

**The neural basis of effort valuation:
A meta-analysis of functional magnetic resonance imaging studies**

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Abstract

Choosing how much effort to expend is a critical for everyday decisions. While effort-based decision-making is altered in common psychopathologies and many neuroimaging studies have been conducted to examine how effort is valued, it remains unclear where the brain processes effort-related costs and integrates them with rewards. Using meta-analyses of combined maps and coordinates of functional magnetic resonance imaging (fMRI) studies (total N = 22), we showed that raw effort demands consistently activated the pre-supplementary motor area (pre-SMA). In contrast, the net value of effortful reward consistently activated regions, such as the ventromedial prefrontal cortex (vmPFC) and ventral striatum (VS), that have been previously implicated in value integration in other cost domains. The opposite activation patterns of the pre-SMA and vmPFC imply a double dissociation of these two regions, in which the pre-SMA is involved in pure effort cost representation and the vmPFC in net value integration. These findings advance our understanding of the neural basis of effort-related valuation and reveal potential brain targets to treat motivation-related disorders.

Key words: Effort; subjective value; effort based decision making; value integration; fMRI; ventromedial prefrontal cortex; supplementary motor area, meta-analysis

1 1. Introduction

2 Every day, we are faced with choices about whether to invest effort to attain certain goals
3 (Bailey et al., 2016; Salamone et al., 2009). These effort demands are often regarded as costly, such that
4 individuals tend to avoid one action if it requires too much effort (Kool et al., 2010; Kurniawan et al.,
5 2010, 2011). The ability to accurately weigh energy requirements against potential benefits (e.g.,
6 “effort-based decision-making”), is therefore crucial for optimal goal-directed action, and alterations in
7 this function are believed to be a core component of motivational disorders, such as apathy (Chong and
8 Husain, 2016; Hartmann et al., 2015; Husain and Roiser, 2018), and have been found across a variety of
9 psychopathologies, including depression (Treadway et al., 2012; Yang et al., 2014), schizophrenia (Barch
10 et al., 2014; Park et al., 2017), Parkinson’s disease (Chong, 2018; den Brok et al., 2015; Le Heron et al.,
11 2018), and substance dependence (Grodin et al., 2016). Due to its clear clinical importance, there has
12 been a recent surge of interest in how effort devalues prospective rewards, and such studies have
13 demonstrated that effort might be a unique cost, distinct from other more investigated cost domains,
14 such as risk and delay. However, work on the neural mechanisms underlying effort-based valuation have
15 yielded heterogeneous results, and the question of how humans integrate effort and reward remains a
16 subject of contention.

17 Most behavioral economic theories of reward-related behavior rely on the assumption that an
18 organism weighs a reward and its associated costs to generate a net value of an option (Kahneman and
19 Tversky, 1979; Sutton and Barto, 1998; Von Neumann and Morgenstern, 1990). A popular hypothesis
20 proposes that, to effectively compare different options, the net value of each must be represented in a
21 ‘common currency’ (Padoa-Schioppa, 2011; Rangel et al., 2008; Westbrook and Braver, 2015). A
22 network of regions, including the ventromedial prefrontal cortex (vmPFC; and adjacent orbitofrontal
23 cortex) and ventral striatum (VS), have been repeatedly implicated in the encoding of the net value of
24 rewards discounted by the costs associated with obtaining them (Bartra et al., 2013; Levy and Glimcher,
25 2012). Based on these data, this valuation network is posited to be ‘domain-general’, as it tracks net
26 value representations regardless of the nature of the reward (e.g., primary vs secondary) (Bartra et al.,
27 2013; Sescousse et al., 2013) or of the type of cost (e.g., risk vs delay) (Kable and Glimcher, 2007; Peters
28 and Büchel, 2009; Prévost et al., 2010).

