temporal window was a necessity. In addition, in this experiment subjects could cancel up to 14
287 targets, more than the maximum instructed number of 12, regardless of how many cancellations
288 they were required to make. This created the potential for catch trials, where the confederate made
289 an error in the number of cancellations, which the subject would need to identify correctly in order
290 to maximise their own financial rewards and perform the judgement task correctly. These two
291 distinctions from the task used by Croxson et al., (2009) ensured subjects attended to both the effort
292 and reward level on every confederate trial.

293

294

295 *Procedure*

296 *Training*

297 Subjects were trained in two phases one day prior to scanning. In the first phase, the subject was
298 seated in front of a monitor with a confederate (third-person). They were each provided with a
299 response keypad. Both the confederate and the subject performed the effort task on separate trials.
300 During this session both the confederate and subject learned the contingency between the position
301 of the crosshairs on the instruction cue stimulus, the amount of reward (16p or 4p) and the required
302 number of cancellations (button presses) to receive the reward. They were informed before this that
303 there would be two levels of reward and that they would have to make two, three, eight or twelve
304 button presses. During training there were 64 'first-person' trials where the subject performed the
305 cancellations and 64 'third-person' trials performed by the confederate. The subjects were told that
306 the rewards were fictional during training and their payment for the experiment would be based
307 solely on performance during the scanning session.

308

309 In this session, as the subjects were seated next to the confederate, the confederates performed the
310 effort task on separate trials from the subject. As the confederates were paired with multiple
311 different subjects throughout the piloting and experimental phases, they were highly over-trained
312 on the effort task. To ensure that subjects maintained the belief that the confederates were naïve
313 participants like themselves, they were told to make deliberate errors in the number of cancellations
314 performed during the first phase of training, to mimic the learning of a real participant.

315 In the second phase of training, subjects practised the task that would be performed during the
316 scanning session (see below). The subject performed this from inside a mock scanner, with the
317 confederate seated in front of a monitor adjacent to the mock scanner. The subject was played the
318 sound of a genuine scanner's EPI sequence via headphones. During this training phase and during
319 scanning the responses on the third-person trials were computer controlled.

320 *Scanning Session*

321 Prior to scanning subjects were shown the confederate seated in front of a monitor in the control
322 room next to the scanner. They were told that they would see all of the responses of the third-
323 person in real-time inside the scanner. In fact these responses were all computer controlled, pre-
324 programmed responses. The apparent reaction times of the confederate during the effort task were
325 pseudorandomly organised. The reaction times of the second to twelfth button presses fitted a
326 normal distribution around a mean (525ms), with a range of 325ms to 725ms. The confederate's
327 reaction times to the first target were extended, to reflect the unpredictability of the onset of this
328 target. These formed a normal distribution around a mean of 600ms, with a range of 400ms to
329 800ms. These timings were based on the reaction times of five participants during a pilot
330 experiment. The apparent reaction times of the confederate were programmed to not be different
331 regardless of the number of cancellations to be made on the trial, such that the confederate
332 behaviour appeared to conform to the instruction responding as quickly and accurately as possible.
333 It was also noted that such behaviour was exhibited by subjects in a pilot experiment, where no
334 difference was found between reaction times of the first two button presses in the 2 cancellations
335 conditions compared to the 12 cancellations conditions.

336 Key for the design of this experiment was that subjects attended to both their own instruction cues
337 and those of the third-person in the same manner. There was one potential caveat to the judgement
338 task used to motivate subjects to attend to the instruction cues of confederate. Specifically, if the
339 confederate performed the correct number of cancellations on every trial, the subject could, over
340 time, learn to perform the judgement without attending to the level of effort, only the reward level.
341 To address this potential confound, errors were pre-programmed into the behaviour of the
342 confederate. On nine of the trials where the effort task was performed by the confederate, the
343 number of cancellations performed was not correct for the instruction cue presented. These 'catch'
344 trials were used as an index of the extent to which subjects were attending to the effort expended
345 by the confederate.

346

347 *Behavioural Analysis*

348 Behavioural analyses were performed in SPSS16. Performance on the effort task was analysed by
349 performing a repeated measures ANOVA on the effect of effort on task accuracy. Planned pairwise
350 comparisons were then performed between the 2 and 12 button press conditions, to ensure that
351 there was no significant effect of the number of button presses (i.e. difficulty) on performance of the
352 task. For the judgement task, paired samples *t*-tests were performed to examine the difference
353 between the accuracy on the task (i.e. judging the correct reward level on the trial) and chance level
354 (33%). Trials in which the subject failed to respond within the 750ms response window were
355 included as errors. In addition, we performed two ANOVAS on the accuracy on the judgement task,
356 One which looked for an effect of reward level or effort level on accuracy and a second that looked
357 for an effect of net-value on accuracy.

358

359 *Functional Imaging and analysis*

360 *Data Acquisition*

361

362 T1-weighted structural images were acquired at a resolution of 1×1×1 mm using an MPRAGE
363 sequence. 1164 EPI scans were acquired from each participant. 34 slices were acquired in an
364 ascending manner, at an oblique angle ($\approx 30^\circ$) to the AC-PC line to decrease the impact of
365 susceptibility artefact in subgenual cortex (Deichmann et al., 2003). A voxel size of 3×3×3 mm (25%
366 slice gap, 0.8 mm) was used; TR=2.5s, TE=32, flip angle=81°. The functional sequence lasted 48.5
367 minutes. Immediately following the functional sequence, phase and magnitude maps were collected
368 using a GRE field map sequence ($TE_1 = 5.19\text{ms}$, $TE_2 = 7.65\text{ms}$).

