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37 **Abstract**

38 A distinct aspect of the sense of fairness in humans is that we care not only about
39 equality in material rewards but also about equality in non-material values. One such
40 value is the opportunity to choose freely among many options, often regarded as a
41 fundamental right to economic freedom. In modern developed societies, equal
42 opportunities in work, living, and lifestyle are enforced by anti-discrimination laws.
43 Despite the widespread endorsement of equal opportunity, no studies have explored
44 how people assign value to it. We used functional magnetic resonance imaging to
45 identify the neural substrates for subjective valuation of equality in choice opportunity.
46 Participants performed a two-person choice task in which the number of choices
47 available was varied across trials independently of choice outcomes. By using this
48 procedure, we manipulated the degree of equality in choice opportunity between players
49 and dissociated it from the value of reward outcomes and their equality. We found that
50 activation in the ventromedial prefrontal cortex tracked the degree to which the number
51 of options between the two players was equal. In contrast, activation in the ventral
52 striatum tracked the number of options available to participants themselves but not the
53 equality between players. Our results demonstrate that the vmPFC, a key brain region
54 previously implicated in the processing of social values, is also involved in valuation of

55 equality in choice opportunity between individuals. These findings may provide
56 valuable insight into the human ability to value equal opportunity, a characteristic long
57 emphasized in politics, economics, and philosophy.

58 **Introduction**

59 Opportunities to choose freely, whether over health care, marriage partners, or political
60 representatives, are considered a fundamental human right in most developed and
61 democratic societies (Inglehart et al., 2008; Delhey, 2009; Welzel and Inglehart, 2010).
62 However, inequality in opportunity to choose is also a pervasive feature of many
63 societies and cultures. Historical examples include slavery, voting restrictions, political
64 participation, civil rights, marriage, apartheid and segregation. Struggles to equalize
65 freedom to choose can span decades and require extraordinary efforts by historical
66 figures such as Martin Luther King, Nelson Mandela, and Aung San Suu Kyi (Kennedy,
67 1989; Silverstein, 1996; Brookfield, 2008). Modern examples exist, such as societal
68 debates over same-sex marriage and women's rights to choose in many countries. These
69 examples also remind us that equality in opportunity is not universally accepted for all
70 choices, by all people and societies.

71 There is an important distinction between equality in *opportunity* and equality in
72 *outcome*, which are different dimensions of social equality (Arneson, 1989; Roemer,
73 2002; Breen, 2010). Humans are unique in having developed social systems that value
74 equality in opportunity (Béteille, 1986, 1994; Flemming et al., 2006). Modern
75 developed societies seem to generally more clearly and universally value equality in

76 opportunity than equality in outcomes (Marshall et al., 1999; Breen, 2010). Of course,
77 equal opportunities do not ensure equal outcomes. However, inequality in outcomes is
78 tolerated, and even celebrated, if it results from fair competition based on equal
79 opportunity (Marshall et al., 1999).

80 Despite these examples of the apparent societal importance of equality in
81 opportunity, previous studies have exclusively focused on neural underpinnings of
82 equality in outcomes (Sanfey et al., 2003; Tabibnia et al., 2008; Tricomi et al., 2010;
83 Baumgartner et al., 2011). Our study is the first to investigate the neural basis of
84 people's subjective valuation of equality in opportunity to choose, using functional
85 magnetic resonance imaging (fMRI). To disentangle the effect of equality in opportunity
86 from that of equality in outcome, we developed a novel task derived from the economic
87 theories that characterize the value of opportunity of choice based on the sheer number
88 of options available, regardless of the value of outcome (Pattanaik and Xu, 1990;
89 Kranich, 1996). In this "two-person choice task" (Fig. 1A), the numbers of options
90 available to a participant ("SELF") and a confederate ("OTHER") were individually
91 manipulated on a trial-by-trial basis, which yielded equal and unequal social situations
92 in terms of their opportunities to choose. Of note, the probability of obtaining a reward
93 outcome was fixed regardless of the numbers of options available. We focused on the

94 neural activity in the ventral striatum (VS) and ventromedial prefrontal cortex (vmPFC),
95 which are known to be involved in value processing (Fliessbach et al., 2007; Behrens et
96 al., 2009; Kringelbach and Berridge, 2009; Mobbs et al., 2009; Haber and Knutson,
97 2010; Clithero et al., 2011; Bartra et al., 2013). We predicted that these regions would
98 be responsive to the value represented by the number of options, even though it was not
99 associated with monetary value in and of itself.

100

101 **Methods**

102 **Participants**

103 Twenty-three undergraduates participated in the study after providing written informed
104 consent. Two females did not complete the experiment due to time constraints. One
105 male completed the experiment but was excluded from the analysis because of
106 excessive head motion (>2 mm) during the main task. The remaining twenty
107 participants (8 females, 12 males; mean age = 20.8 years, range = 19-23, SD = 1.28)
108 were included in the analysis. All participants had normal or corrected-to-normal vision
109 and had no history of psychiatric illness or neurological disease. The study was
110 approved by the ethical committee of Tamagawa University.

111 **Two-person choice task**

112 Participants were instructed to perform a two-person choice task with another person,
113 who was actually a confederate and his/her choices were determined by the computer.
114 The task was designed to dissociate the numbers of options for players from the
115 probability of obtaining a reward outcome. A trial (shown in Fig. 1A) started with the
116 presentation of an “opportunity stimulus,” which signaled the numbers of options
117 available to a participant (SELF) and a confederate (OTHER). The colors indicating the
118 option numbers for SELF and OTHER were counterbalanced across participants. After

119 a 3-7 s randomized interval, positions of options available to the players were displayed,
120 and participants had to choose one of the available options within 4 s. The option
121 chosen by participants was highlighted, and after a short delay (0.8-1.6 s) the
122 confederate's choice was also displayed. After a 2-s interval, reward outcomes for SELF
123 and OTHER were displayed for 5 s. Outcomes were either 1,000 yen ("reward":
124 indicated by a face card) or 0 yen ("no reward": indicated by a deuce). In all trials, two
125 of the four cards were face cards, so that the probability of a reward outcome was 50%
126 regardless of the number of options available. The inter-trial interval (ITI) was
127 randomized from 3 s to 7 s.

