

1 **The neural correlates of economic value and valuation context: An event-related**  
2 **potentials study**

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4 John Tyson-Carr <sup>1</sup>, Katerina Kokmotou <sup>1,2</sup>, Vicente Soto <sup>1</sup>, Stephanie Cook <sup>1</sup>, Nicholas Fallon  
5 <sup>1</sup>, Timo Giesbrecht <sup>3</sup>, Andrej Stancak <sup>1,2</sup>

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7 <sup>1</sup> Department of Psychological Sciences, University of Liverpool, Liverpool, UK.

8 <sup>2</sup> Institute for Risk and Uncertainty, University of Liverpool, Liverpool, UK.

9 <sup>3</sup> Unilever Research and Development, Port Sunlight, UK.

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11 Corresponding author:

12 John Tyson-Carr

13 Department of Psychological Sciences

14 University of Liverpool

15 Liverpool, L69 7ZA

16 United Kingdom

17 Email: [hljtyson@liverpool.ac.uk](mailto:hljtyson@liverpool.ac.uk)

18 Phone: +44 151 794 6956

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26 **Abstract**

27           The value of environmental cues and internal states is continuously evaluated by the  
28 human brain and it is this subjective value that largely guides decision-making. The present  
29 study aimed to investigate the initial value attribution process, specifically the spatio-  
30 temporal activation patterns associated with values and valuation context using  
31 electroencephalographic event-related potentials (ERPs). Participants completed a stimulus  
32 rating task in which everyday household items marketed up to a price of £4 were evaluated  
33 with respect to their desirability or material properties. The subjective values of items were  
34 evaluated as willingness-to-pay (WTP) in a Becker-DeGroot-Marschak auction. Based on the  
35 individual's subjective WTP values, the stimuli were divided into high and low value items.  
36 Source dipole modelling was applied to estimate the cortical sources underlying ERP  
37 components modulated by subjective values (high vs. low WTP) and the evaluation condition  
38 (value-relevant vs. value-irrelevant judgments).

39           Low WTP items and value-relevant judgements both led to a more pronounced N2  
40 visual evoked potential at right frontal scalp electrodes. Source activity in right anterior insula  
41 and left orbitofrontal cortex was larger for low vs. high WTP at around 200 ms. At a similar  
42 latency, source activity in right anterior insula and right parahippocampal gyrus was larger  
43 for value-relevant vs. value irrelevant judgements. A stronger response for low- than high-  
44 value items in anterior insula and orbitofrontal cortex appears to reflect aversion to low-  
45 valued item acquisition which, in an auction experiment, would be perceived as a relative  
46 loss. This initial low-value bias occurs automatically irrespective of the valuation context.

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50 **New & Noteworthy**

51 We demonstrate the spatio-temporal characteristics of the brain valuation process using  
52 event-related potentials and willingness-to-pay as a measure of subjective value. The N2  
53 component resolves values of objects with a bias toward low-value items. The value-related  
54 changes of N2 component are part of an automatic valuation process.

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## 75 **1. Introduction**

76 Economic values of stimuli are continuously and automatically encoded in the  
77 human brain. Previous brain imaging studies show that valuation occurs predominantly in the  
78 orbitofrontal cortex (OFC), ventromedial prefrontal cortex (vmPFC) and the ventral striatum  
79 (Bartra et al. 2013; Clithero and Rangel 2014; Padoa-Schioppa 2007; Raghuraman and  
80 Padoa-Schioppa 2014).

81 Value attribution is one of the first stages of any value based decision (Rangel et al.  
82 2008). Previous studies investigated the modulation of event-related potential (ERP)  
83 components by hedonic aspects of visual stimuli (for a review, see Hajcak et al. 2012). For  
84 example, a negativity bias reflecting preferential processing of unpleasant stimuli may result  
85 in greater ERP responses (Delplanque et al. 2006; Huang and Luo 2006; Smith et al. 2003).  
86 Some studies identified the role of the late positive potential in the encoding of emotional  
87 stimulus valence (Foti et al. 2009; Macnamara et al. 2009; Moser et al. 2006), however, the  
88 late positive potential also varies as a function of motivational significance (i.e., salience;  
89 Weinberg and Hajcak 2010). Although the subjective pleasantness of a stimulus may  
90 contribute to the value of perceived goods, economic value is not identical to emotional  
91 valence.

92 Electrophysiological studies have highlighted that value-related signals appear as  
93 early as 200 ms post-stimulus presentation in binary decision tasks where a choice between  
94 two options is required (Larsen and O'Doherty 2014; Tzovara et al. 2015). Differences in  
95 ERPs were also observed across multiple time windows ranging from 150 to 800 ms (Harris  
96 et al. 2011). However, ERPs were not investigated in relation to behavioural measures  
97 concerning economic value directly. Other investigations of the value-encoding phase were  
98 focussed within specific brain regions (Hunt et al. 2012). A common finding in previous ERP  
99 studies investigating the representation of value-based preferences in binary reaction time

100 tasks was a progression of activations from the occipito-temporal cortical regions to frontal  
101 and prefrontal sites over the course of the ERP (Harris et al. 2011; Larsen and O'Doherty  
102 2014). However, the involvement of a reaction time response in experiments investigating the  
103 representation of value also adds a motor readiness component to ERPs which may interact  
104 with activations related to the automatic valuation process occurring in absence of decision  
105 making (Gluth et al. 2013; Polania et al. 2014). Further, binary decision making as compared  
106 to reporting hedonic ratings has been found to involve different brain regions, such as  
107 anterior cingulate cortex (Rolls et al. 2009).