29 However, much of these data have focused on outcome-related costs such as risk or delay.
30 Notably, research on effort-based valuation suggests a limited role for the vmPFC and VS for value
31 integration. Instead, other frontal regions beyond this core valuation network, including the anterior

32 cingulate cortex (ACC), supplementary motor area (SMA), and anterior insula (AI), have been shown to
33 signal net value discounted by effort costs (Arulpragasam et al., 2018; Camille et al., 2011; Chong et al.,
34 2017; Klein-Flugge et al., 2016; Massar et al., 2015; Skvortsova et al., 2014; Walton et al., 2003). These
35 findings are consistent with animal studies showing that lesions to the ACC, but not the nucleus
36 accumbens, prelimbic/infralimbic cortex (homologous to the vmPFC), or orbitofrontal cortex, reduce the
37 amount of effort rats invested for rewards (Rudebeck et al., 2006; Walton et al., 2009, 2003).
38 Furthermore, neural activity in the ACC, as measured by single unit recordings, varies with cost-benefit
39 weighting (Hillman and Bilkey, 2012, 2010) and effort-related choice (Cowen et al., 2012). This body of
40 work thus raises the possibility that a distinct frontal network is specifically recruited to integrate effort-
41 related value.

42 On the other hand, these frontal regions (i.e. ACC, pre-SMA, AI, etc.) are also commonly
43 implicated in cognitive control processes (Wu et al., 2020), which may overlap or obscure value signals.
44 For example, value-based decision-making may trigger cognitive control functions such as conflict
45 detection and response inhibition (Botvinick and Braver, 2015; Botvinick et al., 2001), surprise and/or
46 prediction error signaling (Vassena et al., 2020, 2017), and invigoration of goal-directed behavior
47 (Kouneiher et al., 2009; Kurniawan et al., 2013; Mulert et al., 2005). Therefore, it is plausible that these
48 regions are recruited to prepare and invigorate behaviors necessary for realizing a prospective reward
49 instead of for computing prepotent net values per se. Another situation that requires cognitive control is
50 difficult decision-making when two simultaneously presented options have similar net value (Chong et
51 al., 2017; Hunt et al., 2012; Klein-Flugge et al., 2016; Massar et al., 2015; Shenhav et al., 2013). Indeed,
52 studies that have independently manipulated net value and decision difficulty showed that these frontal
53 regions, particularly the dorsal ACC, specifically tracked decision difficulty (Hogan et al., 2017;
54 Westbrook et al., 2019) while, in contrast, the vmPFC uniquely tracked net value (Westbrook et al.,
55 2019). Taken together, these findings suggest that this distinct frontal network is recruited more
56 specifically for cognitive control, such as response planning and option comparison, and that effort-
57 related value integration is still processed in the core valuation network (e.g., vmPFC and VS) that have
58 been identified in other cost domains.

59 The inconsistencies in previous studies may be related to several issues. For example, some may
60 have been statistically underpowered due to small sample sizes, which may have reduced the
61 probability of detecting significant effects, and/or reduce the reliability of their findings (Müller et al.,
62 2018; Poldrack et al., 2017). Furthermore, the specific effort requirements of each task may have

63 induced different patterns of brain activity, making it difficult to judge whether findings from individual
64 studies can be generalized to the cognitive process of interest. A promising approach to address these
65 issues is to quantitatively synthesize fMRI data across multiple studies using an image-based meta-
66 analysis (Muller et al., 2018). Relative to traditional meta-analyses based only on peak coordinates of
67 significant activity, an image-based meta-analytic approach uses the full information of the statistical
68 maps from each study, and has greater power to detect small effect sizes (Luijten et al., 2017; Salimi-
69 Khorshidi et al., 2009). A previous study showed that even the inclusion of 20% of statistical maps for
70 included studies could significantly improve the precision of a meta-analysis (Radua et al., 2012).

71 Here, we conducted a hybrid coordinate- and image-based fMRI meta-analysis to identify the
72 neural correlates of effort-related cost processing and value integration. Considering their critical roles
73 in response planning, we hypothesized that frontal regions like the ACC, SMA, and AI would be
74 consistently involved in representing prospective effort, independent of the reward offer. We also
75 aimed to test whether effort-related value integration (i.e., the integration of reward value with the
76 effort required to obtain it) relied on the core valuation areas such as the vmPFC and VS or broader
77 frontal regions.