128 There were 1, 2, or 4 available options for SELF and OTHER, independently
129 manipulated on a trial-by-trial basis, resulting in nine (3×3) conditions for the
130 opportunity stimulus (Fig. 1B). The degree of equality in opportunity to choose
131 (hereafter referred to as "choice equality") was defined on the basis of how small the
132 difference in the numbers of options between the two players was, regardless of the
133 outcomes of their choices (Fig. 1C). For example, the choice equality was defined to be
134 highest when the two players had the same numbers of options available (Arneson,
135 1989; Kranich, 1996). Each opportunity-stimulus condition was repeated 12 times in the
136 scanner (108 trials in total). The outcomes for SELF and OTHER (either reward or no

137 reward) were determined independent of the opportunity-stimulus conditions, resulting
138 in four (2×2) conditions for the outcome. Unbeknownst to participants, the outcomes for
139 the players were controlled by the computer to balance the actual frequencies of a
140 reward outcome among the nine opportunity-stimulus conditions. This ensured that the
141 number of options had indeed no effect on the expected value of the outcome. Note that
142 this task involved no direct competition between the players. In the decision phase,
143 participants could choose any one of the available options regardless of whether it was
144 also available to the confederate; in the outcome phase, both players could be rewarded
145 individually (rather than sharing a reward) when they had chosen the same option that
146 was revealed to be a reward outcome.

147 **Monetary incentive delay (MID) task**

148 Participants also performed the MID task to help us independently localize regions
149 sensitive to monetary reward (Knutson et al., 2001; Kuhl et al., 2010; Zaki et al., 2011).
150 Each trial started with an 800-ms cue indicating the amount of potential monetary gain
151 or loss (neutral: ±0 yen, low gain: +20 yen, high gain: +400 yen, low loss: -10 yen, or
152 high loss: -200 yen; 20 trials for each cue), followed by a fixation cross (2.0-2.5 s). A
153 white square (“target”) was then presented for 100-700 ms, and participants had to press
154 a button before the target disappeared. Subsequently, a feedback message indicating

155 whether participants successfully responded or not (“hit” or “miss”; accompanied by the
156 amount of gain/loss in the trial) was presented for 800 ms. In gain trials, participants
157 earned the indicated money for a hit response, but earned no money for a miss response.
158 In loss trials, they avoided losing the indicated money for a hit response but lost the
159 money for a miss response. The inter-trial interval was jittered between 2.0 s and 4.0 s.

160 In order to equate the task performance (hit rates) across participants, we adjusted
161 task difficulty for each participant by adaptively changing the duration of the target
162 presentation: If the participant’s hit rate after the n th trial was more than 66%, the
163 duration of target presentation (initialized to 250 ms) for the next trial was decreased by
164 25 ms (minimum: 100 ms); if the hit rate after the n th trial was less than 66%, the target
165 duration for the next trial was increased by 25 ms (maximum: 700 ms). This procedure
166 ensured that a participant’s hit rate was around 66% (Knutson et al., 2001; Kuhl et al.,
167 2010; Zaki et al., 2011).

168 **Experimental procedure**

169 The experiment consisted of four phases: 1) pre-task instruction, 2) fMRI scan for the
170 main task, 3) post-scan subjective ratings, and 4) the second fMRI scan for the MID
171 task. Participants were first introduced to a same-sex confederate. Participants and the

172 confederate were recruited from different universities and had never met each other
173 before. Both the participant and confederate received the instructions, but they did not
174 meet again after the participant entered the scanner.

175 During the instructions, participants were told that the positions of available
176 options and the face cards (associated with reward outcomes) were independently
177 determined at random in each trial so that no effective strategy could be learned. In
178 addition, to avoid forming the incorrect belief that the probability of a reward outcome
179 depended on the number of options, we explicitly told participants that it was always
180 50% for both players, regardless of the numbers of available options. Furthermore, to
181 confirm whether they correctly understood the task instructions, participants were asked
182 to fill in the blanks of the following question:

183 *“Given the fact that the number of the face cards is always __ out of the 4 cards,*
184 *the probability that you obtain a reward outcome in a trial is __%, regardless of*
185 *the number of options available. Likewise, the probability that the other player*
186 *obtains a reward outcome is __%.”*

187 All participants answered correctly (2, 50, and 50), indicating that they clearly
188 understood this point before the fMRI scan. In the instruction phase, participants and the

189 confederate were seated face-to-face at a table and performed several practice trials to
190 make participants believe that they were playing the game with another person.
191 Participants were told that the amount of a reward per trial in the practice was set to 500
192 yen (one-half of that in the actual experiment) and that the players could earn some
193 money depending on the outcomes of three randomly selected trials. In actuality, the
194 outcomes were controlled by the computer and the payoff for participants and the
195 confederate were always 500 yen and 1,000 yen, respectively. The difference in their
196 payoffs was intended to make participants more sensitive to the existence of the
197 confederate while they performed the main task in the scanner.

198 After the instruction phase, participants entered the MRI scanner and performed
199 the main task. The task was organized into three 13-min sessions, each consisting of 36
200 trials. Participants were told prior to the scan that the outcomes of three randomly
201 chosen trials (one from each session) would actually be paid to them. Thus, each
202 participant had a chance to earn 0-3,000 yen. In fact, the payment for the main task was
203 fixed for all participants (1,000 yen) so as not to influence the results of the subsequent
204 MID task.

205 After the scan, participants completed a self-report questionnaire assessing the

206 subjective emotions (happiness, sadness, anger, and disgust) to the opportunity stimuli.
207 The question was “how did you feel (happy, sad, angry, or disgusted) when you saw the
208 opportunity stimuli?” Participants rated their emotions for each of the nine opportunity
209 stimuli using a 7-point scale (1 = not at all, 7 = extremely). The raw ratings were
210 transformed into *z*-scores for each participant and emotion in order to normalize
211 individual differences in the use of rating scales (Hare et al., 2010). The resulting scores
212 were aggregated across the scales to produce a composite measure (happiness –
213 [sadness + anger + disgust]), which was used for the analysis of subjective rating data
214 (Fig. 2). The *z*-scores of the nine opportunity stimuli showed a similar pattern across the
215 four subscales (Pearson correlation coefficients between any two subscales: $|r|$ ranged
216 from 0.52 to 0.86; mean $|r| = 0.70$, $p < 0.05$), which validated the use of the composite
217 measure. We refer to this measure as “subjective emotional pleasantness.” Participants
218 were also asked to answer the perceived probability (% of all trials) of face-card
219 appearance for each of the four option positions. Their answers were used to analyze the
220 potential influence of perceived variance in option values on the value of the number of
221 options (see Results).

222 After a short break, participants received an instruction for the MID task, and
223 re-entered the scanner. The MID task was separated into two sessions (50 trials per

224 session). Participants were told that the payment for the MID task was the sum of the
225 outcomes of all trials. The actual payment for the MID task was 4,620 yen for all
226 participants.

227 **fMRI data acquisition**

228 Functional imaging was conducted using a 3-Tesla Siemens Trio A Tim MRI scanner.
229 Interleaved T2*-weighted gradient-echo echo-planar imaging (EPI) sequences were
230 used to obtain functional images (42 slices, 3 mm × 3 mm × 3 mm voxels, field of view
231 = 192 mm², 64 × 64 matrix, slice gap = 0 mm, repetition time = 2,500 ms, echo time =
232 25 ms, flip angle = 90°). Slice orientation was tilted -30° from the AC-PC line to reduce
233 the signal dropout in the vmPFC (Deichmann et al., 2003). A high-resolution anatomical
234 T1-weighted image (1 mm × 1 mm × 1 mm) was also acquired for each participant.