108         Several ERP components relevant to value-based decision making have been revealed  
109 in previous literature. The event-related negativity (ERN) and feedback-related negativity  
110 (FRN) are two ERP components that, due to their nature, allow us to investigate decision  
111 making processes (Walsh and Anderson 2012). These two components are elicited by  
112 feedback following decision tasks and are relevant to reward-prediction errors (Gehring et al.  
113 2012; Nieuwenhuis et al. 2004; Yu and Huang 2013). Additionally, the P300 ERP component  
114 is often implicated in which the P300 encodes outcome valence (San Martin 2012; Yeung and  
115 Sanfey 2004). It is generally found that these ERP components are specific to outcome  
116 processing, though it has been revealed that the eliciting stimuli can modulate the ERP  
117 magnitude at the outcome stage (Yeung and Cohen 2006).

118         A common method for estimating the economic value of goods is via auction tasks  
119 such as the Becker-DeGroot-Marschak (BDM) mechanism (Becker et al. 1964). The BDM  
120 mechanism is an incentive compatible method for estimating a subject's willingness-to-pay  
121 (WTP) for goods and prospects (Wilkinson and Klaes 2012). Previous functional magnetic  
122 resonance imaging (fMRI) studies have established that the brain valuation system activates  
123 during the BDM mechanism (Chib et al. 2009; Plassmann et al. 2010; 2007).

124           The context in which economic decisions are made can also influence the neural  
125           activations within the brain valuation system. For example, neural responses within valuation  
126           regions can be modulated during an auction task in which bids may be forced (Plassmann et  
127           al. 2010; 2007), passive viewing tasks (Levy et al. 2011) and tasks in which value is  
128           irrelevant (Grueschow et al. 2015; Polania et al. 2014) or where outcomes are uncertain  
129           (Payzan-LeNestour et al. 2013). Activation of the brain valuation system during tasks in  
130           which it was not required demonstrates the automaticity of valuation processes (Lebreton et  
131           al. 2009).

132           The aim of the present study was to investigate the spatio-temporal aspects of brain  
133           economic evaluation of everyday household items during a task in which value was either  
134           task-relevant or irrelevant. Subjects viewed each item but were not requested to make a  
135           speeded response, rather, they rated the likeability or the material features of the item. A  
136           BDM auction experiment was used to evaluate WTP in a separate session, and the WTP  
137           values were correlated with ERPs and subjective ratings.

## 138   **2. Methods**

### 139   *2.1. Participants*

140           Twenty-five healthy participants (14 females) with a mean age of  $24 \pm 4.67$  (mean  $\pm$   
141           SD) years took part in the study. The experimental procedures were approved by the  
142           Research Ethics Committee of the University of Liverpool. All participants gave written  
143           informed consent in accordance with the declaration of Helsinki. Participants were  
144           reimbursed for their time and travel expenses.

### 145   *2.2. Procedure*

146           All experimental procedures were carried out in a dimly lit, sound attenuated room.  
147           Participants sat in front of a 19-inch LCD monitor. The study was carried out in two sessions  
148           approximately 2-5 days apart. During the first session, participants completed the auction

149 task. During the second session, participants completed the rating task. The stimuli comprised  
150 90 everyday household items varying in value from £0.75 to £4.00 with a mean value of  
151 £2.52 ± £1.01 (mean ± SD) obtained from a shopping catalogue. Food items were excluded to  
152 avoid confounds arising from difference in the appetitive value of stimuli between session 1  
153 and 2 of the study. Stimuli were presented in random order. Presentation of stimuli was  
154 controlled using Cogent 2000 (UCL, London, UK) in Matlab 7.8 (Mathworks, Inc., USA).  
155 Experimental protocols and stimulus timings are illustrated in Figure 1.

### 156 2.3. Auction task

157 The protocol for the auction task was adapted from previous studies (Plassmann et al.  
158 2007, 2010) and employed the BDM mechanism (Becker et al. 1964; Wilkinson and Klaes  
159 2012). Each stimulus was presented once resulting in a total of 90 auctions.

160 Each auction consisted of a fixation cross followed by an evaluation stage, a bidding  
161 period and then feedback. During the evaluation stage, participants appraised the stimulus  
162 that was presented on-screen. The bidding period required the participants to bid on the item.  
163 Here, participants were asked to bid between £0 and £4 in increments of £0.50 giving a total  
164 of nine options. During the feedback stage, participants were notified as to whether or not the  
165 item was won. The outcome of an auction was dependent on the bid and a randomly  
166 generated number, in which the item was purchased when  $b \geq r$ , where  $b$  represents the bid  
167 and  $r$  represents the randomly generated number for that auction. At the end of the  
168 experiment, three auctions resulting in a purchase were selected at random. For each auction  
169 selected, a price equal to  $r$  was subtracted from an initial endowment of £12. Therefore, the  
170 actual endowment could vary between £0 and £12. The participant could pick up the items  
171 won within a few days of completion of the full experiment.

### 172 2.4. Rating task

173           Approximately 2-5 days following completion of the auction task, participants  
174 returned to take part in session 2. EEG was recorded continuously using the 128-channel  
175 Geodesics EGI system (Electrical Geodesics, Inc., Eugene, Oregon, USA) with the sponge-  
176 based HydroCel Sensor Net. The sensor net was aligned with respect to three anatomical  
177 landmarks (two pre-auricular points and the nasion). Electrode-to-skin impedances were kept  
178 below 50k $\Omega$  and at equal levels across all electrodes as recommended for the system (Ferree  
179 et al. 2001; Luu et al. 2003; Picton et al. 2000). The sampling rate was 1000 Hz and Cz was  
180 used as the initial reference. Data was filtered online using a 0.1-200 Hz bandpass filter.

181           After fitting the EEG cap, participants completed a computerized rating task. Each  
182 trial began with a fixation cross followed by an instruction stage, evaluation period and then  
183 rating. During the instruction stage, participants were presented with either the word  
184 ‘DESIRABILITY’ or ‘MATERIAL’, which served to cue the participant to the required type  
185 of evaluation. The evaluation stage began with the presentation of one of the visual stimuli,  
186 followed by the presentation of a visual analogue scale (VAS) for the rating stage. In the  
187 value-relevant condition, the participant would have to rate the desirability of the preceding  
188 stimulus (anchors: “neutral”-“very desirable”), while in the value-irrelevant condition, the  
189 participant would rate the proportion of the preceding stimulus composed of a certain  
190 material (for example, “none”-“plastic”). Here, the proportion of the scale that is shaded  
191 indicated the percentage of plastic composition. Desirability and material estimation trials  
192 were randomly intermixed within blocks.