78

79 **2. Materials and Methods**

80 2.1. Literature Screen, Data Collection, and Preparation

81 *2.1.1 Exhaustive Literature Search.*

82 We conducted a systematic literature search to identify neuroimaging studies on prospective
83 effort and the integration of reward value and effort costs in healthy adults. Candidates for inclusion
84 were initially identified by searching PubMed, ProQuest, and Web of Science on June 29, 2020 using the
85 grouped terms (“fMRI” OR “functional magnetic resonance imaging”) AND (“effort discounting” OR
86 “effort-based decision-making” OR “effort valuation” OR “effort anticipation” OR “cost-benefit
87 valuation” OR “cognitive effort” OR “physical effort” OR “effort expenditure” OR “effort allocation” OR
88 “effortful goal directed action” OR “reward related motivation” OR “reward related effort”). Searches
89 were limited to human studies where databases would allow. 121, 787, and 127 studies were identified
90 on PubMed, ProQuest, and Web of Science, respectively. We also searched existing in-house reference
91 libraries and names of prominent authors in the field, resulting in the addition of candidate studies. 934
92 candidate studies remained after search results were pooled and duplicates removed. Two researchers

93 (PL-G, Y-WY) then independently reviewed the title and abstract of candidate papers to determine
94 relevance, resulting in a pool of 72 studies that underwent a full-text review (Figure 1).

95

96 *2.1.2 Inclusion/Exclusion Criteria.*

97 Studies were included if they: 1) had a healthy adult human sample in the non-elderly age range
98 (ages 18 to 65, with one exception detailed below); 2) used functional MRI; 3) either reported or
99 referenced a whole-brain analysis; and 4) utilized a task with an effort component with clear effort (or
100 combined effort and reward) cues during an ‘anticipation’ phase. Please note that ‘anticipation’ in this
101 case refers to the evaluation of prospective effortful rewards before or during decision-making, and
102 does not include anticipatory responses to reward post-effort exertion (e.g., the ‘evaluation’ phase
103 described in Assadi et al., (2009)).

104 To ensure that the selected studies could be meaningfully compared, we limited the final corpus
105 to those that used experimental paradigms with certain characteristics. First, because studies have
106 found that loss and gain are asymmetric and partially dissociable (Chen et al., 2020; Porat et al., 2014;
107 Tanaka et al., 2014), we excluded studies that used paradigms with only loss conditions, or that only
108 conducted gain vs loss comparisons. Second, we excluded studies that only used a single speeded
109 response as its effort component (e.g. classical Monetary Incentive Delay task (Knutson et al., 2000)), as
110 this was not deemed as a significant effort demand, and other reviews and meta-analyses focusing on
111 reward anticipation with these paradigms can be found elsewhere (Diekhof et al., 2012; Knutson and
112 Greer, 2008; Wilson et al., 2018). Finally, we only included those studies which measured activity during
113 the *prospective* valuation of an action and its rewards, rather than only at the time of reward outcome,
114 as estimates of previously expended effort can be biased by reward receipt (Pooresmaeili et al., 2015).

115 We contacted the corresponding authors of 28 candidate studies to request whole-brain
116 statistical maps for the analyses of interest, and received whole-brain statistical maps or peak
117 coordinates from 25 studies. In cases where only between-group (e.g. clinical studies) and/or ROI results
118 were reported, we contacted corresponding authors to inquire about the availability of whole-brain
119 results for relevant contrasts in healthy adult subjects. If images were not available, we requested they
120 provide us with peak activation foci in stereotactic spatial coordinates (i.e., Talairach or MNI space),
121 together with the direction of the effect (positive or negative).

122

123 *2.1.3 Data collection and preparation.*

124 We performed two analyses of interest. The first examined activity related to the raw effort
125 involved in the option itself. We included analyses that examined high vs. low effort demands (i.e.,
126 categorical contrasts) and those that examined continuous changes in effort (i.e., parametric
127 modulation). The second analysis examined activity related to the prospective net value of an effortful
128 reward. Whenever possible, we used the contrast related to the net value of a single option (i.e., the
129 subjective value of the chosen option discounted by the effort required to obtain it). When this contrast
130 was unavailable, we used the contrast related to the differences between options instead. Studies that
131 only investigated BOLD activity associated with interactions between reward and effort were excluded,
132 as they did not rely on the same discounting assumptions as other measures of net value. It should be
133 noted that one study (Nagase et al., 2018) included two experiments with six common participants, so
134 we selected the experiment with a larger sample size for the meta-analysis. In another study (Chong et
135 al., 2017), all participants took part in both cognitive and physical effort-based decision-making tasks.
136 Thus, we combined the statistical maps from both tasks to avoid selection bias. Finally, one study
137 (Seaman et al., 2018) had a sample that included participants ranging from 22 to 83 years old. However,
138 the authors of this study provided whole-brain maps that controlled for the effect of age, and we chose
139 to include this data in the net value meta-analysis.