235 **fMRI data preprocessing**

236 Data were analyzed using Statistical Parametric Mapping (SPM8, Wellcome
237 Department of Imaging Neuroscience, Institute of Neurology, London, UK,
238 <http://www.fil.ion.ucl.ac.uk/spm/>). The first three volumes of each scanning session
239 were discarded before data processing to allow for stabilization of the magnetization.
240 Images were corrected for slice acquisition time within each volume, motion-corrected

241 with realignment to the first volume, spatially normalized to the standard Montreal
242 Neurological Institute EPI template (resampled to 3 mm × 3 mm × 3 mm voxels), and
243 spatially smoothed using a Gaussian kernel with a full width at half maximum of 8 mm.

244 **fMRI data analysis**

245 For each participant, the blood oxygen-level dependent (BOLD) responses were
246 modeled with general linear models (GLMs). Trial-related regressors were convolved
247 with a canonical hemodynamic response function provided by SPM8. For the main task,
248 the GLM included the following parametric regressors: 1) presentation of the
249 opportunity stimulus, modulated by a) the number of available options for SELF, b) that
250 for OTHER, and c) the choice equality (Fig. 1C), and 2) presentation of the reward
251 outcomes, modulated by a) the outcome for SELF (reward = 1, no reward = 0), b) that
252 for OTHER (reward = 1, no reward = 0), and c) the equality in the outcomes between
253 the players (equal outcome = 1, unequal outcome = 0). This model yielded six beta
254 values of interest (β_{OP_SELF} , β_{OP_OTHER} , β_{OP_EQUAL} for activation responding to
255 opportunity stimuli; β_{OU_SELF} , β_{OU_OTHER} , β_{OU_EQUAL} for activation responding to reward
256 outcomes). The model also included the following regressors of no interest: the decision
257 period (with duration of reaction time) and presentation of the confederate's choice. The
258 regressor for the decision period and the regressor for presentation of the confederate's

259 choice were parametrically modulated by the number of options for SELF, that for
260 OTHER, and the degree of equality in the option numbers between the players (identical
261 to the regressor for the opportunity stimulus). A regressor for error trials and six motion
262 parameters were also included in the model.

263 For the MID task, the GLM included the following regressors of interest: 1)
264 presentation of the cue, modulated by potential monetary gain (neutral = 0, low gain = 1,
265 high gain = 2), 2) presentation of the gain outcome, 3) presentation of the no-gain
266 outcome. The model also included the following regressors of no interest: presentation
267 of the cues in the loss trials (low-loss and high-loss cues) and presentation of the
268 outcomes in the loss trials (loss and no-loss outcomes). The loss trials were not used for
269 localizing the reward systems in accordance with previous studies (Kuhl et al., 2010). A
270 regressor for error trials and six motion parameters were also included in the model.

271 Because we had *a priori* hypothesis focusing on the activations of the reward
272 system (i.e., the VS and vmPFC), the second-level group analysis was performed for the
273 voxels within these regions identified by the independent reward-localizer task (i.e., the
274 MID task). First, we created anatomical masks encompassing the VS and vmPFC, using
275 the Automated Anatomical Labeling (AAL) atlas of the WFU Pickatlas toolbox for SPM

276 (Tzourio-Mazoyer et al., 2002; Maldjian et al., 2003). The mask for the VS consisted of
277 the bilateral caudate and putamen and bounded caudally at $y = 0$ to include only the
278 anterior parts of the striatum (Izuma et al., 2010). The mask for the vmPFC consisted of
279 the bilateral medial orbitofrontal gyrus and gyrus rectus (FitzGerald et al., 2012;
280 Janowski et al., 2013; Murayama et al., 2013). Second, within these anatomical masks,
281 we identified the peak activation voxels responding to monetary rewards during the
282 MID task (determined by a second-level group analysis). For the VS, we selected a
283 voxel showing the maximum effect of potential monetary gains, identified using the
284 parametric regressor for the cue (Kuhl et al., 2010). For the vmPFC, we selected a voxel
285 showing the maximum effect in the contrast of monetary gain versus no-gain outcome
286 (Kuhl et al., 2010). Third, we averaged the neural beta values (β_{OP_SELF} , β_{OP_OTHER} ,
287 β_{OP_EQUAL} , β_{OU_SELF} , β_{OU_OTHER} , and β_{OU_EQUAL}) within a 6-mm radius sphere
288 surrounding each of these activation peaks, and performed a one-sample t test (vs. 0).
289 The variables followed a normal distribution ($p > 0.235$, Kolmogorov-Smirnov test).
290 This procedure ensured that the selection of the voxels and subsequent analysis were
291 statistically independent. We also performed an exploratory whole-brain analysis for
292 completeness, with a height threshold of $p < 0.05$, corrected for family-wise error
293 (FWE) across whole brain.

294 **Brain-Behavior correlations**

295 Neural betas (β_{OP_SELF} , β_{OP_OTHER} , and β_{OP_EQUAL}) for individual participants were
296 averaged within the same 6-mm radius spheres used in the group-average analysis.
297 Behavioral betas were obtained by submitting the subjective-rating data (the composite
298 measure) to the same three-factor regression model used in the analysis of the neural
299 responses to the opportunity stimuli (Fig.1C). The variables derived from subjective
300 ratings followed a normal distribution ($p > 0.230$). Relations between the neural beta
301 and subjective emotional pleasantness beta were examined using Pearson correlations.

302

303 **Results**

304 **Subjective emotional pleasantness**

305 We first examined self-reported emotional ratings for various choice opportunities.
306 Participants rated their subjective emotional pleasantness (see Methods for details) of
307 each of the nine opportunity stimuli (Fig. 1B) immediately after the scan. Although the
308 probabilities of the reward outcome were the same for all conditions, and participants
309 were explicitly informed of this fact prior to the scan, the subjective emotional
310 pleasantness of the opportunity stimuli varied significantly across conditions (Fig. 2A).
311 To examine the effects of the numbers of options quantitatively, we analyzed the
312 subjective emotional pleasantness of each participant using a three-factor regression
313 model (Fig.1C). This model assessed the dependencies of the individual subjective
314 emotional pleasantness on 1) the number of options for SELF, 2) the number of options
315 for OTHER, and 3) the choice equality, or the degree of equality in the numbers of
316 options between SELF and OTHER (Fig. 2B). The regression showed that subjective
317 emotional pleasantness became more positive as the choice equality increased
318 ($\beta_{OP_EQUAL}: t_{(19)} = 2.69, p = 0.015$, one-sample t test), and they became more negative as
319 the number of options for OTHER increased ($\beta_{OP_OTHER}: t_{(19)} = -2.27, p = 0.035$). The
320 number of options for SELF had no significant effect ($\beta_{OP_SELF}: t_{(19)} = 1.08, p = 0.294$),