193           Investigating the neural basis of subjective value is complicated by the multiple non-  
194 specific neural processes elicited during experimental paradigms used to reveal subjective  
195 value. During the rating task, the only difference between these two conditions was the  
196 calculation of subjective value for the trials in which desirability was rated. Any differences  
197 in ERPs between these two trials can, therefore, be attributed to computation required to

198 report subjective value. Of course, automatic processes involved in valuation would still be  
199 present. Each stimulus was presented in both conditions, yielding a total of 180 trials, split  
200 into three blocks.

### 201 *2.5. Median split of WTP values*

202 The stimulus set was divided into high and low WTP items using a median split of  
203 subjective values. In the case of items with identical value on both sides of the split, the items  
204 with that value were removed in such a manner that there was no overlap in value between  
205 the two sides and there was an equal number of stimuli in each category. For an unequal  
206 number of stimuli of identical value on each side of the split, stimuli of that value were  
207 removed randomly from the side with more. This produced two categories of stimuli (high  
208 and low value) of equal size for each participant, with a mean of  $38.48 \pm 5.02$  (mean  $\pm$  SD)  
209 items remaining in each condition.

### 210 *2.6. ERP analysis*

211 EEG data were pre-processed using BESA v. 6.0 program (MEGIS GmbH, Munich,  
212 Germany). Oculographic artefacts and electrocardiographic artefacts were removed using  
213 principle component analysis based on averaged eye-blinks and artefact topographies (Berg  
214 and Scherg 1994). Data were also visually inspected for the presence of atypical electrode  
215 artefacts due to muscle movement. Data were filtered from 1-45 Hz and epochs contaminated  
216 with artefacts were excluded manually.

217 ERPs in response to stimulus presentation were computed separately for each level  
218 within conditions (High Value Item & Desirability Rating; High Value Item & Material  
219 Estimation; Low Value Item & Desirability Rating; Low Value Item & Material Estimation)  
220 by averaging respective epochs in the intervals ranging from 300 ms before image onset to  
221 1000 ms following image onset. Epochs were baseline corrected using a time window of -300

222 to 0 ms relative to stimulus onset. The mean number of accepted trials in each condition  
223 (following the median split and artefact rejection) was  $32.4 \pm 5.8$  (mean  $\pm$  SD).

## 224 *2.7. Source dipole reconstruction*

225 Grand average potentials were computed by combining all conditions. The grand  
226 average waveform was used to define a source dipole model in BESA v. 6.0 program. Using  
227 a sequential strategy (Hoechstetter et al. 2001; Stancak et al. 2002), Equivalent Current  
228 Dipoles (ECDs) were fitted to describe the 3-dimensional source currents in the regions  
229 contributing predominantly to the data (Scherg and Von Cramon 1986). Six ECDs were  
230 consecutively seeded until the source mode explained 91.6% of the variance. This amount of  
231 explained variance is comparable to previous ERP source dipole localisation studies  
232 (Hämäläinen et al. 1993; Schlereth et al. 2003; Stancak et al. 2012; Vrana et al. 2005), and  
233 suggests that the six-dipole model explained all major ERP components. Classical LORETA  
234 analysis recursively applied (CLARA) method, which is an iterative application of the  
235 LORETA algorithm (Pascual-Marqui et al. 1994), was used as an independent source  
236 localisation method to confirm the locations of the ECDs (Wright et al. 2015). The  
237 orientations of ECDs were fitted with the constraint of fixed dipole locations and determined  
238 at the maximum of the source strength. A 4-shell ellipsoid head volume conductor model was  
239 employed, using the following conductivities (S/m = Siemens per meter): brain = 0.33 S/m;  
240 scalp = 0.33 S/m; bone = 0.0042 S/m; cerebrospinal fluid = 1 S/m.

241 Source waveforms for each condition were exported and analysed using the EEGLab  
242 toolbox (Delorme and Makeig 2004). Due to the large number of statistical tests that this  
243 requires, P values were corrected using permutation-based repeated-measures ANOVA  
244 utilising 5000 permutations (Maris and Oostenveld 2007). For each latency identified, mean  
245 activation over a 10 ms period was calculated, centred on the peak of the observed effect and

246 for each participant. The data were exported to SPSS Statistics version 22.0 (IBM Corp,  
247 2013) for further analysis.

248 It is important to note the limitations of source analysis techniques due to the inverse  
249 problem manifesting in the possibility to generate a number of plausible source dipole models  
250 (Michel and Murray 2012). Therefore, a priori information, such as constraining the source  
251 dipole locations to the cortical mantle, has been implemented in source dipole localisation  
252 methods to reduce the number of possible solutions (Michel et al. 2004). To build a plausible  
253 source dipole model, we applied two different source dipole modelling methods. Firstly, the  
254 sequential method consisting of fitting equivalent current dipoles sequentially, and secondly,  
255 a distributed source dipole modelling method (CLARA). Both methods yielded highly  
256 convergent source dipole models which mitigates but does not completely overcome the  
257 limitations associated with the large number of potential source dipole solutions given the  
258 mathematical features of the inverse problem

### 259 **3. Results**

#### 260 *3.1. Behavioural data*

261 The high value items had a mean WTP of  $2.1 \pm 0.87$  (mean  $\pm$  SD) and desirability  
262 rating of  $50.4 \pm 29.7$ , whereas the low value items had a mean WTP of  $0.66 \pm 0.62$  and  
263 desirability rating of  $27 \pm 25.3$ . To ensure this finding was not confounded by individual  
264 differences, a regression model for each participant was created with WTP as a predictor and  
265 desirability as a dependent variable. This produced a mean unstandardized coefficient of  $15.5$   
266  $\pm 9.37$ ; a one-sample t-test revealed this to be significantly different from zero,  $t(24) = 8.27$ ,  $P$   
267  $< .001$ . A mean adjusted  $R^2$  of  $0.23 \pm 0.17$  (mean  $\pm$  SD) was also found across subjects.  
268 Therefore, desirability of objects was linearly related to WTP (see Figure 2).

