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## **Reverse engineering cash: Coin designs mark out high value differentials and coin sizes track values logarithmically**

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1 **Reverse engineering cash: Coin designs mark out high value differentials and coin sizes**  
2 **track values logarithmically**

3

4 Abstract

5 Coins are physical representations of monetary values. Like mental or verbal representations  
6 of quantities, coins encode sums of money in formats shaped, in part, by cognitive and  
7 communicative needs. Studying the coins circulating today, we consider how their design,  
8 colour, and size reflect their value. We show that coin designs solve a trade-off between  
9 informativeness—the pressure to highlight distinct denominations—and simplicity—the  
10 pressure to limit the number of designs that coin users must memorise. Coinage worldwide is  
11 more likely to display distinctive graphic designs and distinct colours on pairs of coins with  
12 large differences in value, thus minimising the aggregate cost of mistaking one coin for  
13 another. Coin size differentials, in contrast, do not seem to indicate greater value differentials,  
14 although absolute coin sizes do reflect monetary values. Log-transformed values predict  
15 design and colour distinctiveness in coin pairs, as well as absolute coin sizes, better than raw  
16 values, consistent with research suggesting that monetary quantities may recruit the  
17 "numerosity system" for magnitude representations, thought to track quantities  
18 logarithmically. These results show that coins obey similar informational constraints as  
19 linguistic and mental representations.

20

21 **Keywords:** money, value, design, magnitudes, numerosity, currency.

22

23

## 24 Introduction

25

26 When evaluating sums of money, we are subject to biases such as the money illusion (where  
27 one hundred cents appear greater than one dollar; Shafir, Diamond, and Tversky 1997).

28 Perceived physical magnitudes (e.g., sizes) interfere with our perception of monetary  
29 quantities (Goldman, Ganor-Stern, and Tzelgov 2012). Crumpled bills appear less valuable  
30 than bills in mint condition (Di Muro and Noseworthy 2013). Bills are seen as more valuable  
31 than coins, keeping values equal (Dolansky 2014; Tessari et al. 2011). We are less likely to  
32 part with a 50 euro bill than to let go of five 10 euro bills (Mishra, Mishra, and  
33 Nayakankuppam 2006; Raghurir and Srivastava 2009).

34

35 These studies, together with the rich literature on the perception of coins and their value  
36 (following Bruner and Goodman 1947), show how the appearance of cash money can  
37 influence economic behaviours. Yet, little research has investigated whether coin properties  
38 reflect these biases. The relationship between cultural artefacts and cognitive biases can be  
39 studied experimentally, but it can also be observed by analysing cultural data directly (Kelly  
40 and Keil 1985; Sperber and Hirschfeld 2004). Testing hypotheses on real-world corpora is a  
41 fruitful method in linguistics (Piantadosi, Tily, and Gibson 2011; Kemp and Regier 2012) and  
42 elsewhere. Studying the shape of letters in the world's writing systems, for instance, reveals  
43 formal constraints derivable from the structure of visual cognition (Changizi and Shimojo  
44 2005; Morin 2018). The invention of written letters took into account readers' visual biases;  
45 likewise, coins should be sensitive to the way coin users represent physical and monetary  
46 magnitudes. Testing this point is of practical interest, to promote ergonomic currencies and  
47 avoid costly design errors. On a theoretical level, it links the study of numerical cognition  
48 with research on everyday economic behaviour.

49

50 This study, covering the most recent coin series in circulation for the world's currencies,  
51 shows how the appearance of coins reflects their value. Modern coins indicate their nominal  
52 value in writing, but also through their size, their colour, and the images minted on them. We  
53 focused on the differences between "adjacent pairs" of coins, i.e., any two coins of  
54 neighbouring values belonging to the same currency (e.g., two cents-five cents, one euro-two  
55 euros). We considered differences between these coins' colours, sizes, and "designs" (the

56 images on both sides of a coin, excluding inscriptions and value marks). We hypothesised that  
57 two coins are more likely to be distinct to the extent that they differ in value.