321 possibly due to large inter-individual variation (the variance of β_{OP_SELF} differed
322 significantly from that of β_{OP_OTHER} ; $\chi^2_{(1)} = 24.1$, $p < 0.001$, likelihood-ratio test for
323 equivalence of variances). These results suggest that the subjective emotional
324 pleasantness of choice opportunity is substantially modulated by social comparison of
325 the number of available options. In particular, the choice equality between individuals
326 had a positive effect on subjective emotional pleasantness. It is also notable that the
327 subjective emotional pleasantness β_{OP_SELF} and β_{OP_OTHER} were negatively correlated
328 across participants ($r = -0.55$, $p = 0.012$), indicating that the more individuals valued
329 their own choice opportunities, the more they tended to devalue the other player's. The
330 subjective emotional pleasantness β_{OP_EQUAL} was not correlated with β_{OP_SELF} ($r = -0.05$,
331 $p = 0.826$) or with β_{OP_OTHER} ($r = -0.11$, $p = 0.655$).

332 **Neural response to reward outcome**

333 Before analyzing the neural responses to the opportunity stimuli, we confirmed that the
334 reward-coding voxels identified by the independent reward-localizer task (activation
335 peaks: $x = 15$, $y = 11$, $z = -5$ for the VS, Fig. 3A; $x = 9$, $y = 44$, $z = -14$ for the vmPFC,
336 Fig. 4A) also responded to the reward outcome during the two-person choice task. The
337 neural responses to the reward outcomes were analyzed based on a three-factor model
338 that separated the effects of the outcome for SELF, that for OTHER, and equality in the

339 outcomes between the players (see Methods). As expected, both the VS and vmPFC
340 were sensitive to the reward outcome for SELF (Table 1), consistent with the large
341 literature describing the role of these regions in processing monetary reward outcomes
342 (Tricomi et al., 2004; Fliessbach et al., 2007; Mobbs et al., 2009; Haber and Knutson,
343 2010; Kang et al., 2013). Furthermore, the vmPFC showed an increased activation to
344 the equality in the outcomes between the players (Table 1), in line with the results of
345 previous studies reporting vmPFC activations to equitable monetary allocations between
346 self and other (Tabibnia et al., 2008; Tricomi et al., 2010; Baumgartner et al., 2011; Zaki
347 and Mitchell, 2011).

348 **Neural response to opportunity stimulus**

349 The neural responses to the opportunity stimuli were analyzed using the same
350 three-factor regression model as was used in the analysis of subjective emotional
351 pleasantness (Fig. 1C). The VS showed significantly greater activation in response to an
352 increasing number of available options for SELF (Fig. 3B; β_{OP_SELF} : $t_{(19)} = 4.43$, $p <$
353 0.001 ; one-sample t test). This VS activation was not explained by the expected
354 outcome values because the probability and magnitude of the reward outcome was fixed
355 across conditions. The VS activation was not significantly modulated either by the
356 number of options for OTHER (β_{OP_OTHER} : $t_{(19)} = -0.10$, $p = 0.918$) or by the choice

357 equality (β_{OP_EQUAL} : $t_{(19)} = -0.41$, $p = 0.690$). We further examined whether
358 inter-individual variations in VS reactivity to the number of options were associated
359 with variations in self-reported emotional pleasantness. The sensitivity of the VS
360 activation to the number of options for SELF with reference to that for OTHER (i.e.,
361 neural $\beta_{OP_SELF} - \beta_{OP_OTHER}$) was positively correlated with that of the subjective
362 emotional pleasantness (i.e., subjective emotional pleasantness $\beta_{OP_SELF} - \beta_{OP_OTHER}$;
363 derived from the regression analysis of the subjective rating data) across participants
364 (Fig. 3C; Pearson correlation coefficient $r = 0.44$, $p = 0.050$; after controlling for age
365 and gender, $r = 0.44$, $p = 0.069$). In contrast, the sensitivity of the VS activation to the
366 choice equality (i.e., neural β_{OP_EQUAL}) was not significantly correlated with that of the
367 subjective emotional pleasantness (i.e., subjective emotional pleasantness β_{OP_EQUAL} ;
368 derived from the regression analysis of the subjective rating data) (Fig. 3D; $r = 0.04$, $p =$
369 0.858).

370 In contrast, the vmPFC activation significantly increased with the choice equality
371 (Fig. 4B; β_{OP_EQUAL} : $t_{(19)} = 2.15$, $p = 0.045$), but not with the number of available options
372 for SELF (β_{OP_SELF} : $t_{(19)} = 0.26$, $p = 0.801$) or for OTHER (β_{OP_OTHER} : $t_{(19)} = -0.06$, $p =$
373 0.950). In other words, the vmPFC activation was enhanced when the options available
374 to each of the two players were more equal, regardless of the absolute number of

375 options for each player. Furthermore, the sensitivity of the vmPFC to the choice equality
376 (i.e., neural β_{OP_EQUAL}) was positively correlated with the sensitivity of the subjective
377 emotional pleasantness (i.e., subjective emotional pleasantness β_{OP_EQUAL}) across
378 participants (Fig. 4D; $r = 0.47$, $p = 0.034$; after controlling for age and gender, $r = 0.48$,
379 $p = 0.043$). The vmPFC response to the number of options for SELF with reference to
380 that for OTHER (i.e., neural $\beta_{OP_SELF} - \beta_{OP_OTHER}$) was not significantly correlated with
381 the corresponding subjective emotional pleasantness (i.e., subjective emotional
382 pleasantness $\beta_{OP_SELF} - \beta_{OP_OTHER}$) across participants (Fig. 4C; $r = 0.17$, $p = 0.484$).

383 To examine whether neural activation patterns observed in the VS and vmPFC
384 were statistically different or not, we performed a 2×2 ANOVA with region (the VS or
385 vmPFC) and regressor (SELF or EQUAL) as within-subject factors. We found no
386 significant main effect of the region ($F_{(1, 19)} = 1.74$, $p = 0.203$) or regressor ($F_{(1, 19)} =$
387 2.65 , $p = 0.120$), but we did find a significant interaction between the two factors ($F_{(1, 19)}$
388 $= 19.9$, $p < 0.001$). This significant region \times regressor interaction confirmed a
389 differential activation pattern between the VS and vmPFC. Specifically, the VS is
390 preferentially activated by the number of options for participants themselves, whereas
391 the vmPFC is preferentially activated by the choice equality. To further characterize the
392 regional specificity, we also looked at brain activation in all voxels within the combined

393 anatomical mask of VS and vmPFC. When we applied a statistical threshold equivalent
394 to that used in the localizer-based analysis ($p < 0.05$, uncorrected, without an extent
395 threshold; note that this analysis is not for statistical significance testing, but to assess
396 the spatial distributions of activated voxels), we found that all voxels responding to the
397 increased number of options for SELF ($2 \leq y \leq 23$ in the MNI coordinates) belonged to
398 clusters in the bilateral VS, whereas all voxels responding to the increased choice
399 equality ($26 \leq y \leq 50$ in the MNI coordinates) belonged to clusters in the vmPFC. These
400 results indicated a robust regional specificity without any bias in voxel selection that
401 might have been caused by the localizer task.