#### 269 *3.2. Source dipole model*

270 Figure 3 illustrates the ERPs at each electrode site in response to stimulus  
271 presentation across all conditions in the form of a butterfly plot; ERP components and their  
272 corresponding latencies and topographies are labelled. Four distinct ERP components were  
273 observed across the epoch beginning with the visually evoked P1 component peaking at 99  
274 ms, a component related to the early processing of visual stimuli (Hopf et al. 2002) and  
275 characterised by the strong positivity over the central occipital electrodes with reversed  
276 polarity over the frontal electrodes. A P2 component peaked at 209 ms with bilateral  
277 positivity over the occipital electrodes but with negativity restricted over a frontal region on  
278 the right side of the head (Freunberger et al. 2007; Luck 2005). Although clearly overlapping  
279 with the P2, the N2 component peaking at 243 ms can be differentiated by the additional  
280 negativity over a frontal region (Folstein and Van Petten 2008). The P3 component (Polich  
281 2007) emerges at approximately 316 ms in a parietal region on the right side of the scalp,  
282 before reaching a positive maximum at 354 ms over the midline frontal electrodes.

283 Figure 4A shows the source waveforms and the appropriate topographic maps for  
284 different ECDs and Figure 4B illustrates the spatial localisation of the ECDs. ECD 1 was  
285 located in the right lingual gyrus (Brodmann area 18; approximate Talairach coordinates:  $x =$   
286  $18$  mm,  $y = -59$  mm,  $z = 9$  mm) with a peak latency at 95 ms and again at 121 ms. ECD 2  
287 showed similar characteristics being located in the left lingual gyrus (Brodmann area 18;  $x = -$   
288  $17$  mm,  $y = -59$  mm,  $z = 9$  mm) with a peak latency at both 100 ms and 215 ms. Both ECD 1  
289 and 2 showed a positive maximum over the medial occipital electrodes and a negative  
290 potential over a frontal region of the scalp. The latency and the topographical pattern indicate  
291 that these two sources were equivalent to the visual P1 component. ECD 3 was located in the  
292 right anterior insula cortex (Brodmann area 13;  $x = 32$  mm,  $y = 15$  mm,  $z = 0$  mm), peaking at  
293 233 ms and showing maximum negativity over a frontal region on the right side of the scalp.  
294 This spatial map corresponds to the frontal portion of the N2 component. ECD 4 was located

295 in the left orbitofrontal cortex (Brodmann area 11;  $x = -26$  mm,  $y = 34$  mm,  $z = -2$  mm)  
296 showing a small peak at 230 ms. ECD 4 projected positivity over a frontal region localised  
297 marginally on the left side. However, this was masked by the N2 component. ECD 5 was  
298 located in the right parahippocampal gyrus (Brodmann area 28;  $x = 19$  mm,  $y = -17$  mm,  $z = -$   
299 21 mm), showing two peak latencies of 215 ms and 316 ms corresponding to both the P2 and  
300 the early P3 component. ECD 5 accounted for positivity over a posterior region, localised  
301 primarily on the right side of the scalp. ECD 6 was fitted in the posterior cingulate cortex  
302 (bordering closely with the anterior cingulate cortex; Brodmann area 31;  $x = 3$  mm,  $y = -18$   
303 mm,  $z = 42$  mm). The source peaked at 248 ms and 431 ms with negativity being distributed  
304 across a frontal region of the scalp at 248 ms (contributing to the N2 component at the vertex)  
305 and positivity at 431 ms. The final source dipole model accounted for 91.6% of the total  
306 variance. CLARA method was used to verify the origins of the fitted ECDs. A mean  
307 discrepancy of approximately 15 mm was found between the location of each ECD and the  
308 maxima of the nearest cluster.

### 309 *3.3. Effects of rating task and WTP*

310 To test the effect of rating task and value on ERPs, a two-way ANOVA for repeated  
311 measures was carried out over the latency interval ranging from -200 ms to 450 ms using  
312 permutation analysis (Maris and Oostenveld 2007) with 5000 permutations. The F value  
313 waveforms were masked inclusively to highlight significant latencies that extended beyond  
314 three standard deviations of the source's mean baseline amplitude. Figure 4 shows the  
315 topographies at the peak significance of each observed main effect with the corresponding  
316 source waveform. Activity over a 10 ms interval centred on the peak significance for each  
317 effect (indicated by the shaded region on the source waveform) was exported for further  
318 analysis. Table 2A and 2B summarise the mean amplitude and test statistics for each

319 condition over the stated time interval for the main effects of rating task (desirability vs.  
320 material) and value (high vs. low); significant interactions are highlighted in Table 2C.

321 Figure 5A indicates three significant main effects of rating task on the activity from  
322 ECD 2, 3 and 5. The waveforms for these ECDs all demonstrate larger activation for  
323 desirability ratings than for material estimation ratings. Figure 5B illustrates the two  
324 significant main effects of value on the activity from ECD 3 and 4, each displaying greater  
325 activation for low value items. Despite the main effect of value at 233ms in ECD 4, it is  
326 important to note the difficulty in discerning the differences on scalp topographies due to the  
327 dominance of the negativity originating from ECD 3 which peaked at approximately the same  
328 time. Only one significant interaction between rating task and value was observed (ECD 6)  
329 which is visualised in Figure 5C. During the value rating condition, source activation for a  
330 desirability rating of a high value item was higher than in other conditions. Pairwise  
331 comparisons indicate that this activation was significantly stronger than during the material  
332 estimation and high value condition,  $t(24) = 2.23$ ,  $P = 0.035$ , and also the desirability rating  
333 and low value condition,  $t(24) = 2.1$ ,  $P = 0.046$ , but not the material estimation and low value  
334 condition,  $t(24) = 0.65$ ,  $P = 0.524$ . No other significant differences were found ( $P > 0.05$ ).