58

59 The task of encoding monetary values with images (i.e., designs) raises a problem that verbal  
60 labelling also faces: a trade-off between simplicity and informativeness (Regier, Kemp, and  
61 Kay 2015). Minting all denominations with one identical image would result in designs that  
62 carry no information about denominations (informativeness deficit). Conversely, minting each  
63 denomination with a different design may put excessive pressure on the users' memory and  
64 attention (simplicity deficit). Even frequent words are exposed to a simplification pressure  
65 keeping word inventories low. Such trade-offs are typically solved by taking into account the  
66 users' communicative needs (Gibson et al. 2017; Kemp and Regier 2012). For currencies,  
67 similar pressures likely obtain, given the difficulties experienced by infrequent (Vranka et al.  
68 2019) and even frequent coin users (Gallup & Eurobarometer, 2006; Kantar Public &  
69 Eurobarometer, 2018) in telling coins apart.

70

71 On this basis, we hypothesised that coin designs should be distributed over the different  
72 denominations of a given currency in a cost-sensitive fashion, taking into account the value  
73 differentials between denominations, which are identical to the cost of mistaking one  
74 denomination for another. Considering, within each currency, all pairs of coins of adjacent  
75 value, the chances that the designs minted on both coins differ should increase along with the  
76 pair's value differential (e.g., one cent for the one cents–two cents pair, three for the two  
77 cents–five cents pair, etc.). (Prediction 1.1.) We also expected the differences in colour  
78 between the coins in such a pair to reflect the value differentials in a similar way as proposed  
79 for coin designs. (Prediction 1.2.) (The “colour” of a coin's metal alloy is reminiscent of  
80 precious metals—copper, silver, gold—historically used in coin production, and now  
81 associated with coin values.)

82

83 The relation between coin sizes and coin values raises a different issue. Monetary value and  
84 diameter size are continuous quantities: they can be mapped onto each other by making coin  
85 sizes co-vary with their face value (e.g. one cent for a one-cent coin). Accordingly, we  
86 expected that size differentials in pairs of coins of adjacent value (“adjacent pairs”) would  
87 correlate with value differentials (Prediction 2).

88

89 What exact shape should this value-size correlation assume? Two independent research  
90 traditions, psychophysics and the theory of marginal utility, can be read as implying that  
91 monetary values are represented on a logarithmic scale. Marginal utility theory and its  
92 precursors (starting with Bernoulli, 1738/1954) assume a logarithmic mapping between a sum  
93 of money and the utility derived therefrom. Prospect theory incorporates this view in the way  
94 that it models loss aversion (Kahneman and Tversky 2012). Psychophysics, building upon the  
95 work of Weber and Fechner, has shown that the representation of prices tends to follow  
96 Weber's law (Cheng and Monroe 2013; Dehaene and Marques 2002). As a consequence, the  
97 same price differential is less likely to be noticed in a high price range, compared to a low  
98 price range. As far as we know, this claim concerning the perception of prices has not been  
99 generalised to other types of monetary quantities, such as the value of coins. We predicted  
100 that log-transformed values would predict size differentials better than non-transformed  
101 values, since, in our view, coin designs should track monetary quantities as represented by the  
102 numerosity system (Feigenson, Dehaene, and Spelke 2004). By the same logic, log-  
103 transformed values should also provide a better predictor of whether two coins share the same  
104 design or colour (Prediction 3.). We aimed to test these predictions on all coins in circulation  
105 today.

106

## 107 Methods & Results

108

109 Our predictions, methods, and models were preregistered on the Open Science Framework<sup>1</sup>.  
110 All preregistered analyses and their associated results are reported there<sup>2</sup>. The analyses  
111 described here occasionally include data inclusion criteria and model specifications that differ  
112 from the preregistered ones. These changes do not affect the results of the preregistered  
113 analysis (AIC differentials, direction and significance of fixed effects estimates, etc.). Since  
114 there is, to our knowledge, no pre-existing literature on the particular effects that we  
115 predicted, no power analysis was carried out, but we made sure that our sample was  
116 exhaustive in the sense that it included all currencies in use today, as listed by the  
117 International Organisation for Standardisation (ISO).