402 An exploratory whole-brain analysis identified significant activation to the
403 number of options for SELF in the several brain areas outside the *a priori* regions of
404 interest (Table 2). The neural responses to the number of options for OTHER and to the
405 choice equality were not significant outside the *a priori* regions of interest (Table 2).

406 **Does perceived probability of reward outcome explain VS response to the number**
407 **of options?**

408 Although the objective probability of a reward outcome was fixed across conditions,
409 there was a concern that a perceived bias in the probability of a reward outcome had

410 influenced the VS activation to the number of options for SELF. However, the results of
411 the following additional analyses suggest that the observed VS activation is not
412 explained by the perceived probability of a reward outcome. First, before scanning,
413 participants actively answered to a question asking the probability of a reward outcome
414 independent of the number of options, confirming that they had explicit knowledge
415 about the objective probability (see Methods). If participants still had an implicit belief
416 that a larger number of options was associated with a higher probability of a reward
417 outcome, the VS activation to the number of options for SELF (i.e., the neural β_{OP_SELF})
418 should be largest in the first session and decrease over the sessions, because participants
419 would learn through the experience that the number of options was not related to the
420 probability of a reward outcome. However, our data indicates that this was not the case:
421 There was no trend in the neural β_{OP_SELF} over the three sessions ($F_{(2, 38)} = 0.33, p =$
422 0.721 , one-way repeated-measures ANOVA with session as a factor; Session 1: $t_{(19)} =$
423 $3.00, p = 0.007$; Session 2: $t_{(19)} = 1.92, p = 0.069$; Session 3: $t_{(19)} = 2.98, p = 0.008$),
424 suggesting little effect of learning on the VS response to the number of options for
425 SELF. The vmPFC response to the choice equality was also unchanged over the session
426 ($F_{(2, 38)} = 0.09, p = 0.913$).

427 Second, we examined whether the subjective value of the number of options
428 for SELF depended on the variance in perceived probability of face-card appearance.
429 The reason we assessed the variance in the perceived probability is as follows: In theory,
430 if participants perceived that each option was associated with different reward
431 probabilities, they might think that a larger number of available options would allow
432 them to choose a “better” option, thereby increasing the probability of obtaining a
433 reward. For instance, if participants perceived that the probabilities of face-card
434 appearance were 30%, 40%, 50%, and 60% for the respective option positions, they
435 might expect that the probability of obtaining a reward would increase with the number
436 of options available. In contrast, if another participant perceived that the probabilities of
437 face-card appearance were 90% for all four option positions, they would not expect that
438 the probability of obtaining a reward would depend on the number of options available
439 (because there were no better or worse options). To assess the possible effect of the
440 variance in perceived option values on the subjective value of choice, we asked
441 participants after the scan to indicate their perceived probability (% out of all trials) of
442 face-card appearance for each option position. We defined their answers as the
443 perceived option values, and calculated the perceived option-value variance (the
444 standard deviation of the perceived option value among the four options). The VS

445 response (neural β_{OP_SELF}) for the participants who reported no perceived option-value
446 variance (i.e., the perceived option values were 50% for all four options; $n = 10$) was
447 significant ($t_{(9)} = 2.51, p = 0.034$) and not statistically different from that for the other
448 participants ($t_{(18)} = -0.54, p = 0.598$; two-sample t test), suggesting that the VS response
449 to the number of options for SELF was not due to the perceived variance in the option
450 values. The perceived option-value variance (mean \pm SD across participants = $6.84 \pm$
451 8.44) was not significantly correlated with the VS response (neural β_{OP_SELF} ; $r = 0.26, p$
452 $= 0.272$) or with the subjective valuation of the number of options for SELF (subjective
453 emotional pleasantness β_{OP_SELF} ; $r = 0.31, p = 0.182$). Based on these results, we
454 concluded that the perceived variance in the option values had little influence on the VS
455 activation to the number of options for SELF. The perceived option-value variance was
456 also not significantly correlated with the vmPFC response to the choice equality (neural
457 β_{OP_EQUAL} ; $r = 0.26, p = 0.266$) or with the subjective valuation of the choice equality
458 (subjective emotional pleasantness β_{OP_EQUAL} ; $r = 0.21, p = 0.376$).

459 Discussion

460 The present study aimed to identify the neural substrate for subjective value of equality
461 in choice opportunity. We set up an experimental situation in which participants
462 compared their number of available options with those of another. By using this task
463 procedure, we were able to probe specifically the value of social equality in the number
464 of options without confounding by reward-outcome values or their equality. Our
465 findings demonstrate that the vmPFC showed greater activation as the number of
466 options between two players became equal. In contrast, the VS activation increased with
467 the absolute number of options available to participants themselves and did not respond
468 to the relative equality between the players. These results suggest that the vmPFC plays
469 a critical role in subjective valuation of equality in choice opportunity.

470 While the importance of equal opportunity and its distinction from equal outcome
471 have long been emphasized in the fields of politics and economics (Arneson, 1989;
472 Roemer, 2002; Breen, 2010), experimental research has never explored the neural basis
473 of how humans subjectively value equal opportunity. We found that the vmPFC
474 activation tracks the degree of equality in the numbers of options between two people.
475 This vmPFC activation paralleled the result of self-reported emotional pleasantness,
476 which also increased with the relative equality in the number of options. These findings

477 suggest that the vmPFC, a region previously implicated in ethical judgment (Heekeren
478 et al., 2003; Prehn et al., 2008), plays an important role in valuation of equality in
479 choice opportunity. Moreover, the vmPFC reactivity to equality in the number of
480 options varied across participants and was positively correlated with the subjective
481 emotional pleasantness sensitivity. The vmPFC reactivity might therefore reflect
482 individual differences in the extent to which a person values equality in choice
483 opportunity. Thus, our subjective-rating and neuroimaging results provide the first
484 empirical evidence that humans do value equality in choice opportunity and that the
485 specific neural substrate involved in its valuation is the vmPFC.