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371

372 *Image Preprocessing*

373 Scans were pre-processed using SPM8 (www.fil.ion.ucl.ac.uk/spm). The EPI images from each
374 subject were corrected for distortions caused by susceptibility-induced field inhomogeneities using
375 the FieldMap toolbox (Andersson et al., 2001). This approach corrects for both static distortions and
376 changes in these distortions attributable to head motion (Hutton et al., 2002). The static distortions
377 were calculated using the phase and magnitude field maps acquired after the EPI sequence. The EPI
378 images were then realigned, and coregistered to the subject's own anatomical image. The structural
379 image was processed using a unified segmentation procedure combining segmentation, bias
380 correction, and spatial normalization to the MNI template (Ashburner and Friston, 2005); the same
381 normalization parameters were then used to normalize the EPI images. Lastly, a Gaussian kernel of 8
382 mm FWHM was applied to spatially smooth the images in order to conform to the assumptions of
383 the GLM implemented in SPM8.

384

385

386 *Statistical Analysis*

387 *First-Level analyses*

388 First-level GLMs were created for both factorial and parametric analyses.

389

390 1. *Factorial Analysis.* There were 10 event types. Each event-type was used to construct a
391 regressor by convolving the stimulus timings with the canonical HRF. Each of the eight
392 conditions was modelled as a separate regressor. In addition, one regressor modelled the
393 activity during the effort periods (regardless of whether it was a first-person or third-person
394 trial) and another regressor modelled the onsets of the other trial elements on every trial.
395 Trials in which the subject failed to perform the correct number of cancellations during the
396 effort period, failed to respond within 750ms of the onset of the trigger cue for the

397 judgement task, or failed to make the correct response on the judgement task were
398 modelled separately as an extra regressor. This regressor included the onsets from all of the
399 trial elements from these events. The residual effects of head motion were modelled as
400 covariates of no interest in the analysis by including the six head motion parameters
401 estimated during realignment.

402 2. *Parametric Analysis.* Two GLMs were created at the first-level which employed a parametric
403 approach. Each of these GLMs was constructed using the same events as those used in the
404 factorial analysis (see above). For these GLMs, however, the instruction cue regressors were
405 collapsed down into one regressor for the first-person instruction cues and one regressor for
406 the third-person instruction cues. To create parametric regressors we divided the reward
407 magnitude by the number of cancellations required and log-transformed these values, as in
408 Croxson et al., (2009). The parameters outlined in fig.1 (the log-transformed net-values)
409 were used as first-order parametric modulators of first-person and third-person instruction
410 cue events. In addition, we included additional parametric modulators that were scaled with
411 the effort level. To examine activity which varied with net-value, the net-value parameters
412 were orthogonalised with respect to the effort parameters. This ensured that activity which
413 varied with either first-person net reward values, third-person net reward values or both
414 could not be explained by the level of effort alone. The second GLM was similar except that
415 the effort parameters were orthogonalised with respect to the net value parameters.

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420 *Second-level analysis*

421 Random effects analyses (Full-Factorial ANOVAs) were applied to determine voxels significantly
422 different at the group level. SPM{t} contrast images from all subjects at the first-level were input into
423 second-level full factorial design matrices. *F*-contrasts were conducted in each of the second-level
424 Random-effects analyses. For the whole brain analyses, FDR correction was applied. To test the
425 specific hypotheses in the ACC, 80% probability masks of the ACC_g and ACC_s were created and used
426 as the search volumes for small volume correction (see anatomical localization). In addition, we also
427 used the coordinates of Croxson et al. (2009) for small volume correction, as their study examined
428 activity at the time of instruction cues that indicated to a subject the effort level required, and the
429 level of reward available to them. Small volume corrections were applied as a sphere with 8mm
430 radius around the peak coordinates from their analysis that looked for an interaction between
431 reward and effort. This correction was applied by making a mask combining each of the spheres
432 around their peak coordinates for the comparable contrast.

433

434

435 Anatomical Localization

436 For our main correction for multiple comparisons, we used 80% probability anatomical masks of the
437 ACC_g and ACC_s. To create each mask, subject-specific masks of the ACC_g and ACC_s were constructed
438 in FSL (<http://www.fmrib.ox.ac.uk/fsl/>). Although the cytoarchitectonic boundaries of the ACC have
439 no corresponding gross anatomical landmarks, we defined the anatomical boundaries based on the
440 location of these boundaries in previous literature investigating cingulate cytoarchitecture (Vogt et
441 al., 1995). We used a posterior horizontal extent to each mask that lay 22 mm posterior to the
442 Anterior Commissure, i.e. the posterior border of the midcingulate cortex (Vogt et al., 1995). We
443 included all voxels that lay within the ACC_s or the ACC_g extending anterior to this border, including
444 subgenual cingulate cortex. The final ACC_s and ACC_g masks included only voxels which were within
445 each region in 80% of our subjects. We defined our anatomical mask of the ACCs as
446 cytoarchitectonic zones 24c, 24c', 32 and 32' as defined by Vogt and colleagues (2005). Vogt and

447 colleagues (2005) note that when there is only a single cingulate sulcus and no paracingulate sulcus,
448 areas 24c and 24c' lie on the ventral bank of the sulcus and areas 32 and 32' lie in the dorsal bank of
449 the sulcus. When a paracingulate sulcus is present areas 24c and 24c' lie in the both the ventral and
450 dorsal banks of the primary cingulate sulcus and areas 32 and 32' lie on the additional paracingulate
451 gyrus and extend over the ventral bank of the paracingulate sulcus. We created masks of the ACCs
452 using exactly same anatomical criteria. When there was a single cingulate sulcus, the mask covered
453 the dorsal and ventral banks of the sulcus. When there was an additional paracingulate sulcus, the
454 mask included both the dorsal and ventral banks of the cingulate sulcus, and extended up to and
455 including the ventral bank of the paracingulate sulcus.