140

141 *2.1.4 Final Corpus.*

142 As shown in Figure 1, 25 studies were ultimately included in the final corpus of studies, which
143 were considered in one or both meta-analyses on raw effort evaluation and effort-reward integration.
144 The raw effort valuation analysis included 15 maps (65%) and 7 coordinates for raw effort processing,
145 resulting in 22 studies with a total sample of N = 549 (mean = 24.95; median = 22.5, range = [16-50]). A
146 description of the final corpus of studies can be found in Table 1. The value integration analysis included
147 11 maps (73%) and 4 coordinates, resulting in 15 studies, with a total sample of N = 428 participants
148 (mean = 28.5; median = 23, range = [16-75]).

149

150 *2.2 Meta-Analytic Procedures*

151 *2.2.1 Seed-based d Mapping.*

152 The combined image- and coordinate-based meta-analyses were performed using the software
153 Seed-based d Mapping with Permutation of Subject Images (SDM-PSI, version 6.21;
154 <https://www.sdmproject.com>). SDM-PSI preserves the information about the sign of the effect and the
155 methods have been validated in previous studies (Albajes-Eizagirre et al., 2019; Radua et al., 2012).
156 During preprocessing, SDM-PSI recreated voxel-level maps of standardized effect sizes (i.e., Hedge's g)
157 and their variances and allowed the incorporation of both whole-brain t -maps and peak information
158 (i.e., coordinates and t -values). The inclusion of statistical maps can substantially increase the sensitivity
159 of meta-analyses compared with the pure coordinate-based approach (Radua et al., 2012). When t -
160 maps were unavailable, SDM-PSI estimated them based on coordinates and their effect sizes using
161 anisotropic kernels (Radua et al., 2014).

162

163 *2.2.2 Meta-analysis.*

164 Two separate whole-brain meta-analyses were conducted to examine consistent neural
165 correlates of prospective effort and net value processing, respectively. Random-effect models were used
166 to assess the mean effect size of each study, where the weight of a study is the inverse of the sum of its
167 variance and the between-study variance. SDM z -maps were generated by dividing the voxel-wise effect
168 sizes by their standard errors. As these z -values may deviate from a normal distribution, a null-
169 distribution was estimated for each meta-analysis from 50 whole-brain permutations.

170

171 *2.2.2.1 Region-of-Interest (ROI) Analysis.*

172 To directly investigate the involvement of key brain regions in effort-related cost processing and
173 value integration, we focused on seven *a priori* regions of interest (ROIs) derived from an independent
174 meta-analysis (Bartra et al., 2013) that examined valuation network in general. Those ROIs included: the
175 vmPFC, right and left VS, ACC, pre-SMA, and right and left AI, which generally covered the core valuation
176 network and additional frontal regions of interest. A spherical mask of radius 6mm was created for each
177 ROI centered on the respective peak coordinates. Mean effect sizes and variances of those ROIs were
178 extracted from individual studies with statistical maps.

179

180 *2.2.2.2 Whole-Brain Analysis.*

181 We also examined the whole-brain results beyond these *a priori* ROIs. To reduce the false-
182 positive results due to multiple comparisons, we applied a familywise error (FWE) correction with 1000
183 subject-based permutations (Albajes-Eizagirre et al., 2019). In accordance with SDM-PSI's
184 recommendations, a threshold-free cluster enhancement (TFCE) corrected $p < 0.025$ was used (Albajes-
185 Eizagirre et al., 2019).

186 In addition, we performed a conjunction analysis to identify regions that were associated with
187 both raw effort demand and net value. For exploratory purposes, we created maps using a voxel-level
188 uncorrected threshold of $p < 0.001$ and a cluster size > 20 voxels for both meta-analyses. Masks were
189 generated from significant clusters that activated or deactivated in both processes (i.e., based on
190 absolute values). We then used SPM12 (<http://www.fil.ion.ucl.ac.uk/spm>) to perform a conjunction
191 analysis to extract overlapping areas for both processes, regardless of the direction (Culter & Campbell-
192 Meiklejohn, 2019).