486 In contrast to the vmPFC, activation in the VS did not reflect the option-number
487 equality between the players. Instead, the VS activation increased with the number of
488 options available to the participants themselves, but not their partners. Importantly, the
489 VS activation was not explained by between-condition differences in the objective
490 probabilities and risks of the reward outcome, because these factors were fixed
491 regardless of the number of options. Our finding was consistent with recent fMRI
492 studies that reported greater striatal activation to a stimulus indicating choice
493 opportunity than to a stimulus indicating no choice, without regard to the expected
494 outcome value of a choice (Leotti and Delgado, 2011; Fujiwara et al., 2013; Murayama

495 et al., 2013). These findings provide the neural evidence for the value of choice
496 opportunity, supporting the psychological literature describing the beneficial effects of
497 choice opportunity on decision-making behaviors and subjective emotions (Suzuki,
498 2000; Tricomi et al., 2004; Patall et al., 2008; Leotti et al., 2010; Fischer and Boer,
499 2011). Of note, unlike the previous study (Leotti and Delgado, 2011), we explicitly
500 instructed our participants that the number of options were irrelevant to the probability
501 of obtaining a reward outcome. In addition, the VS activation was significant already in
502 the initial session and unchanged over the experimental sessions, suggesting that the
503 value associated with the number of options was little affected by learning from
504 outcome feedback. Furthermore, the perceived variance in the probability of a reward
505 outcome among the options was not related to the VS activation associated with the
506 subjective value of the number of options. These results may further indicate that the
507 value of choice represented in the VS is distinct of the value of reward outcomes.

508 The differential activation pattern we observed between the vmPFC and VS is
509 notable. Specifically, the vmPFC activity reflected the degree of social equality (as
510 indexed by similarity in option numbers) between the two players, while the VS
511 reflected participants' own number of options, regardless of how many the other player
512 had. These findings are consistent with the idea that the vmPFC play critical roles in

513 processing social information, which has been supported by patient studies
514 demonstrating that selective damages to the vmPFC cause the absence of emotions
515 involving social comparison (Koenigs and Tranel, 2007; Shamay-Tsoory et al., 2007)
516 and a reduction in inferred prosociality (Krajbich et al., 2009). Although fMRI studies
517 have frequently reported co-activations of the vmPFC and VS, these two regions
518 differentially contribute to value computation (Hare et al., 2008; Basten et al., 2010;
519 Philiastides et al., 2010). Recent fMRI studies have begun to elucidate distinct roles of
520 the vmPFC and VS in processing social values (Mobbs et al., 2009; Cooper et al., 2010;
521 Zaki and Mitchell, 2011; Suzuki et al., 2012). For instance, Suzuki et al. (2012)
522 examined the neural representation of reward values for self and others, and found that
523 the vmPFC encoded reward prediction error for both self and others, whereas the VS
524 encoded reward prediction error only for self, not for the other person. Zaki and
525 Mitchell (2011) examined the brain activation in a social decision-making task, and
526 reported that the activation to monetary outcomes in the vmPFC, but not in the VS, was
527 modulated by social contexts. Taken together, the vmPFC seems to play a more
528 important role than the VS in valuation of social information including equality in
529 opportunity. Meanwhile, some other studies have reported that the vmPFC and VS show
530 similar responses to social contexts (Tricomi et al., 2010; Bault et al., 2011; Kang et al.,

531 2013). Future research will benefit from clarifying whether and how the vmPFC and VS
532 are differentially involved in reward processing within a range of social contexts.

533 Several other patterns in our findings are also worth noting. First, the fact that
534 vmPFC activity was not modulated by the choice opportunities of participants
535 themselves is consistent with fMRI studies that have investigated the effect of choice
536 opportunities on brain activation in non-social situations (Leotti and Delgado, 2011;
537 Fujiwara et al., 2013). The vmPFC seems to be important for how self-determined
538 choice influences subjective value of reward outcomes (Murayama et al., 2013), which
539 should be distinguished from the value of choice in itself. Second, our behavioral results
540 indicate that when the other player's choice opportunities increase, one's own emotional
541 pleasantness decreases, although no corresponding effect is observed in activation of the
542 VS or vmPFC. This apparent discrepancy between behavior and brain activation may be
543 explained by differences between the post-scan subjective rating task and the fMRI task:
544 participants made active evaluations regarding the opportunity stimuli and spent as
545 much time as they needed to do so in the post-scan rating task, whereas they passively
546 viewed the opportunity stimuli for only a few seconds in the fMRI task. In a situation
547 like our fMRI task, individuals might focus primarily on features that are salient to them,
548 and it may be that only those features affect subjective values. Our fMRI results imply

549 that participants focused predominantly on their own choice opportunities and the
550 choice equality between the players during the in-scanner task. This interpretation
551 accords with previous studies showing that activation associated with subjective value
552 in the reward system is dramatically influenced by what participants attend to (Hare et
553 al., 2011; Lim et al., 2011). It is conceivable that the number of options available to
554 others would also modulate reward system activity if participants were explicitly
555 instructed to pay attention to it, which could be tested in future research. Third, we
556 found that the sensitivity of subjective emotional pleasantness to the participants' own
557 choice opportunities markedly varied across participants, and that the variation was
558 greater than that for sensitivity to the other player's choice opportunities. Other studies
559 have suggested that the value of one's own choice opportunities may change depending
560 on various psychological factors such as depressed mood and susceptibility to illusion
561 of control (Taylor and Brown, 1988; Leotti et al., 2010). Interestingly, these factors can
562 have a greater influence on the value of one's own choice than on those of others (Golin
563 et al., 1979), which may underlie our finding that inter-individual variation in sensitivity
564 of subjective emotional pleasantness to choice opportunity was larger when considering
565 the participants' own number of options than those of the other players.

566 To conclude, our study demonstrates that the vmPFC, which has been implicated

567 in reward-related information processing in a variety of situations, is also involved in
568 valuation of social equality in choice opportunity. Although several animals seems to be
569 sensitive to fairness and equality in reward outcomes (Brosnan, 2006; Range et al.,
570 2009; Proctor et al., 2013), only humans care about equality in choice opportunity, a
571 distinctive dimension of social equality that has been developed and enforced by
572 modern social-cultural systems (Béteille, 1986, 1994; Buckholtz and Marois, 2012). The
573 ability to value both equal opportunity and equal outcome and to take balance between
574 them may be a hallmark of the ethical and moral sense that is uniquely human. Our
575 findings may shed light on how a subjective value of equality in choice opportunity
576 emerged in the human brain.