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460 *Results*

461 *Behavioural results*

462

463 The subjects performed two tasks whilst inside the MRI scanner. On first-person trials they
464 performed button presses in order to receive rewards themselves. On the third-person trials (see
465 fig.1) they performed a second task, judging the level of reward (16p, 4p or 0p) that the confederate
466 would receive on that trial, after they had monitored the confederate's responses. For the effort
467 task, subjects were required to make 2, 3, 8 or 12 button presses (cancelling out one of four visually
468 cued targets by pressing one of four corresponding buttons on a keypad) in order to receive a
469 financial reward (16p or 4p). These button presses were made during a 6600ms effort period. An
470 important issue in this experiment was that the effort task constituted effort and not difficulty. In
471 previous studies, the effort period (Botvinick et al., 2009; Croxson et al., 2009) was not constrained
472 by a time-period, and as such cancelling out a large number of targets was not more difficult than a
473 small number. In this study, the fixed response window may have caused subjects to find it more
474 difficult to complete the 12 button presses than to make 8, 3 or 2 responses. This would confound
475 any interpretation as effort-related activity would have been confounded with activity occurring due
476 to the probability of success on the task. In turn, this could have led to subjects making a negative
477 reward prediction or risk related prediction at the time of the cues on the third-person trials.
478 However, if subjects performance was high and consistent across the effort and reward levels, then
479 any potential confounds would be orthogonal to first-person or third-person net-value and therefore
480 could not account for activity covarying with net-value at the time of the instruction cues.

481

482 To determine whether effort was confounded with first-person effort task difficulty, the behavioural
483 accuracy of subjects across each of the four effort levels were examined on the first-person trials
484 (see fig.2a). Correct response trials were those where the subject made exactly the same number of
485 cancellations as those specified by the cue. Notably, task accuracy was high (mean = 96.71%),

486 suggesting that subjects did not find the task difficult. Also, as can be seen in figure 2a, the accuracy
487 was high for all four effort levels on the task. A repeated measures ANOVA was performed
488 examining the effect of effort on task accuracy (% of correct responses). No main effect of effort on
489 task accuracy was identified ($F(2.18,28.37) = 2.098, p = 0.198$). A planned pairwise comparison
490 between the 2 and 12 button press trials showed no significant difference in accuracy ($t(13) = 1.528,$
491 $p = 0.151$), indicating that they were not significantly less accurate at performing 12 button presses
492 compared to two button presses. This suggests that the increased amount of effort in the task did
493 not cause a significantly increased level of difficulty.

494

495 The second task performed by subjects was a judgement of the reward level that would be received
496 by the third-person. Subjects were required to monitor the responses of a third-person
497 (confederate) and indicate whether they would receive a high reward (16p), low reward (4p), or no
498 reward (0p) on each trial. Performance on this task was an important index of subjects'
499 understanding of the level of reward available and the effort necessary for its receipt on the third-
500 person's trials. It was of particular importance that subjects performed 'catch trials', where the
501 third-person made the incorrect number of button presses above chance level (33.3%). On these
502 trials subjects could not perform the judgement task correctly without attending to the reward level
503 and required effort level at the time of the instruction cue and also the number of button presses
504 actually made by the third-person (see fig.2b). A paired samples *t*-test revealed that subjects' overall
505 task accuracy (mean = 93.93%) was significantly better than chance ($t(14) = 54.5, p < 0.0001$). On the
506 catch trials the accuracy was (mean = 78.64%) also significantly greater than chance ($t(14) = 12.76; p$
507 < 0.001). These results indicate that subjects were attending to the reward value and the level of
508 effort at the time of the instruction cues and also the number of button presses actually made by the
509 third-person. However, it was also important to demonstrate that the all subjects' performance was
510 similar for each level of effort and reward on the third-person trials, to ensure that the instruction
511 cues for the effort and reward levels were not acting as first-person risk or negative reward

512 predictors on the third-person trials. To test this possibility we performed a 2x2 repeated measures
513 ANOVA with the first factor being the reward level and the second being the amount of effort. There
514 was no main effect of effort ($F(2.41, 31.31) = 2.579, p = 0.083$), reward ($F(1,13) = 0.024, p = 0.880$)
515 and no interaction ($F(2.18, 28.32) = 1.543, p = 0.231$) on task accuracy. This would suggest that the
516 level of reward, and crucially the number of cancellations being made by the confederate, did not
517 affect the subjects ability to monitor the responses or indicate what level of reward was going to be
518 received.

519

520 We also performed a repeated measures ANOVA to examine whether there was a significant effect
521 of net-value on accuracy, by breaking down the accuracy into 6 net-value conditions. We found no
522 significant effect of net-value on task accuracy ($F(2.431, 31.599) = 2.571, p > 0.05$). Thus, our
523 behavioural data suggests that there is no effect of net-value, reward or effort on the ability to
524 perform the judgement task. As such, there is no difference in the risk of losing money between
525 each of the different conditions on the third-person trials. Thus, the effect of predicting a loss of
526 money on the third-person trials would not vary across conditions and therefore would not vary with
527 social net-value. Consequently, risk cannot account for the activity we identified in the ACC_g. The
528 high-level of performance of subjects across all third-person conditions also, importantly, ensures
529 that any activity we identified cannot be related to the subject predicting a reward in the first-
530 person conditions and predicting a punishment in the third-person condition. The performance of
531 subjects on both tasks indicates that they were processing the reward value and the effort level at
532 the time of the instructions cues on both first-person and third-person trials.