118

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<sup>1</sup> <http://osf.io/ekcdb/>

<sup>2</sup> [https://osf.io/2vuba/?view\\_only=c843d9c30fe24721a1202ccc65fed7d2](https://osf.io/2vuba/?view_only=c843d9c30fe24721a1202ccc65fed7d2)

119 We assembled a corpus of 182 currencies, comprising 1132 coins (950 adjacent pairs).  
120 Information concerning designs, colours, and diameter sizes was gathered from the respective  
121 central banks' websites and the Standard Catalogue of World Coins (Cuhaj 2015),  
122 supplemented by two online sources (Wikipedia and Numista catalogue). We took into  
123 account only the most recent coin denominations currently in circulation, disregarding  
124 infrequent older variants as well as commemorative coins. For each pair, we asked two  
125 independent coders to determine, based on written descriptions, whether the two coins had the  
126 same design (0) or not (1)<sup>3</sup>. They agreed upon 943 pairs and disagreed upon seven (Cohen's  
127 kappa = .98), which we discarded from all analyses bearing upon design differences. All  
128 nominal values were standardised as multiples of the value of the smallest coined  
129 denomination in each currency, or "Smallest Coins". The Smallest Coin for euros is one cent,  
130 so two euros are worth two hundred Smallest Coins, whilst the Smallest Coin for the  
131 Vietnamese dong is two hundred dongs, thus five thousand dongs = twenty-five Smallest  
132 Coins. Value differentials between pairs of coins of adjacent value were similarly  
133 standardised (e.g. the differential between one euro cent and two euro cents is one Smallest  
134 Coin; that between one euro and two euros is one hundred Smallest Coins).<sup>4</sup>

135

136 To test prediction 1.1, we focused on the currencies that produced at least one adjacent pair of  
137 coins with identical designs, and one pair with different designs. We excluded the currencies  
138 that systematically bear a different design on every denomination (n = 99), along with those  
139 that carry the same design on all denominations (n = 19). Excluding these currencies does not  
140 change the results given below. We built three mixed effects logistic models to predict, for all  
141 adjacent pairs of coins (n = 386) in each currency (n = 64), whether the two coins' designs  
142 were the same (0) or different (1). For instance, the two-cents and five-cents German euro  
143 coins share the same design: an oak leaf on the German side, a globe and twelve stars on the  
144 common side. The five-cents coin and the ten-cents coin bear distinct designs (the ten-cents  
145 coin features the Brandenburg Gate and a map of Europe). The first, "null" model included a

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<sup>3</sup> Our test of prediction 1.1. was repeated using a different measure of design similarity in adjacent pairs. Two independent coders judged whether the two designs were the same (0) or different (1) by comparing pictures of coins, not written descriptions (Cohen's kappa = .90). The results replicate the pattern of significant results reported in this paper (see sup. mat. sections 4.1. and 4.2.1).