335 A possible explanation for this interaction could be a result of task-switching. For  
336 example, upon presentation of a high value item, participants would need to suppress their  
337 response if the task required material estimation with a low composition of the given  
338 material, with the same going for a low value item in the material estimation task in which  
339 composition was high. To test this, a regression model was produced for each subject with  
340 desirability as the independent variable and material composition as the dependent variable.  
341 This produced a mean unstandardized coefficient of -0.063 which was not significantly  
342 different from zero,  $t(24) = -1.51$ ,  $P = .145$ , thus suggesting that task-switching does not  
343 adequately explain the interaction effect in PCC.

#### 344 4. Discussion

345 This study explored the cortical representation of value by comparing items  
346 associated with high or low WTP, and recorded ERPs during passive viewing of items in two  
347 different valuation contexts, allowing us to disentangle the automatic and the elaborate and  
348 conscious valuation processes. Results showed increased cortical activity following the  
349 presentation of low value stimuli at the latency of approximately 200 ms, corresponding to  
350 the N2 and P2 components of ERPs. Although multiple sources contributed to ERP data at  
351 this latency, the economic value of items only modulated the activation in the right AIC and  
352 the left OFC. The effects of valuation context were seen in the left LG, right AIC and right  
353 PHG.

354 Modulation of source activity within the right AIC peaked at 200 ms, and activity was  
355 the strongest for rating of low value items. Although overlapping with the P2 component,  
356 source dipole orientation and topographical differences in the negativity over the forehead  
357 indicated that the N2 component that demonstrated an effect of value was distinct from the  
358 P2 component. The N2 potential was previously reported as being related to aspects of  
359 attentional selection (Codispoti et al. 2006; Näätänen and Picton 1986; Patel and Azzam  
360 2005), or emotional content of visual stimuli (Olofsson and Polich 2007). The anterior N2  
361 component has been related more specifically to novelty detection and cognitive control  
362 (Folstein and Van Petten 2008). The present study shows that the right AIC, a region known  
363 to be involved together with the OFC and amygdala in loss aversion (Canessa et al. 2017;  
364 Canessa et al. 2013; Markett et al. 2016; Tom et al. 2007), contributed to effects of economic  
365 value on the amplitude of the N2 component. Therefore, it is possible that the bias towards  
366 low value items reflects a loss averse response as low value items could represent possible  
367 sources of financial loss. However, without more experimental control, it is difficult to  
368 speculate on the underlying cognitive processes.

369           The low-value bias seen in the N2 component might have been boosted in the present  
370 study by the relatively limited range of value among the items on offer. Bartra et al. (2013)  
371 report a quadratic pattern within the AIC showing increased BOLD signal in response to  
372 extreme outcomes, positive or negative, and decreased BOLD for neutral stimuli. With a  
373 relatively small range of values in the current study (£0 - £4), the low value items may well  
374 have been negatively encoded (high arousal). In contrast, the high-value items may not have  
375 passed a threshold in order to be perceived as truly rewarding thus eliciting no arousal  
376 response.

377           A similar low-value bias was also seen in left OFC at a latency of 233 ms; despite  
378 falling within the N2 component latency, this effect was characterised by increased positivity  
379 over the left frontal region but masked by the negativity of the N2. The modulation of source  
380 activity for this ECD by stimulus value exhibits an automatic valuation, independent of the  
381 valuation context. Modulation of BOLD signal by subjective value has been observed  
382 frequently, often within the OFC (Clithero and Rangel 2014). Interestingly, this modulation  
383 has been observed for various paradigms utilising several measures of value such as  
384 hedonicity ratings (Grabenhorst and Rolls 2009; Lebreton et al. 2009), binary choice tasks  
385 (FitzGerald et al. 2009) and importantly, BDM auctions (Plassmann et al. 2010; 2007). The  
386 same modulation is also found for multiple reward types and across multiple stages of the  
387 decision making process (for a review, see Peters and Buchel 2010). Further to this, animal  
388 research utilising electrophysiological methods have highlighted the encoding of subjective  
389 value within the OFC (Padoa-Schioppa 2013; Padoa-Schioppa and Assad 2006). Similar  
390 conclusions have been drawn regarding the vmPFC (Bartra et al. 2013; Clithero and Rangel  
391 2014), however given the limitations to spatial resolution that EEG presents, the current  
392 findings may not differentiate the activation of the OFC from the neighbouring vmPFC. The  
393 emergence of value-based signals in electrophysiological animal research has been observed

394 in OFC at latencies as early as 150 ms (Padoa-Schioppa 2013). Thus, formation of subjective  
395 value occurs automatically at an early stage and aids subsequent decision, regardless of  
396 whether this signal is an accurate depiction of the ultimate value assigned to the stimulus  
397 after further deliberation. However, given the task order in the current study, it is important to  
398 recognise the potential role that memory may have played in producing this automatic  
399 valuation. The auction task always preceded the stimulus rating task resulting in participants  
400 having already reported their valuation of each of the stimuli. Although the time between the  
401 two tasks was between two and five days, it is possible that the valuation of the stimuli prior  
402 to the EEG task may have contributed to this finding due to memories originating from the  
403 auction task.