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752

753

754 **Figure legends**

755 **Figure 1.** Two-person choice task. (A) A trial started with the presentation of an
756 “opportunity stimulus” that indicated the number of choice options available to a
757 participant (SELF) and confederate (OTHER). During the subsequent decision period,
758 each player chose one of the options available to them (the confederate’s choice was
759 actually determined by computer). The reward outcomes of their choices were indicated
760 by cards (a face card was associated with monetary rewards whereas a deuce was
761 associated with no reward). In the example shown in the figure, there are two options
762 available to the participant, and four to the confederate. Upon choice, the participant's
763 chosen option is highlighted, followed by the revealed choice of the confederate,
764 followed by simultaneous showing of both of their outcomes (“no reward” for the
765 participant and “reward” for the confederate in this case). (B) Opportunity-stimulus
766 conditions. The numbers of choice options for SELF and OTHER were manipulated
767 independently. (C) The regression model used to analyze the neural responses to the
768 opportunity stimuli. The 3×3 matrices represent the nine opportunity-stimulus
769 conditions shown in B. The same model was also used to analyze subjective emotional
770 pleasantness (see Fig. 2B). The beta coefficients indicate how the dependent variables
771 ($R_{(s, o)}$: the neural responses or subjective emotional pleasantness) of an individual are
772 sensitive to 1) the number of available options for the participant (β_{OP_SELF}), 2) those for
773 the confederate (β_{OP_OTHER}), and 3) the “choice equality” or the degree of equality in the
774 numbers of available options between the two players (β_{OP_EQUAL}), quantified using the
775 absolute value of their difference.

776

777 **Figure 2.** Sensitivity of subjective emotional pleasantness on the numbers of options
778 available. (A) Self-reported emotional pleasantness of opportunity stimuli. Participants
779 rated the subjective emotional pleasantness of each of the nine combinations of the
780 opportunity stimuli immediately after the scan. (B) The effects on the subjective
781 emotional pleasantness of the number of options for SELF (β_{OP_SELF}), that for OTHER
782 (β_{OP_OTHER}), and the equality in option numbers (i.e., choice equality) between the two
783 players (β_{OP_EQUAL} , quantified using the absolutely value of the difference between self
784 and other options). Error bars depict SEM. * $p < 0.05$ (one-sample t test, two tailed).

785

786 **Figure 3.** Neural responses in the VS. (A) The VS as identified by the independent
787 reward-localizer task. The VS was significantly activated ($p < 0.05$, FWE-corrected
788 within the VS anatomical mask) during the MID task in response to potential monetary
789 gains. Image is shown at a stringent threshold ($p < 0.0001$, whole-brain FWE-corrected;
790 $k \geq 10$) for display. (B) Activation in the VS in response to the opportunity stimuli.
791 Neural beta values were averaged within a 6-mm radius sphere surrounding the peak
792 voxel determined by the group-level random-effects analysis for the reward-localizer
793 task. Error bars depict SEM. * $p < 0.05$ (one-sample t test, two-tailed). (C, D) Relations
794 between neural responses and subjective emotional pleasantness sensitivities. The
795 neural beta for the number of options for SELF minus that for OTHER ($\beta_{OP_SELF} -$
796 β_{OP_OTHER}) was positively correlated with that derived from the subjective emotional
797 pleasantness across participants (C). On the other hand, the neural beta for choice
798 equality (β_{OP_EQUAL}) was not correlated with that derived from the subjective emotional
799 pleasantness (D). Pearson correlation coefficients (r) and associated p values (two
800 tailed) are shown in the figure.

801

802 **Figure 4.** Neural responses in the vmPFC. (A) The vmPFC as identified by the
803 independent reward-localizer task. The vmPFC was significantly activated ($p < 0.05$,
804 FWE-corrected within the vmPFC anatomical mask) in response to monetary gain
805 versus no-gain outcomes during the MID task. Image is thresholded at $p < 0.001$,
806 uncorrected; $k \geq 10$ for display. (B) Activation in the vmPFC in response to the
807 opportunity stimuli. Neural beta values were averaged within a 6-mm radius sphere
808 surrounding the peak voxel determined by group-level random-effects analysis for the
809 reward-localizer task. Error bars depict SEM. $*p < 0.05$ (one-sample t test, two-tailed).
810 (C, D) Relations between neural responses and subjective emotional pleasantness
811 sensitivities. The neural beta for the number of options for SELF minus that for OTHER
812 ($\beta_{OP_SELF} - \beta_{OP_OTHER}$) was not significantly correlated with that derived from the
813 subjective emotional pleasantness across participants (C). On the other hand, the neural
814 beta for choice equality (β_{OP_EQUAL}) was positively correlated with that derived from
815 subjective emotional pleasantness (D). Pearson correlation coefficients (r) and
816 associated p values (two tailed) are shown in the figure.

817

818 **Tables**819 **Table 1.** Neural responses to reward outcome in the two-person choice task.

820

Region	Contrast	<i>t</i>	<i>p</i>
VS (15, 11, -5)	$\beta_{\text{OU_SELF}} > 0$	3.48	0.003
	$\beta_{\text{OU_OTHER}} > 0$	-1.04	0.309
	$\beta_{\text{OU_EQUAL}} > 0$	-0.92	0.368
vmPFC (9, 44, -14)	$\beta_{\text{OU_SELF}} > 0$	2.67	0.015
	$\beta_{\text{OU_OTHER}} > 0$	-0.58	0.567
	$\beta_{\text{OU_EQUAL}} > 0$	3.27	0.004

821

822
823
824**Table 2.** Significant activations identified by whole-brain analysis for the two-person choice task.

Contrast	Brain region (Peak activation)	MNI-coordinates			Peak Z	Cluster size (#voxels)
		<i>x</i>	<i>y</i>	<i>z</i>		
$\beta_{OP_SELF} > 0$	^a Occipital cortex (Left)	-27	-73	37	5.19	2
	^a Supplementary motor area (Right)	3	17	52	5.13	26
	^b Occipital cortex (Right)	15	-103	4	4.94	2
	^a Dorsomedial prefrontal cortex (Left)	-6	32	37	4.82	1
$\beta_{OP_OTHER} > 0$	-					
$\beta_{OP_EQUAL} > 0$	-					
$\beta_{OU_SELF} > 0$	^c Occipital cortex (Left)	-27	-103	1	5.35	20
	^d Occipital cortex (Right)	27	-103	4	5.25	34
	^e Posterior orbitofrontal cortex (Right)	24	17	-20	5.10	2
	^e Ventral striatum (Left)	-12	5	-14	4.93	6
	^e Ventral striatum (Right)	9	5	-11	4.91	3
	^f Rostral anterior cingulate cortex (Left)	-3	41	7	4.89	1
	^g Central orbitofrontal cortex	-36	35	-11	4.84	1