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539 *Imaging results*

540 This study tested two hypotheses about the processing of cost-benefit analyses in the ACC. First,
541 that activity in the ACC_g covaries with the net-value of rewards to be received by a third-person,
542 signalling a cost-benefit analysis for others' rewards. Second, that activity in the ACC_s covaries with
543 the net-value of rewards on first-person trials, signalling one's own cost-benefit analysis. We
544 examined activity time-locked to the instruction cues and performed a parametric analysis to
545 examine activity that covaried with the net-value of rewards, on both the first-person and third-
546 person trials. We also performed a 2x2x2 factorial analysis to confirm the results of the parametric
547 analysis. The first factor was the Agency (first or third person), the second was Reward level (high or
548 low) and the third was Effort, which was split into Low (2 and 3 button presses) and High (8 and 12
549 button presses) conditions.

550

551 *ACC_g and the net-value of rewards on 3rd-person trials*

552 To test our first hypothesis, we examined whether activity in the ACC_g was scaled with the net-value
553 of rewards on the third-person trials. To constrain our search to a hypothesised area, a mask of the
554 ACC_g was used as a small volume correction for multiple comparisons. This mask ensured that any
555 activated voxel at the group-level would be within the ACC_g in 80% of the subjects. To ensure that
556 the voxels identified in this analysis showed a significant effect on the third-person's trials, but not a
557 significant effect of net-value on the first-person's trials, we excluded any voxels in which activity
558 covaried with the net-value of rewards at the time of the first-person instruction cues. The voxels
559 were excluded at a more liberal threshold ($p < 0.05_{unc}$) to be conservative about the specificity of
560 any response in the ACC_g to third-person net-value. Activity in a cluster in the ACC_g was found to
561 vary with the net-value parameter (4, 22, 20, $Z = 2.8$, $p < 0.05_{svc}$; see fig.3 a,b,c) in the midcingulate
562 cortex (MCC), putatively area 24b'. It is important to note that the parametric effects identified in
563 this analysis are from regressors that are orthogonal to the other parameter in the analysis (i.e. the

564 beta coefficient for net-value is for a regressor that is orthogonalised with respect to effort, and vice
565 versa for the effort beta coefficient). Thus, the absence of a parametric effect of effort (Fig. 3B),
566 reflects only the fact that the unique variance of the effort parameter cannot account for activity in
567 the ACCg and not that effort doesn't influence activity in this area. By showing that the net-value
568 parameter significantly explains a unique portion of the variance, which is parameterised as effort
569 divided by reward, we have shown an effect of both effort and reward on ACCg activity.

570 An overlapping cluster, with the same peak voxel, also showed a significant interaction between
571 Agency, Effort and Reward in the factorial analysis ($Z = 3.09$, $p < 0.05_{\text{svc}}$). An additional, overlapping
572 cluster that contained the peak voxel from the parametric analysis also showed a main effect of
573 Agency ($Z = 5.57$, $p < 0.05_{\text{svc}}$) highlighting this area as differentially sensitive to first-person and
574 third-person information. A cluster that overlapped with the peak voxel from the parametric analysis
575 showed a significant effect of high vs low reward on the third-person trials ($Z = 3.66$, $p < 0.05_{\text{svc}}$). No
576 activity in any part of the ACC_g was found to covary with net-value parameter on the first-person
577 trials, and no voxels showed a main effect of Effort, or Reward ($p > 0.05$ uncorrected). A whole-brain
578 analysis did not identify any voxels outside the ACC_g that covaried with the net-value of rewards on
579 the third-person trials, when using a whole-brain correction for multiple comparisons or when
580 correcting around the coordinates of a previous study that investigated first-person net-value
581 processing (Croxson et al. 2009). In addition, we found a simple effect between the high reward, low
582 effort (2 or 3 cancellations) and the low reward, high effort conditions (8 or 12 cancellations) in a
583 cluster in the ACC_g that overlapped with that showing a parametric effect ($Z = 3.22$, $p < 0.05_{\text{svc}}$).
584 That is we found a significant difference between the trials with the two highest net-value levels and
585 the two lowest net-value levels. We found no differences between the high reward, high effort and
586 the low reward low effort conditions in the ACC_g even at a lowered threshold ($p > 0.01_{\text{unc}}$). As such,
587 we found no difference between the conditions with the same net-value in the ACC_g on the third-
588 person trials. Thus, we identified activity in a portion of the ACC_g was scaled with the net-value of
589 rewards that were to be received specifically by a third-person.

590 In addition to the hypothesised activity in the ACC_g, a second cluster putatively in a posterior portion
591 of area 24b', showed a significant two-way interaction between Agency and Reward in the factorial
592 analysis (4, 16, 26; $p < 0.05_{\text{svc}}$). This cluster did not overlap with that reported above. This effect was
593 driven by a differential response between the HR and LR conditions on the third-person trials ($p <$
594 0.05_{svc}). Therefore, a portion of the ACC_g that is distinct from that reported above is sensitive to the
595 magnitude of a reward that is to be received by another, regardless of how much effort that will
596 have to be exerted by them for its receipt.

597 *ACC_s and first-person effort processing*

598 To test our second hypothesis, we examined whether activity in the ACC_s was scaled with the net-
599 value of rewards on the first-person trials. To constrain the search to our hypothesised area, a mask
600 of the ACC_s was used as a small volume correction for multiple comparisons. This mask (see
601 Methods) ensured that any activated voxel at the group-level would be within the ACC_s in 80% of the
602 subjects. To ensure that any identified voxel in this analysis showed a significant effect exclusively on
603 the first-person's trials, we excluded any voxels that covaried with the net-value of rewards at the
604 time of the third-person instruction cues. The voxels were excluded at a more liberal threshold ($p <$
605 0.05_{unc}) to be conservative about the specificity of any response in the ACC_g to first-person net-
606 value. There were no voxels in the ACC_s in which activity covaried with net-value on the first-person
607 trials. There were also no voxels in the ACC_s in which activity covaried with net-value at the time of
608 the third-person instruction cues.