404         The cortical activity in the 200 ms latency range was also modulated by the valuation  
405 context. Given that the only computational difference between the two rating tasks is the  
406 presence of valuation, any differences in ERPs between the two contexts likely represent the  
407 cortical responses associated with attribution of value. The first modulation by the context  
408 was observed within the latency of the P2 component at 177 ms; the source activity in the LG  
409 was stronger when subjects focused on desirability of items, rather than the material  
410 compositions. It has been suggested that the P2 is involved in working memory processes  
411 (Finnigan et al. 2011; Lefebvre et al. 2005; Taylor et al. 1990; Wolach and Pratt 2001), visual  
412 feature recognition (Hillyard and Münte 1984), and attention allocation (Martin-Loeches et  
413 al. 1997). Federmeier and Kutas (2002) reported context-dependent modulations of the P2 in  
414 the left hemisphere which finding accords the present study.

415         An effect of the valuation context was also observed in the P2 component at a slightly  
416 later latency of 209 ms. This modulation was related to an increase in source activity in right  
417 PHG when evaluating the desirability of items compared to evaluating materials. Given the  
418 role of the PHG in memory processes (Aminoff et al. 2013), it is likely here that focusing on

419 the desirability of a stimulus has elicited working memory processes to a greater extent, or  
420 required a greater magnitude of attentional allocation. This may be due to the more complex  
421 analysis required to reach a decision about value rather than a more simple perceptual  
422 evaluation. Assuming value-based decisions require an in depth analysis of the stimuli, in  
423 contrast to the perceptual decision requiring estimation of a single material, this modulation  
424 may simply be a result of visual feature recognition regarding multiple aspects of the stimuli  
425 (Hillyard and Munte 1984).

426 Finally, the right AIC also showed an increased source activity for the rating of  
427 desirability resulting in greater negativity over the right forehead. Augmentation of anterior  
428 N2 components have been attributed to attentional processes (Codispoti et al. 2006; Näätänen  
429 and Picton 1986; Patel and Azzam 2005) and it seems the differing computational demands  
430 of the value-based and perceptual decisions augmented the observed N2 in the current study.  
431 The additional requirement of value-computation for the value-based decision could be the  
432 contributing factor to this increased amplitude. Indeed, Näätänen and Picton (1986) highlight  
433 that the N2 component can be modulated by conscious processing of stimuli, and thus, this  
434 processing may well be value specific.

435 A final modulation of ERPs by the valuation context was observed at approximately  
436 429 ms in PCC. The source activity in PCC, manifested as the negativity potential at vertex  
437 electrodes, was prominent for the rating of desirability of high value items, indicating this  
438 activation to be specific to highly valued stimuli in an economically relevant context.  
439 However, this finding should be interpreted with caution due to the lack of statistically  
440 significant differences between the desirability rating of high value items condition, and the  
441 material estimation of low value items at the same latency.

442 To conclude, we show that the subjective value of simple household items, measured  
443 as WTP in an auction experiment, manifests in ERPs in the latency window and electrodes

444 corresponding to the N2 component. The value-related cortical response, purportedly  
445 originating in right AIC and left OFC, is enhanced for low-value items possibly by eliciting  
446 loss aversion. The low-value bias in these cortical regions occurred across two different  
447 valuation contexts suggesting that this response is a part of an automatic valuation process. In  
448 contrast to the subjective value, the valuation context modulates the P2 and N2 components  
449 with stronger cortical responses in left LG, right AIC and right PHG occurring whilst subjects  
450 focused on desirability than on material aspects of items.

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470 **Figure legends.**

471 **Figure 1** Experimental protocol. A. Timeline of auction task. A fixation cross was presented  
472 at the beginning of each trial for 2 s. Following offset of the fixation cross, an image was  
473 presented for 3 s followed by the bidding options for 4 s. A total of nine options were  
474 available between £0 and £4 in increments of £0.50. Following the selection of a bid,  
475 feedback was presented for 1 s to indicate the outcome of that auction. B. Timeline of EEG  
476 task. A fixation cross was presented at the beginning of each trial for 3 s. Next, an instruction  
477 was presented for 2 s to indicate the demands of the trial, followed by an image for 3 s.  
478 Following image offset, a VAS was presented for 4 s to allow either a desirability rating or  
479 material estimation depending on the preceding instruction.

480 **Figure 2** Regression lines for each subject predicting desirability from WTP. Grand average  
481 regression line is shown in black.

482 **Figure 3** Butterfly plot of grand average ERPs in response to stimulus presentation. Distinct  
483 ERP components are highlighted with arrows (99, 209, 243, 316 and 354 ms). The  
484 topographic map for each ERP component is also displayed.

485 **Figure 4** Source dipole model of ERPs. A. Source dipole waveforms in six ECDs. Peak  
486 latencies and the topographic maps for each of the ECDs are shown. B. Locations and  
487 orientations of the six ECDs in the schematic glass brain.

488 **Figure 5** Effects of subjective value and context on source dipole waveforms. Each line  
489 represents the source dipole waveform for each condition (D = desirability rating; M =  
490 material estimation; H = high value items; L = low value items; desirability of high [HD] and  
491 low [LD] value items; material estimation of high [HM] and low [LM] value items). The  
492 shaded grey region on the source dipole waveforms indicates a 10 ms latency period in which

493 a main effect or interaction was revealed, centred on the peak significance. Topographic  
494 maps for each condition are displayed. A. ECDs demonstrating a main effect of rating task  
495 (ECD 2, 3 and 5). B. ECDs demonstrating a main effect of value (ECD 3 and 4). C. ECD  
496 demonstrating significant interaction between rating task and value (ECD 6).