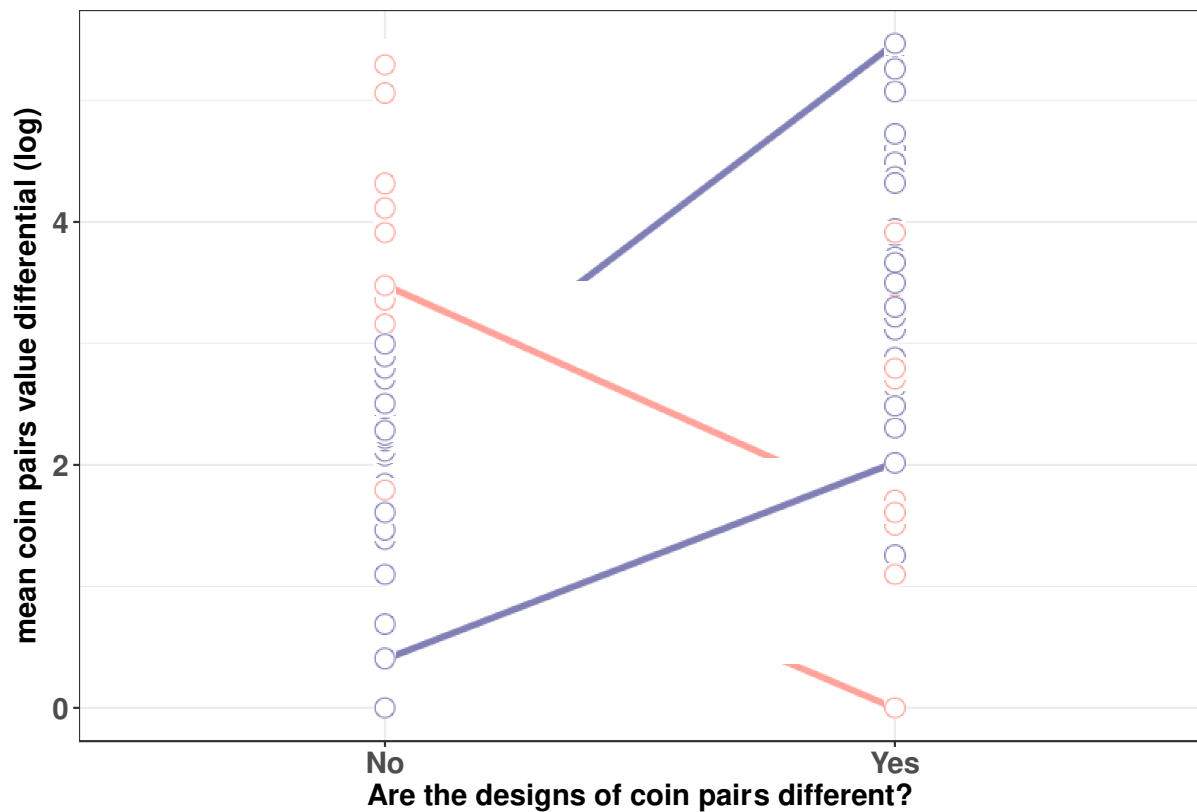
<sup>4</sup> The analyses presented below were also all replicated using a different measure of coin value (US dollar equivalents: sup. mat. section 3.2.), with no change to the pattern of significant results reported here (see sup. mat. section 4.2.).

146 random intercept for each pair's currency. A second model, which included the value  
147 differential between coins (in Smallest Coins) as a fixed effect, proved more informative than  
148 the null model ( $\Delta_{AIC} = 7.60$ ). A third model was built, identical to the previous one except for  
149 the fact that value differentials were log-transformed. It proved more informative than both  
150 previous models ( $\Delta_{AIC} = 17.09$  compared to the null) and included a positive estimate for  
151 value differentials ( $\beta = 0.31$ ,  $SE = 0.07$ ,  $z = 4.16$ ,  $p < 0.0001$ ). Designs are more likely to  
152 differ between adjacent coins to the extent that these two coins are far apart in value (like one  
153 euro - two euros vs. one cent - two cents), verifying prediction 1.1. (**Fig. 1**). Following  
154 prediction 3, log-transformed value differentials are a better predictor of this phenomenon  
155 than raw value differentials.

156

157 The same effect applied to coin colours: the more two adjacent coins differed in (log-  
158 transformed) value, the more likely they were to differ in colours (prediction 1.2.). Log-  
159 transformed values predicted this better than raw values (prediction 3). This prediction was  
160 tested on 950 adjacent pairs of coins. The first, "null" model included a random intercept for  
161 each pair's currency. A second model, which included the value differential between coins (in  
162 Smallest Coins) as a fixed effect, did not prove more informative ( $\Delta_{AIC} = 1.13$  in favour of the  
163 null model). However, a third model, identical to the previous one except for the fact that  
164 value differentials were log-transformed, proved more informative than the null model ( $\Delta_{AIC}$   
165  $= 39.30$ ) and included a positive estimate for value differentials ( $\beta = 0.28$ ,  $SE = 0.05$ ,  $z =$   
166  $5.98$ ,  $p < 0.0001$ ).