193 Finally, we conducted two supplementary analyses. First, because of the possible role of the
194 dorsal ACC and other frontal regions in signaling choice difficulty, we were interested in assessing if our
195 findings were influenced by studies that used net value differences as the parameter, rather than the
196 net value of the chosen option. Thus, we repeated the meta-analysis with a subgroup of studies that
197 used parameters only representing the net value of a single option (N=11). Second, because net value
198 can also be more broadly defined as an interaction between reward and effort, we repeated the net
199 value meta-analysis by including the coordinates of two additional studies (Kurniawan et al., 2010;
200 Stoppel et al., 2011) that used interaction parameters (e.g. Reward X Effort) as opposed to traditional
201 discounting parameters of net value (e.g. SV). These analyses were conducted using the same
202 procedures described above.

203

204 *2.2.3 Heterogeneity and Publication Bias.*

205 Areas of significant activation were assessed for heterogeneity and publication bias. For each
206 meta-analysis, peaks with heterogeneity I^2 values $> 20\%$ were flagged and inspected. In order to assess
207 publication bias, Hedge's g effect size estimates were extracted at the study level for peak voxels of
208 significant clusters. Funnel plots were created and visually inspected. Egger regression tests (Egger et al.,
209 1997) were conducted to quantitatively test the asymmetry of each funnel plot.

210

211 2.3 Data Availability.

212 Unthresholded z-maps of our results are available at NeuroVault:

213 <https://neurovault.org/collections/9286/>. The TFCE-corrected maps as well as publication bias and
214 heterogeneity data are available from the corresponding authors upon request.

215

216 **3. Results**

217

218 3.1. ROI Analysis

219 To directly examine the roles of key regions in raw effort prospect and effort-reward integration,
220 we focused on seven *a priori* ROIs. Results are summarized in Table 2. The vmPFC showed consistent
221 activations related to net value and deactivations related to prospective effort. The bilateral VS showed
222 a similar activity pattern, but smaller effect sizes for both analyses. In contrast, the pre-SMA showed
223 consistent activations related to effort demand and deactivations related to net value. The ACC and
224 bilateral AI showed similar activity pattern, but smaller effect sizes for both analyses. Figures 2 and 3
225 show the Hedge's *g* effect sizes for raw effort prospect and net value analyses in the vmPFC and pre-
226 SMA ROIs. The forest plots for other regions were shown in Figure S1-S10.

227

228 3.2. Whole-Brain Analysis

229 3.2.1 *Prospective Effort*

230 We first examined brain regions that were consistently associated with the valuation of
231 prospective effort demands. As illustrated in Figure 4a, the analysis yielded positive effects clustered in
232 the right pre-SMA and adjacent caudal ACC (see Table 3). At a more lenient, uncorrected $p < 0.001$
233 threshold, other positive foci were detected in the left SMA, right precuneus, and left middle frontal
234 gyrus, and negative foci were detected in the bilateral vmPFC/OFC and left middle temporal gyrus.

235 Heterogeneity I^2 statistics, funnel plots and Egger regressions did not detect excess
236 heterogeneity or publication bias in any significant clusters in the TFCE-corrected findings. However, in
237 the uncorrected analysis, activation in a cluster in the right precuneus was found to be associated with
238 extreme heterogeneity ($I^2=59.50\%$).

239

240 3.2.2. Net Value.

241 Next, we examined brain regions that were consistently associated with net value encoding. As
242 illustrated in Figure 4b, the analysis yielded a large cluster connecting cortical and subcortical regions of
243 the medial PFC, VS, dorsal striatum (bilateral putamen and left caudate), and temporal gyrus (see Table
244 3). Analysis also yielded consistent net value activations in a cluster consisting of the bilateral medial and
245 posterior cingulate cortex and precuneus and a separate cluster in the left middle frontal gyrus.
246 Deactivations were concentrated in small clusters in the left SMA, right dorsolateral PFC (dlPFC), and
247 right superior frontal gyrus, although these deactivations were only detectable at a lenient uncorrected
248 $p < 0.001$ threshold.