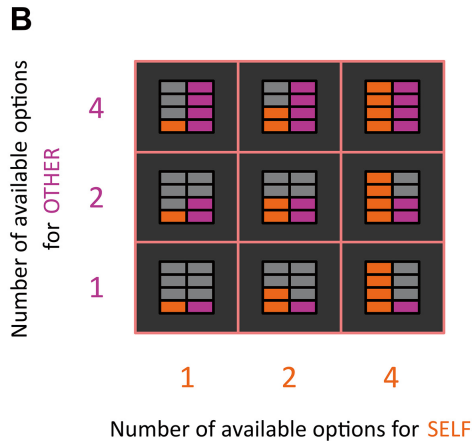
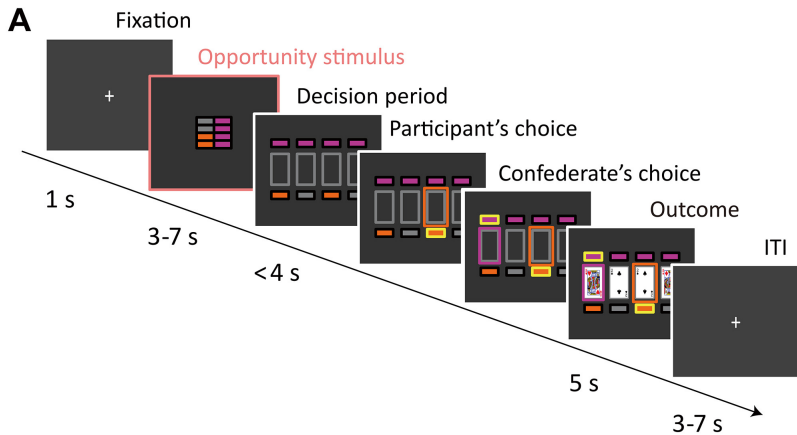
(Left)

$$\beta_{\text{OU_OTHER}} > 0 \quad -$$

$$\beta_{\text{OU_EQUAL}} > 0 \quad -$$

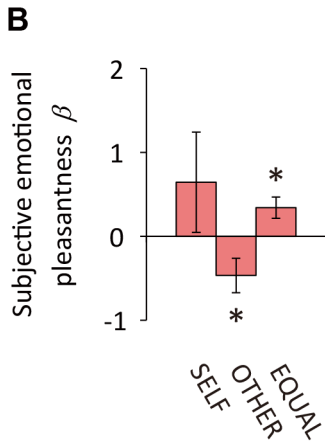
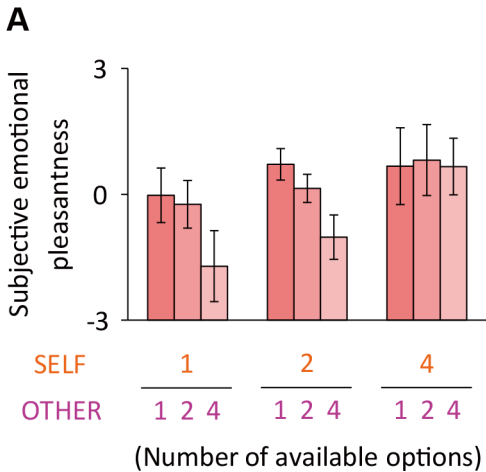
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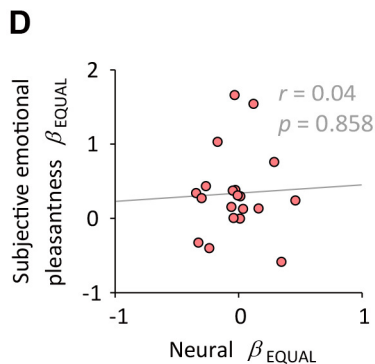
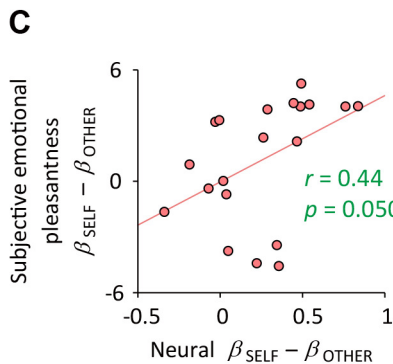
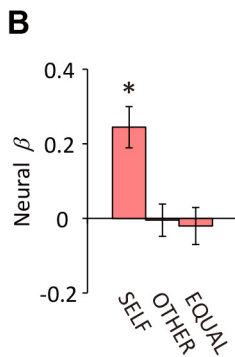
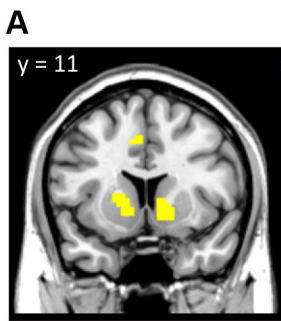
826 *Notes.* Results are based on a second-level random-effects analysis. Activations were
 827 identified by a height threshold of $p < 0.05$, FWE-corrected across the whole brain.
 828 When a height threshold of $p < 0.001$, uncorrected was applied: a) these regions
 829 belonged to a single cluster of 2720 voxels; b) belonged to a cluster of 738 voxels; c)
 830 belonged to a cluster of 289 voxels; d) belonged to a cluster of 462 voxels; e) belonged
 831 to a single cluster of 568 voxels; f) belonged to a cluster of 549 voxels; g) belonged to a
 832 cluster of 375 voxels. All clusters survived at cluster-level $p < 0.05$, FWE-corrected
 833 across whole brain. No activation was found in the inversed contrasts.

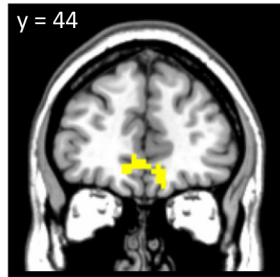


C

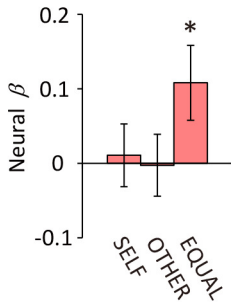
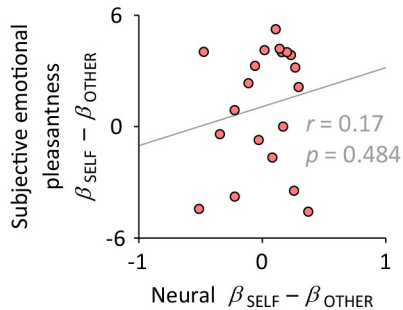
$$R_{(s, o)} = \beta_{OP_SELF} * \begin{bmatrix} 1 & 2 & 4 \\ 1 & 2 & 4 \\ 1 & 2 & 4 \end{bmatrix} + \beta_{OP_OTHER} * \begin{bmatrix} 4 & 4 & 4 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{bmatrix} + \beta_{OP_EQUAL} * \begin{bmatrix} 1 & 2 & 4 \\ 3 & 4 & 2 \\ 4 & 3 & 1 \end{bmatrix} + \beta_0 + \epsilon$$





A

vmPFC (9, 44, -14)

B**C****D**