Currencies that... ○ refute the prediction ○ verify the prediction

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**Fig. 1. In pairs of coins with higher value differentials, coins are marked with distinct designs.** Each line stands for one currency (total  $n = 64$ ), and shows the average value differential between adjacent pairs of coins (e.g. one euro-two euros), depending on whether or not the two coins share the same design (left) or have different designs (right). The majority of currencies verify our prediction (in blue): pairs bearing distinct designs tend to show higher value differentials. Value differentials are given in Smallest Coins, i.e., as multiples of the value of the smallest coined denomination within each currency.

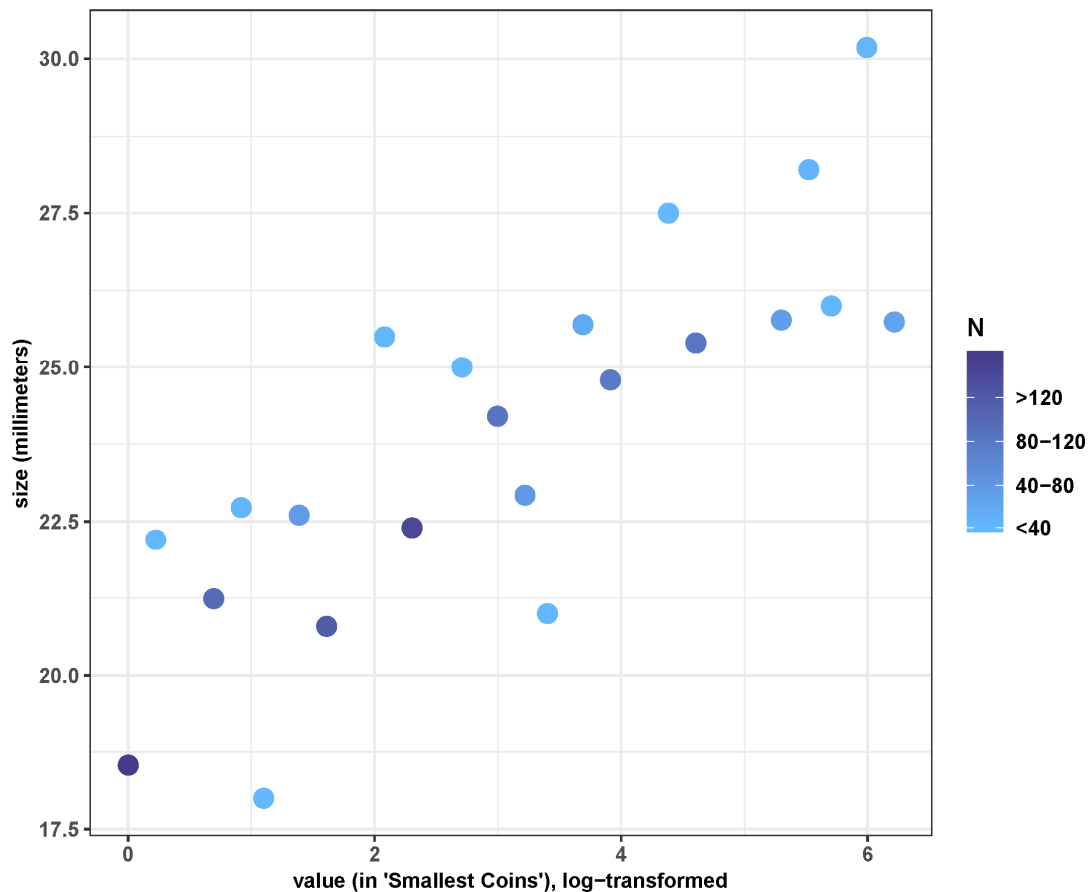
To test prediction 2, we treated all twenty-three national series of the euro as one single currency, and similarly “collapsed” the two variants of the French Pacific franc. These families of currencies showed no internal variation in coin sizes, while exhibiting clear internal variation for designs. Collapsing them does not change the results given below. We built two linear mixed effects models to predict the size differential between coins (diameter size differential, in millimetres) for all adjacent pairs of coins ( $n = 790$ ) in each currency ( $n = 159$ ). The first, “null” model included a fixed effect controlling for whether or not the two coins were of a different colour, a random intercept for each pair’s currency, and a random