609 We did not find activity in the ACCs to be scaled with the net-value of rewards on first-person trials.
610 However, previous studies have shown this area to be engaged during cost-benefit processing. Thus,
611 we performed further exploratory analyses to examine whether activity in the ACCs signalled any
612 other information on the first-person trials. We found activity in a posterior portion of the ACCs, in
613 the Midcingulate cortex (MCC)/Rostral Cingulate Zone (RCZ) (0, -22, 50; $Z = 3.44$, $p < 0.05_{\text{svc}}$,
614 putatively area 23c/24c') that showed a main effect of Effort (fig.3d). This region therefore

615 responded differentially to the level of effort, regardless of the level of Reward or Agency. Notably,
616 the profile of the ACC_s response was consistent with some (Croxson et al., 2009), but not all previous
617 studies examining activity at the time of cues that signal the level of reward and the amount of
618 effort required. Our study found a negative relationship between effort and the BOLD response in
619 the ACCs, whereas other studies have shown a positive relationship (Prevost et al., 2010b; Burke et
620 al., 2013). This discrepancy may be explained by the fact in this study and in Croxson et al., (2009),
621 subjects were not engaged in deciding between differently valued options as they were in the other
622 studies. It is well known that activity in the ACCs is modulated during decision-making by both
623 chosen and unchosen options (Kolling et al., 2012). It is therefore possible that these differences can
624 be accounted for by subjects being able to make choices to minimise costs and maximise rewards
625 during decision-making tasks, but only process the discounted value of the reward when effort and
626 reward are instrumentally instructed, as in our study and that of Croxson et al., (2009). Thus, our
627 results still support previous accounts of this region's involvement in the processing of cost-benefit
628 information, although we did not find this region showing a sensitivity to reward magnitude

629

630 *First-person net-value*

631

632 While we did not find the hypothesised activity in the ACC_s, activity in the nucleus accumbens (NA) (-
633 8, 14, -4, $Z = 2.8$; $p < 0.05$ svc around the peak coordinate from Croxson et al. 2009) was found to
634 covary with net-value parameter, at the time of the first-person instruction cues (fig.3). We
635 therefore support previous findings that highlight the NA in cost-benefit related information
636 processing (Botvinick et al., 2009; Croxson et al., 2009; Ghods-Sharifi and Floresco, 2010; Day et al.,
637 2011)

638

639

640

641 Discussion

642

643 We tested two hypotheses about the role of the ACC in processing the net-value of rewards at the
644 time which cues signalled the costs associated with rewards that would be received oneself or by a
645 third-person. In line with our first hypothesis, activity in the ACC_g covaried with the net-value of
646 rewards to be received by the third-person, when the third-person incurred the cost of the effort.
647 Our second hypothesis that activity in the ACC_s would vary with the net-value of rewards at the time
648 of instruction cues on the subject's own trials was not supported. Rather, this region showed an
649 effect of the anticipated level of effort on both the first-person and third-person trials. That is the
650 ACC_s signalled the effort level regardless of whether the effort was exerted oneself or by a third-
651 person. In addition, we found that activity in the NA scaled with the net-value of rewards on first-
652 person trials. Thus, while the ACC_s processed information about the costs associated with a reward,
653 regardless of who work to receive it, the ACC_g was engaged when weighing up the benefits and costs
654 associated with rewards that others were to receive.

655

656 Previous studies have suggested that the ACC_s processes information about one's own decisions in a
657 manner that conforms to the principles of Reinforcement Learning theory (RLT) (Behrens et al.,
658 2009). In RLT, choices are made based on the predicted net-value of decision-making outcomes.
659 When an outcome is unexpected, prediction error signals code for the surprise evoked by the
660 outcome, which serves to update future predictions (Rescorla and Wagner, 1972; Sutton and Barto,
661 1998). Neurophysiological and neuroimaging studies have identified activity in the ACC_s that reflects
662 the predicted net-value of rewarding stimuli for oneself (Sallet et al., 2007; Quilodran et al., 2008;
663 Jocham et al., 2009; Kennerley et al., 2009) and also neurons which signal that the value of an
664 outcome is unexpectedly different from the predicted value (Amiez et al., 2005; Matsumoto et al.,
665 2007; Sallet et al., 2007; Kennerley et al., 2011; Ribas-Fernandes et al., 2011). This evidence suggests

666 that an important functional property of the ACC_s is to signal predictions about the outcome of one's
667 own decisions and signal when they are discrepant from one's expectations.

668

669 Neuroimaging studies suggest that the ACC_g may mirror this property by showing that this area is
670 activated when monitoring the unexpected outcomes of others' decisions (Apps et al., 2012; Apps et
671 al., 2013b). One recent neurophysiology study found that the ACC_g and not the ACC_s contains
672 neurons that respond when a monkey is anticipating the delivery of a reward to another monkey
673 (Chang et al., 2013). This suggests that the ACC_g processes information about upcoming rewards that
674 others will receive and that it is activated when the outcome of another's choice is unexpected.
675 However, in these studies there were no costs associated with the reward being delivered to
676 another. Our study provides the first evidence that the human ACC_g processes the predicted value of
677 a reward that another will receive, supporting the claim that the ACC_g processes information about
678 others' rewards.