249 In addition, heterogeneity I^2 statistics, funnel plots and Egger regressions showed no evidence of
250 excess heterogeneity or publication bias in any of the significant clusters for the main net value or single
251 SV subgroup TFCE-corrected results. No evidence of publication bias was detected in the uncorrected
252 net value analysis, however deactivations in the left SMA and right dlPFC had I^2 statistics of 64.09% and
253 50.05% respectively, suggesting that findings in these two regions were highly heterogenous.

254

255 3.2.3 Conjunction Analysis

256 Finally, we performed a conjunction analysis to identify areas that are sensitive to *both* net
257 value and effort requirements. Due to the exploratory nature of this analysis, we used a lenient
258 threshold of uncorrected $p < 0.001$ at voxel level and $k > 20$ at cluster level. Note that we used absolute
259 values in the conjunction analysis because of the clearly dissociable effects found in the main
260 prospective effort and net value meta-analyses. We found that the vmPFC and left lateral orbitofrontal
261 cortex were significantly activated by net value but deactivated by effort requirement. The activation
262 pattern was reversed in the pre-SMA and caudal ACC (Figure 4c). However, all of these findings were not
263 detectable after whole-brain TFCE-correction.

264

265 3.2.4 Supplementary analyses

266 To ensure that the results of the net value meta-analysis were not driven by choice difficulty, we
267 reran our analysis excluding four experiments that used the value of two options as their net value
268 metric (e.g. difference in SV of more vs less effortful option). Importantly, the vmPFC and bilateral VS
269 remained to be the foci with highest effect sizes, and the whole-brain activation pattern was
270 qualitatively similar (see Table S1 and Figure S11), suggesting that our main findings were not influenced
271 by the cognitive demands of comparing two options. Moreover, to ensure that our findings were robust
272 when using a broader definition of net value, we also repeated our analysis including two additional
273 studies that used reward and effort interactions as a measure of net value. Main foci and whole-brain
274 activation patterns remained qualitatively similar to the initial net value meta-analysis (see Table S2 and
275 Figure S12). However, deactivations associated with net value were not detected in these
276 supplementary analyses, suggesting that the deactivations in the SMA detected in the main meta-
277 analysis were not robust.

278

279 **4. Discussion**

280 We conducted a series of combined coordinate- and image-based meta-analyses to examine the
281 neural substrates of effort-based valuation. We first investigated neural activity related to raw effort
282 and net value in seven *a priori* ROIs previously implicated in value-based decision-making. We found
283 these regions could be broadly divided into two groups that exhibited distinct activity pattern during
284 these two processes, with the vmPFC and pre-SMA as the central node of each. Specifically, the vmPFC
285 was consistently activated during net value integration but deactivated for raw effort representation,
286 whereas the pre-SMA displayed the opposite pattern. The exploratory whole-brain and conjunction
287 analyses further corroborate the ROI analyses. These findings provide strong evidence for a dissociable
288 role of the vmPFC and pre-SMA in the valuation of effort costs, and implicate these two regions as core
289 components of a network that drives motivated behavior.

290 Our findings provide comprehensive evidence that effort-related net value integration is
291 processed in a network centered around the vmPFC and VS. Accumulating evidence implicates the
292 vmPFC as a general hub for value integration, as it has been identified to signal net value of rewards
293 across different cost domains, such as risk and delay (Croxson et al., 2009; Hogan et al., 2019; Kable and
294 Glimcher, 2007; Levy et al., 2010; Peters and Büchel, 2009; Schmidt et al., 2012; Westbrook et al., 2019).
295 Additionally, the network including the vmPFC have been implicated in tracking net values across reward
296 domains (i.e., primary, secondary, and aesthetic rewards), reward processing phases (Bartra et al., 2013;

297 Clithero and Rangel, 2013; Levy and Glimcher, 2012; Sescousse et al., 2013), reward rates, and the value
298 of current and previous offers (Mehta et al., 2019). These findings are therefore consistent with
299 prominent neuroeconomic accounts which propose that the vmPFC represent the net value of an option
300 in a ‘common currency’, in order to facilitate value comparison during decision-making (Padoa-Schioppa,
301 2011; Rangel et al., 2008; Westbrook and Braver, 2015).