185 slope reflecting the effect of the colour difference for each currency. This “colour difference”  
186 predictor always made the model more informative and had a strongly negative effect. In  
187 other words, in pairs straddling a colour divide (e.g., “copper” five euro cents – “golden” ten  
188 euro cents), the size differential between two denominations is on average less important,  
189 compared to pairs where both coins have the same colour. The null model was compared with  
190 a second model, which included an additional fixed effect for the value differential between  
191 the coins in a pair (in Smallest Coins, log-transformed). That second model did not prove  
192 more informative ( $\Delta_{AIC} = 1.48$ , in favour of the null model). We found a clearly positive  
193 intercept ( $\beta = 2.35$ ,  $SE = 0.18$ ,  $t = 13.12$ ,  $p < 0.0001$ ), indicating that the higher-value coin of  
194 the pair is on average larger than the lower-value coin. These results remained unchanged if  
195 we excluded four outlier pairs presenting excessive size or value differentials, or if we  
196 considered only the pairs of coins that do not differ in colour. Prediction 2 is thus refuted: size  
197 differentials do not increase with value differentials.

198

199 Just because value differentials fail to predict size differentials does not mean that absolute  
200 coin sizes do not reflect absolute coin values. The preceding result strongly suggests that they  
201 do, since higher-value coins in a pair are larger. In an unregistered follow up, we tested an  
202 additional prediction: absolute coin sizes reflect absolute coin values. In keeping with the  
203 logic of prediction 3, coin sizes should track log-transformed coin values better than raw coin  
204 values. We thus considered the absolute size and value of individual coins (as opposed to the  
205 size differentials between the coins in an adjacent pair). We again collapsed the Eurozone and  
206 Pacific franc currencies to one data point each (resulting  $n = 949$  individual coins from 159  
207 currencies) and compared three linear mixed effects models. The first, “null” model predicted  
208 each individual coin’s size with two random intercepts, one for currency, and one for colour.  
209 This model was outperformed by a model including each coin’s value (in Smallest Coins) as a  
210 fixed effect ( $\Delta_{AIC} = 14.54$ ). That model was, in turn, outperformed by a third model using log-  
211 transformed values ( $\Delta_{AIC} = 553.87$ ). Like the previous one, this model included a strong and  
212 significant estimate for the effect of coin value ( $\beta = 1.58$ ,  $SE = 0.04$ ,  $t = 34.61$ ,  $p < 0.0001$ ).  
213 Removing 16 outlier coins with abnormally high values did not change this pattern of results:  
214 coin sizes reflect coin values on a logarithmic scale (**Fig. 2**).

215



216

217 **Fig. 2. The size of coins reflects their value on a logarithmic scale.** Each data point is one  
 218 set of coins sharing the same value (with number of coins indicated by dot colour). (Total n:  
 219 933 coins from 159 currencies, excluding 16 outlier coins.)

220

221 Discussion

222

223 Our tests of predictions 1.1. and 1.2. confirm that coin designs and colours are distributed in  
 224 an economically efficient way, minimising the cumulative cost of confusing coins. Prediction  
 225 2 was not supported: high value coins tend to be bigger than low-value coins, but not  
 226 necessarily in proportion to the value differential between them. Our third prediction, that log-  
 227 transformed differences in value matter more for coin structure than the raw differentials, was  
 228 verified for coin designs but could not be tested for size differentials. We found support for a  
 229 related but *post hoc* prediction: individual coin sizes track coin values on a logarithmic scale.