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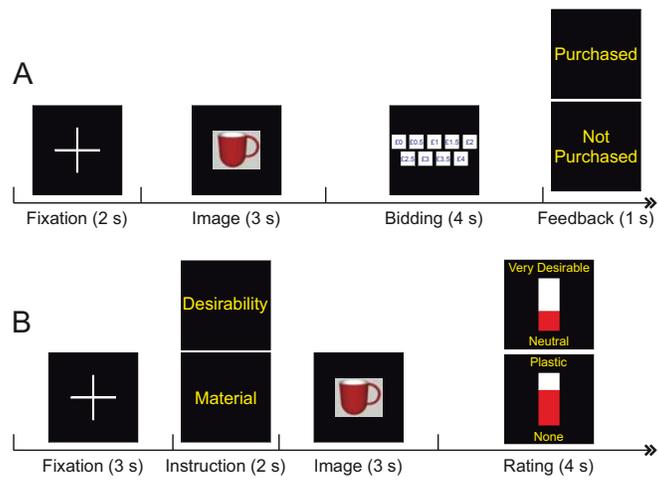
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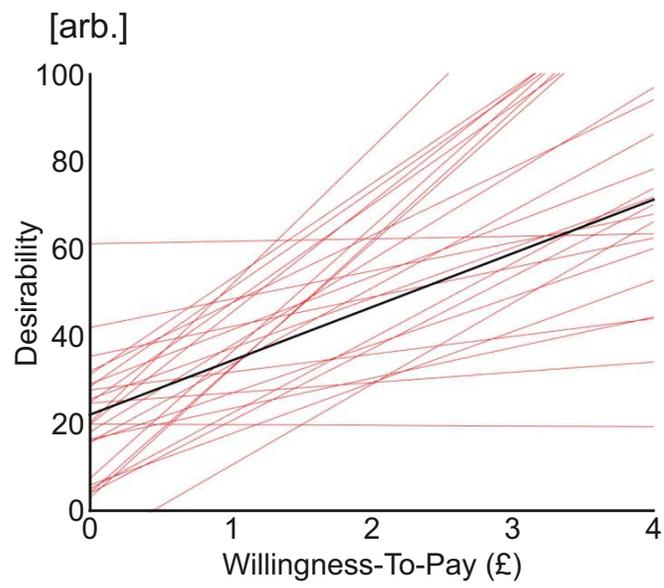
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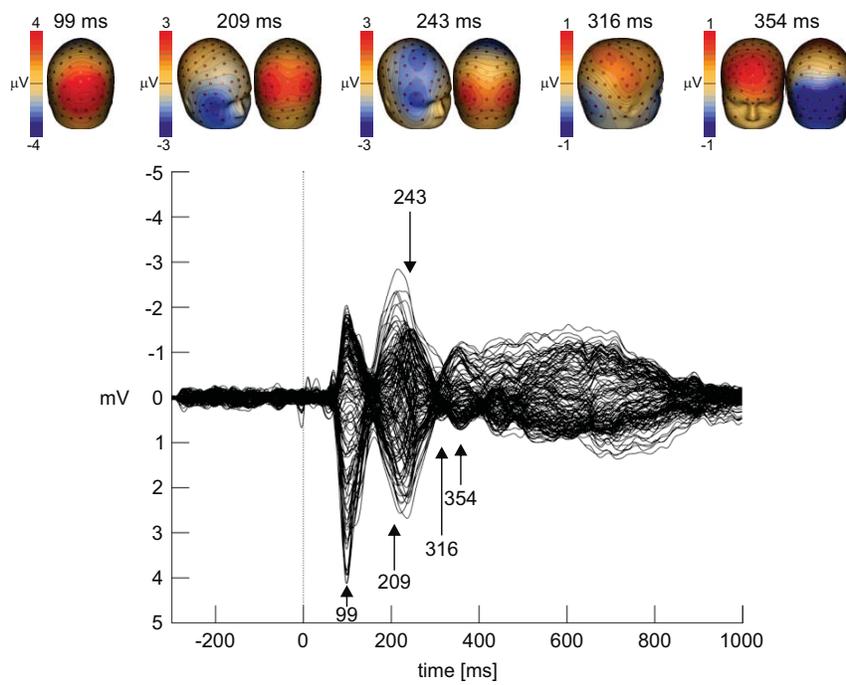
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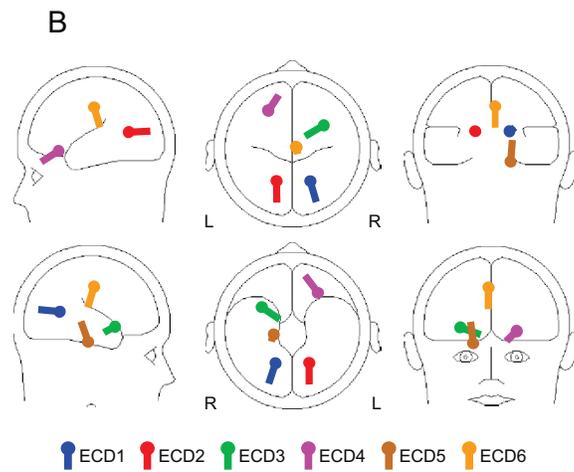
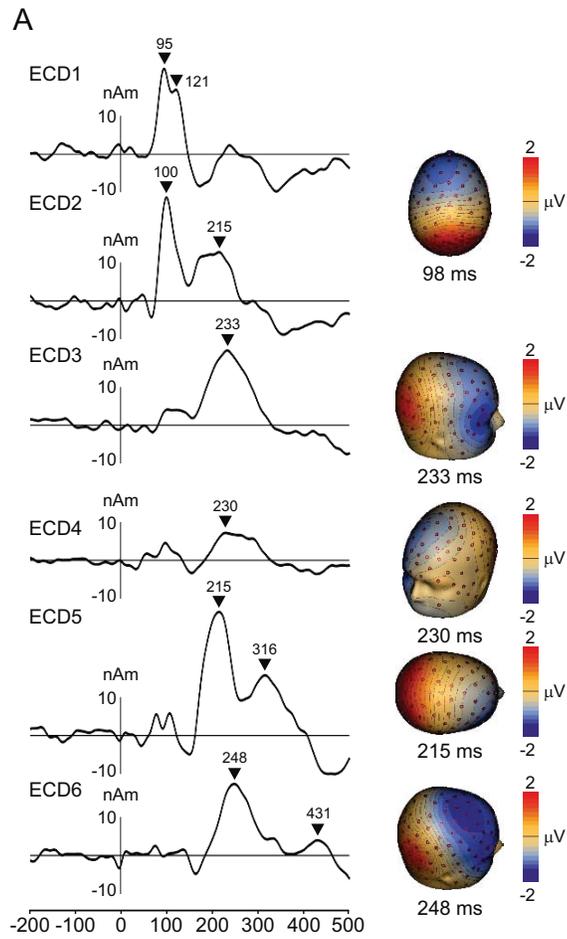
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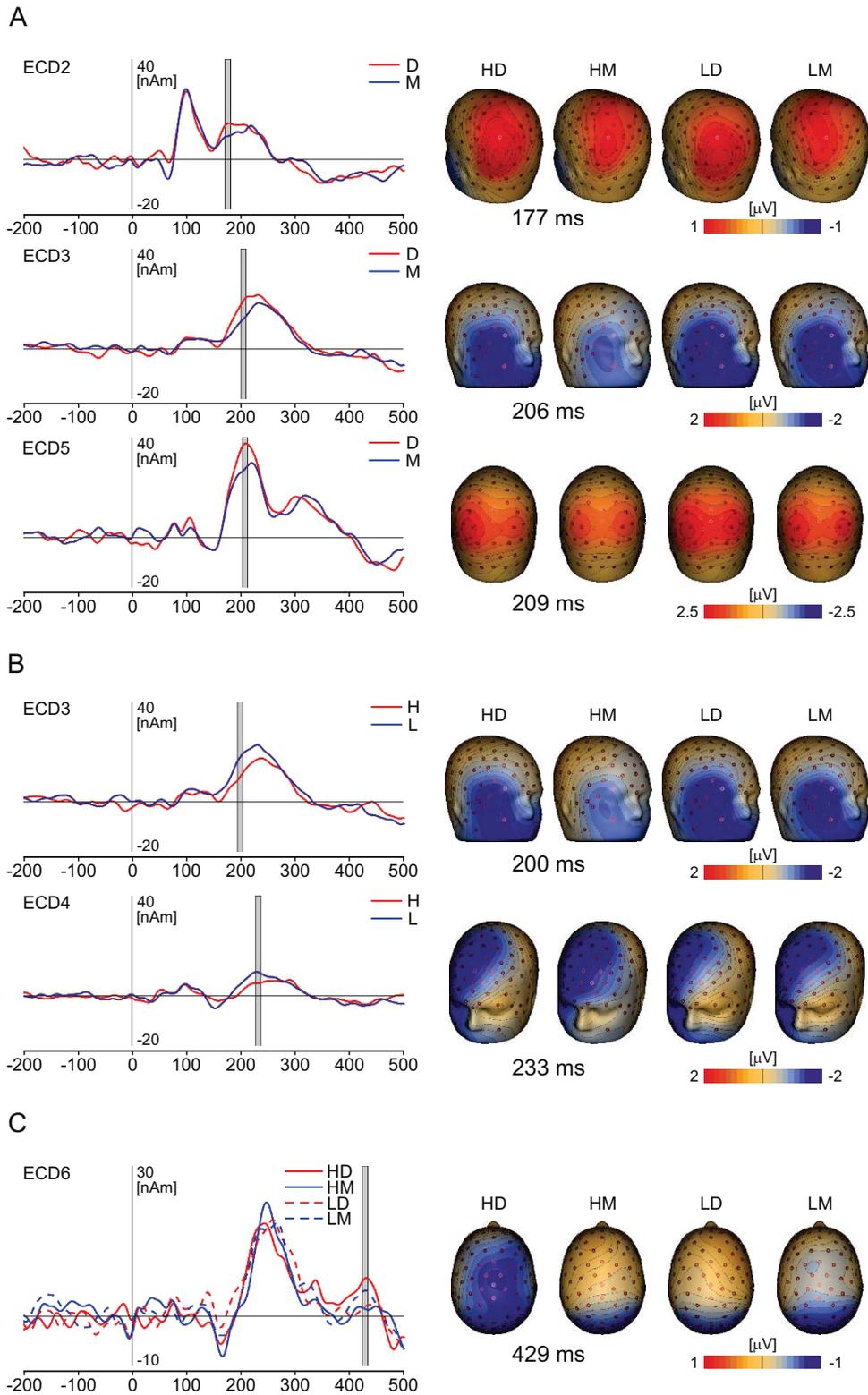
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A. Mean source amplitude  $\pm$  SDs for both desirability and material estimation conditions over the stated time interval for each significant latency and the corresponding ECD.