679

680 Anatomical evidence also supports the notion that the ACC_g is engaged by both social and cost-
681 benefit related information. In monkeys, the homologous portion of the ACC_g that was activated in
682 this study (in the MCC) has strong connections to the posterior portions of the Superior Temporal
683 Sulcus (pSTS), the Temporal Poles (TPs) (Markowitsch et al., 1985; Seltzer and Pandya, 1989; Barbas
684 et al., 1999), and the paracingulate cortex (Pandya et al., 1981; Vogt and Pandya, 1987; Petrides and
685 Pandya, 2007). These three regions are believed to form a core-circuit that is engaged when
686 processing information about the mental states of others (Ramnani and Miall, 2004; Frith and Frith,
687 2006; Hampton et al., 2008). There is no evidence of connections between these regions and the
688 ACC_s, supporting the notion that the information processed in the ACC_g is more strongly linked to
689 social behaviour than that which is processed in the ACC_s. However, there is evidence to suggest that
690 the ACC_g is connected to the ACC_s and the ventral striatum/NA. These two regions form a loop that is
691 closed by return connections via the ventral pallidum and the thalamus (Groenewegen et al., 1993;

692 Kunishio and Haber, 1994; Spooen et al., 1996; Middleton and Strick, 2000; Nakano et al., 2000;
693 Haber and Knutson, 2010). It has been argued that this circuit is important for cost-benefit
694 information processing. Disruptions of the striato-pallidal connection (Mingote et al., 2008) and also
695 to the striato-cingulate connection (Hauber and Sommer, 2009) perturb normal behavioural patterns
696 on tasks that require choices between options that have different associated costs. The connections
697 of the ACC_g with these regions suggest that the ACC_g has access to information about the net-value
698 of rewarding outcomes, whereas as the ACC_s does not. Thus, anatomical evidence is consistent with
699 the view that the ACC_g processes net-value when it relates to a reward another will receive.

700

701 Several lines of evidence support the notion that the ACC_s and the NA are engaged during first-
702 person cost-benefit decision-making. Lesions of the ACC_s disrupt decision-making on cost-benefit
703 tasks (Walton et al., 2006; Hauber and Sommer, 2009). Single-unit recordings from neurons in this
704 region in monkeys (Kennerley et al., 2009) and from homologous areas in rats (Hillman and Bilkey,
705 2010), have identified neurons in which spike frequency is a function of both the magnitude of a
706 reward and the number of lever presses required for receipt. Furthermore, neurons in this region in
707 rats signal the value of rewards discounted by the costs associated with social interaction (Hillman
708 and Bilkey, 2012). Depletions of dopamine in the NA modulate cost-benefit based decision-making
709 and neurophysiological recordings have identified neurons in the nucleus accumbens that show
710 differential spike frequency related to high and low effort conditions (Salamone et al., 2007; Font et
711 al., 2008; Hauber and Sommer, 2009; Walton et al., 2009; Gan et al., 2010; Wanat et al., 2010).
712 Similarly, previous fMRI studies have shown that activity in the ACC_s and the NA is a function of the
713 number of actions (Croxon et al., 2009; Kurniawan et al., 2010; Prevost et al., 2010) or the amount
714 of cognitive effort (Botvinick et al., 2009; Schmidt et al., 2012) that has to be exerted, suggesting
715 that both regions may play an important role in signalling the effortful costs associated with
716 choosing a rewarding option. The results of our study are broadly consistent with these findings,
717 highlighting that activity in the NA signals the net value of first-person rewards and activity in the

718 ACC_s signals the effort-related costs associated with rewards that either oneself or another can
719 obtain.

720

721 Our study is the first to examine activity at the time of cues that signalled the net-value of rewards
722 to be received by another. As a result we were able to extend upon the findings of previous
723 neuroimaging studies investigating the functional properties of the ACC_s in effort-discounting and
724 social decision-making (Behrens et al., 2008; Prevost et al., 2010; Schmidt et al., 2012; Kurniawan et
725 al., 2013; Meyniel et al., 2013). We show that this region processes the costs associated with both
726 one's own and others' rewards, and not just the costs that will be incurred oneself. This finding is
727 consistent with recent single-unit recording studies that identified ACC_s neurons that respond to
728 both one's own or another's decision-making outcomes (Yoshida et al., 2012). However, it is notable
729 that our results are not consistent with those of Croxson et al., (2009) who found a sensitivity to
730 both effort and reward magnitude in the ACC_s. The absence of such an effect in our study could be
731 due to the fact that that the effort period was a fixed time window in this study whereas in Croxson
732 et al., (2009) the duration of the effort period was dependent on the rate at which cancellations
733 were made. It could therefore be argued that ACC_s activity may not be sensitive to the effort-
734 discounted value of a reward, but to temporally discounted reward values. However, such an
735 interpretation is inconsistent with a previous study which showed that activity in the ACC_s is not
736 sensitive to the temporally discounted reward values, but was sensitive to the effort-discounted
737 value of rewards (Prevost et al., 2010). Thus, the absence of an effect of net-value in the ACC_s in this
738 study is likely to be due to differences in the reward magnitudes between this and previous studies
739 and not due to an insensitivity of ACC_s activity to rewards in general.

740

741 In summary, this study investigated the role of the ACC in processing cost-benefit analyses on
742 rewards to be received oneself and by others. Our results highlight the ACC as an important
743 structure in processing the net-value of rewards that will be received by others and also in

744 processing the costs associated with rewards regardless of who will receive them. However, these
745 two functions are supported by the ACC_g and the ACC_s respectively. This study further illuminates
746 the important role that the ACC plays in processing information about others decisions.

747

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749

750 **Figure Legends**

751 Fig.1 (A) Trial structure. Participants performed trials which began with a colour-coded instruction
752 cue. Blue indicated that the subjects (first-person) would perform button presses to receive a
753 financial reward and brown indicated that the button presses would be performed by a confederate
754 (third-person). The position of crosshairs on these stimuli indicated the level of reward available
755 (16p or 4p) and the number of button presses required for reward receipt (two, three, eight or 12).
756 Following this was the effort period, where the required button presses were made by cancelling out
757 highlighted squares that each corresponded to one button on a keypad. Following this was a cue
758 that indicated the number of button presses ('cancellation cue') and then a trigger cue. At the time
759 of the trigger cue, on the third-person trials, the subjects were required to indicate how much
760 reward the third-person would receive (16p, 4p or 0p if they made the incorrect number of button
761 presses). Following this, there was feedback for performance on this judgement task and finally
762 there was feedback for the individual who performed the effort task. The instruction cue onsets
763 were jittered over the first two scans (TRs) of each trial, to sample evoked haemodynamic responses
764 time-locked to these events evenly and independently from the other elements in the trials. The
765 dotted lines indicate the cue that was jittered over the first two TRs. (B) Experimental design
766 displayed in a table showing the 16 different conditions in the experiment. Net-value was calculated
767 as the level of reward divided by the level of effort. These were then log-transformed to create the
768 parameters used for the parametric analysis.