230

231 Psychology does not generally praise the ergonomics of coin designs (Horner and Comstock  
 232 2005), mostly because of Nickerson and Adams' widely cited study (1979), whose subjects  
 233 were surprisingly mediocre at recollecting in detail the features of the 1972 one-cent

234 (“penny”) USD coin. In the same study, however, participants remembered with near-perfect  
235 accuracy the features that made the penny design distinctive from other USD coin designs  
236 (i.e., Lincoln and his memorial). The features they failed to remember were the ones that the  
237 penny shares with other coins (e.g., the word “Liberty”), or those that could be changed  
238 without making pennies any less distinctive (e.g., which side Lincoln faced). Distinctive  
239 design features play a crucial role in identifying coins, superior to other features such as size,  
240 thickness, or indentation (Horner and Comstock 2005). The sparse encoding of coin designs  
241 that Nickerson and Adams evidenced should thus be understood from an efficiency point of  
242 view: people only burden their memories with useful design features. As our data suggest,  
243 coins assist the users in solving this trade-off, only requiring them to memorise distinctive  
244 designs

245

246 The fact that coin designs are more informative for high value differentials confirms that  
247 human communication creates categories that satisfy an informativeness-simplicity trade-off  
248 while respecting functional constraints. This hypothesis had so far only been tested on data  
249 from natural languages (Gibson et al. 2017; Kemp and Regier 2012; Regier, Kemp, and Kay  
250 2015), or experimentally generated ones (Carr et al. 2018). Our findings are also coherent  
251 with those of a previous study (Pavlek, Winters, and Morin 2019) on Ancient Greek coins,  
252 showing that the designs of high-value coins carry more information concerning their  
253 denomination, compared to the designs of low-value coins. Both ancient and modern coinage  
254 displays a non-linear denomination structure, with larger value differentials in the higher-  
255 denominations range. Differences in value between adjacent coins or bills increase in a  
256 roughly exponential manner (Bouhdaoui, Bounie, and Van Hove 2011; Wynne 1997). Larger  
257 value differentials between high value coins are worth signalling with distinctive designs,  
258 since these coins are more costly to confuse.

259

260 Our results also suggest, in three different ways, that log-transformed coin values predict the  
261 structure of coin properties (size, colour and design distinctiveness) better than raw values, in  
262 line with work showing that people represent prices on a logarithmic number line (Cheng and  
263 Monroe 2013; Dehaene and Marques 2002; Marques and Dehaene 2004, but see Fitousi  
264 2010). Such logarithmic representation is a signature of the “numerosity system”, a  
265 specialised mental faculty dealing with estimates of approximate magnitudes (Feigenson,  
266 Dehaene, and Spelke 2004). Such a system appears well equipped to process the economic  
267 utility derived from money (as distinct from the face value of coins), since it is assumed to

268 follow a logarithmic relationship. Should this system be recruited in processing coin values,  
269 this would make sense of interferences between perceived physical magnitudes and perceived  
270 monetary values: prices that seem more expensive when printed in a bigger font (Coulter and  
271 Coulter 2005), coins whose estimated size changes depending on their value (Furnham and  
272 Spencer-Bowdage 2003). Overall, the present findings show coin designers to be intuitive  
273 psychologists, making imperfect but clear use of sound cognitive and ergonomic principles  
274 (Norman 2013).

275

276 **Open practices statement:** The main hypotheses and predictions tested here were  
277 preregistered, along with the methods, statistical tests, and inclusion criteria. The  
278 preregistration can be accessed at <https://osf.io/ekcdb/>. Post-hoc analyses are explicitly  
279 signalled as such. A second preregistration, addressing reviewers comments, can be accessed  
280 at <https://osf.io/tkj8y>. The complete dataset and the code associated with this paper are  
281 accessible at this address:

282 [http://osf.io/2vuba/?view\\_only=c843d9c30fe24721a1202ccc65fcd7d2\\_](http://osf.io/2vuba/?view_only=c843d9c30fe24721a1202ccc65fcd7d2_)

283

284 **Supplementary Materials:** The supplementary materials file,  
285 [currency\\_supplementary\\_material.pdf](#), can be accessed on the OSF repository:

286 [http://osf.io/2vuba/?view\\_only=c843d9c30fe24721a1202ccc65fcd7d2](http://osf.io/2vuba/?view_only=c843d9c30fe24721a1202ccc65fcd7d2)

287

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292

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409