F and P values for the relevant ANOVA are also displayed.

ECD	Time Interval [ms]	Desirability	Material	F <sub>(24)</sub>	P
ECD2	172 – 182	14.2 $\pm$ 23.2	9.32 $\pm$ 22.3	9.93	0.004
ECD3	201 – 211	19.28 $\pm$ 14.51	12.04 $\pm$ 12.2	17.6	< 0.001
ECD5	204 – 214	37.26 $\pm$ 20.81	27.49 $\pm$ 20.09	8.34	0.08

B. Mean source amplitude  $\pm$  SDs for both high and low value conditions over the stated time interval for each significant latency and the corresponding ECD. F and P values for the relevant ANOVA are also displayed.

ECD	Time Interval [ms]	High Value	Low Value	F <sub>(24)</sub>	P
ECD3	195 – 205	10.07 $\pm$ 12.85	17.81 $\pm$ 15.31	9.19	0.006
ECD4	228 – 238	5.09 $\pm$ 8.07	9.36 $\pm$ 8.89	12.57	0.002

C. Mean source amplitude for desirability ratings of high value (HD) and low value (LD) items and for material estimation ratings of high value (HM) and low value (LM) items for each significant latency and the corresponding ECD over the stated time interval. F and P values for the relevant ANOVA are also displayed.

ECD	Time Interval [ms]	HD	HM	LD	LM	F <sub>(24)</sub>	P
ECD6	424 – 434	7.44 ± 12.76	1.85 ± 10.13	1.47 ± 10.32	5.05 ± 15.2	8.25	0.008