769

770 Fig.2. Behavioural Results. (A) Behavioural results for the performance of the effort task by the
771 subjects themselves. Behavioural performance was high for each effort level and showed no
772 significant differences between effort conditions. (B) Performance at judging the level of reward that
773 was being received by the confederate for each of the 6 net-value levels. A Repeated Measures
774 ANOVA showed no difference in performance by net-value. There was also no effect of effort or
775 reward on the task accuracy.

776 Fig.3. fMRI Results. Activity shown in the ACC_g (A) that covaried with the net-value of the rewards.
777 Beta coefficients (parameter estimates) (B) from the parametric analysis and perstimulus time
778 histogram plots (C) of activity from the peak ACC_g voxel. It is important to note that the beta
779 coefficients from the parametric analysis reflect only the unique variance of a regressor. Thus, the
780 absence of a significant beta coefficient for the effort parameter in the ACC_g suggests that activity in
781 this region cannot be explained by the unique variance of the effort parameter. However, as can be
782 seen in the PSTH plot, ACC_g activity is modulated by both the effort level and the reward level. This
783 supports the notion that activity in this portion of the ACC_g covaries with the net-value of another's
784 reward. (D) Activity shown in the ACC_s that covaried with the effort level on both the first-person and
785 third-person trials. (E) Parameter estimates from the peak ACC_s voxel. (F) Activity shown in the NA
786 that covaried with the net-value on the first-person trials only. Parameter estimates from the peak NA
787 voxel (G). All error bars reflect standard error of the mean.

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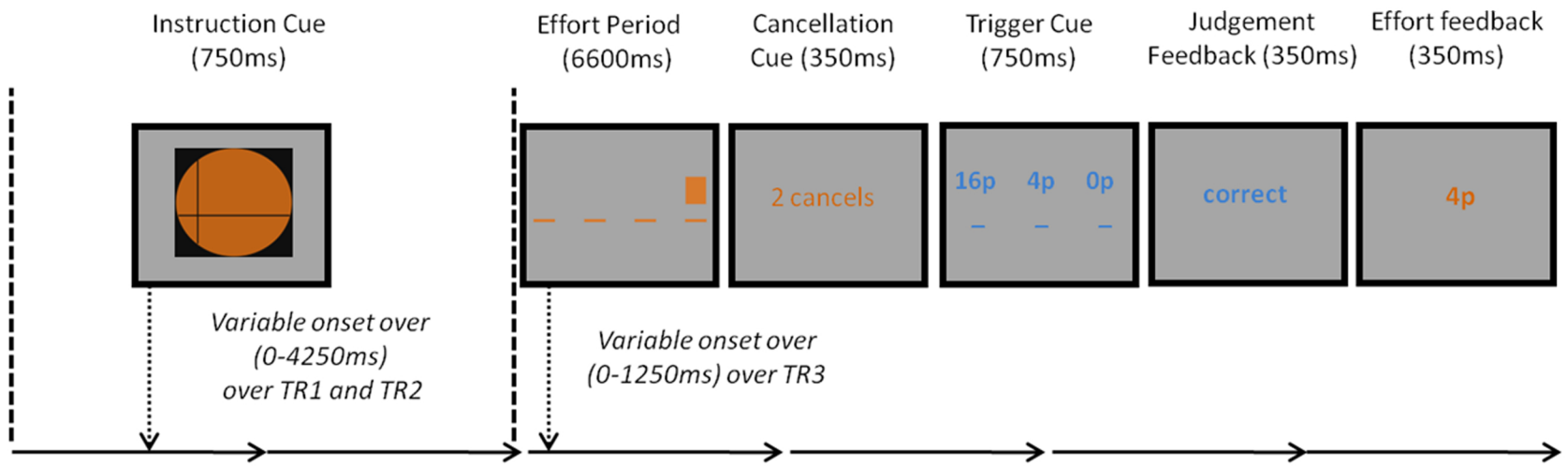
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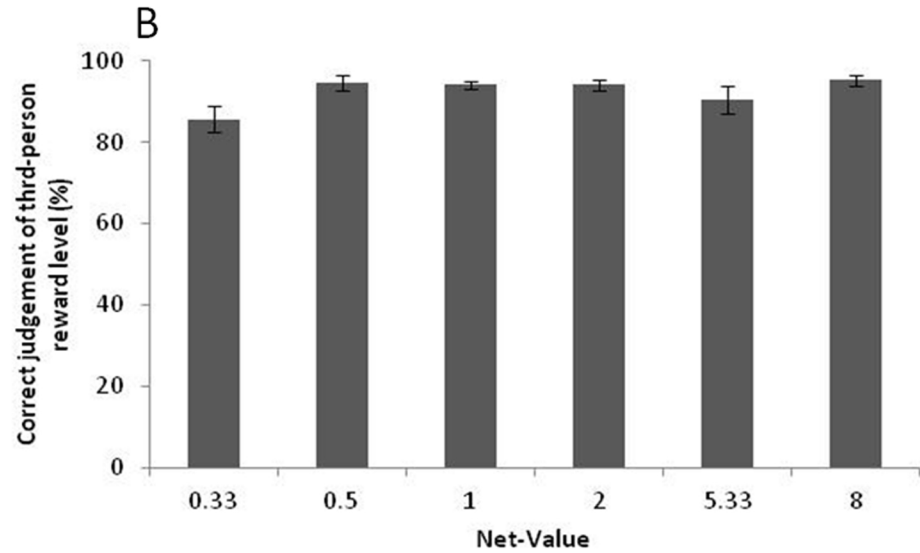
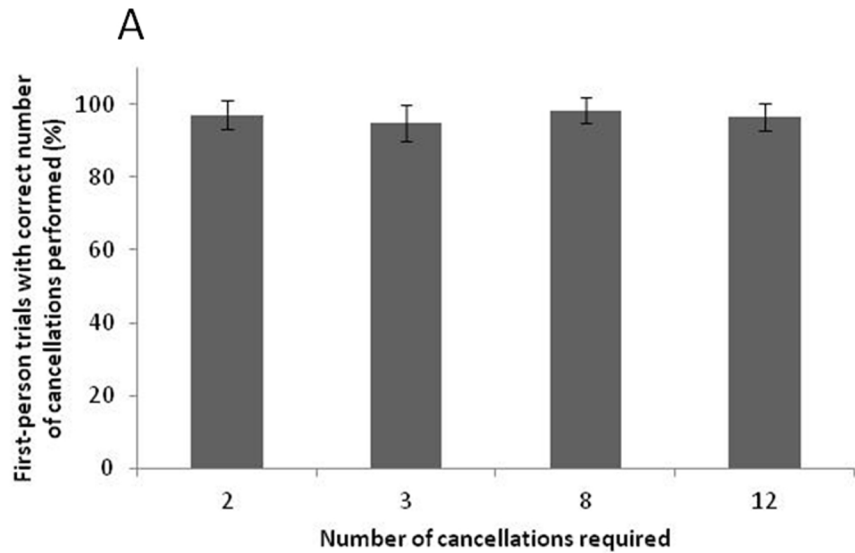
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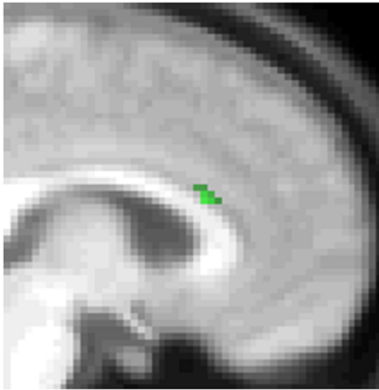
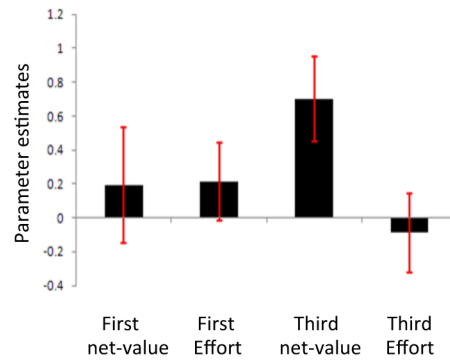
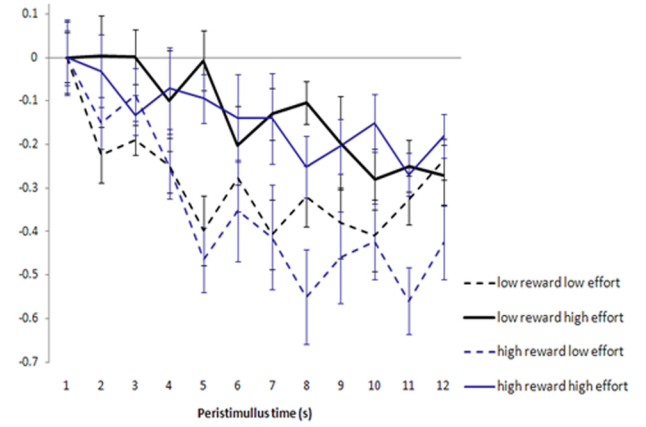
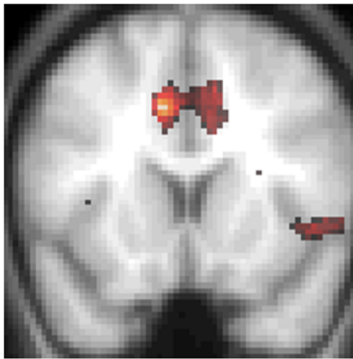
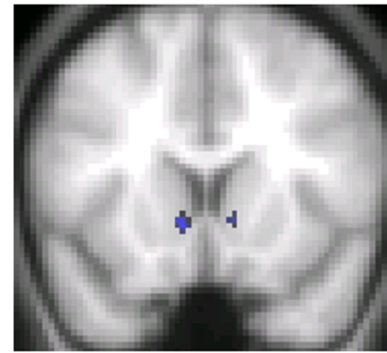
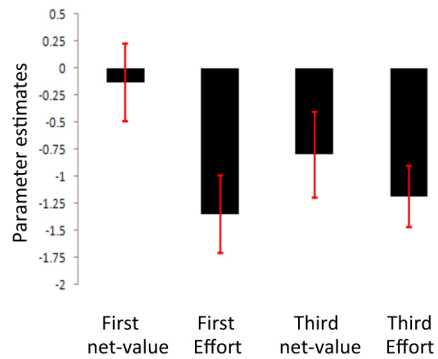
968 Conflicts of interest

969 The authors declare no competing financial interests



	Effort							
	Low				High			
	2		3		8		12	
	1 st	3 rd	1 st	3 rd	1 st	3 rd	1 st	3 rd
High reward (16p)								
Net Value (reward/effort)	8		5.33		2		1.33	
Log net value	0.903		0.727		0.301		0.125	
Low reward (4p)								
Net Value (reward/effort)	2		1.33		0.5		0.33	
Log net value	0.301		0.125		-0.301		-0.477	



A**B****C****D****F****E****G**