302 One would hypothesize that a region involved in representing net value would also scale with
303 effort demands. Except for the vmPFC, our study did not find that other net-value-related regions, such
304 as the VS, meet this requirement. These findings are at odds with previous reports that the VS signals
305 prospective effort costs in humans, both in the presence (Westbrook et al., 2019) and absence (Suzuki et
306 al., 2020) of reward information. Moreover, dorsal parts of the striatum have also been found to track
307 both effort costs (Burke et al., 2013; Guitart-Masip et al., 2012; Klein-Flugge et al., 2016; Kurniawan et
308 al., 2010, 2013; Yang et al., 2016) and net value of prospective effortful rewards (Klein-Flugge et al.,
309 2016; Seaman et al., 2018). However, our results implicate motor-related regions of the striatum,
310 particularly the putamen, as signaling net value alone. One plausible explanation is that the striatum
311 signals both net value and prospective effort during this time window, but that the simultaneous nature
312 of these signals inhibits detection. Studies that have experimentally isolated prospective effort demands
313 from net value, however, did not find that the striatum was activated by effort alone (Arulpragasam et
314 al., 2018), leaving role of the striatum in effort anticipation as a salient question for future investigation.

315 Finally, both main and supplementary analyses consistently identified a variety of
316 parietotemporal regions as scaling positively and uniquely with net value representations. While these
317 regions (i.e. intraparietal lobule, intraparietal sulcus, temporal pole, etc.) have been previously
318 implicated in SV encoding of effortful rewards (Chong et al., 2017; Massar et al., 2015), they also play a
319 critical role in perceptual decision-making (Keuken et al., 2014), attention (Husain, 2019), risk weighting
320 (Mohr et al., 2010), and decision difficulty (Westbrook et al., 2019). Their notable absence in reward
321 processing (Keuken et al., 2014; Sescousse et al., 2013) may thus suggest that these parietotemporal
322 regions are involved in high-level perceptual and cognitive functions associated with task demands as
323 opposed to net value computation.

324 Previous studies have identified effort-related net value signals in other frontal regions, such as
325 the pre-SMA and ACC, which suggests that these regions may be specifically relevant for effort-reward
326 integration. In the current meta-analysis, however, we found that these regions – in particular, the pre-
327 SMA and adjacent caudal ACC – all scaled positively with raw effort costs and, albeit less robustly, scaled
328 negatively with net value. Such a pattern suggests that these regions are more likely to be involved in

329 the processing of effort-related costs, rather than value integration per se. These findings align closely
330 with a previous transcranial magnetic stimulation study, in which disruption of the SMA led to decreased
331 effort perception (Zénon et al., 2015). The pre-SMA and dorsal ACC are also recruited to process other
332 types of costs, such as risk (Mohr et al., 2010) and delay (Schüller et al., 2019). A plausible mechanism,
333 therefore, is that these regions serve as a domain-general hub for cost encoding and transfer the cost
334 information to the vmPFC for calculation of net value. Alternatively, neuroeconomic models of effort-
335 based decision-making have posited that the ACC, in particular, is involved in good-to-action
336 transformation (Padoa-Schioppa, 2011). Thus, another plausible mechanism is that the vmPFC computes
337 and compares the net value of separate options and passes choice preference to action selection
338 regions, such as the pre-SMA and ACC, for conversion to motor output.

339 Despite strong evidence about the involvement of the caudal ACC, which is close to the pre-
340 SMA, in effort costs processing, it should be noted that the ACC, as a whole, is highly heterogeneous
341 (Neubert et al., 2015; Yu et al., 2011). Indeed, the whole-brain results showed distinct activation
342 patterns across the ACC, in which net-value-related activation was mainly observed in the ventral ACC,
343 whereas cost-related activation in the dorsal ACC. These findings suggest that subregions of the ACC
344 could be linked to different aspects of the effort-related valuation, which may also partly explain the fact
345 that some studies identified net value signals in the ACC (Klein-Flugge et al., 2016; Massar et al., 2015).
346 Moreover, net-value-related activation may emerge in the dorsal ACC if it is highly correlated with other
347 confounding variables, such as decision difficulty (Shenhav et al., 2013). It is particularly plausible for
348 studies that have used the SV difference between two options as the net value parameter, as it often
349 approximates decision difficulty (Chong et al., 2017; Klein-Flugge et al., 2016). Notably, studies that have
350 experimentally isolated net value and decision difficulty showed that the cognitive control network,
351 including the dorsal ACC and other frontoparietal regions, tracked the latter but not the former (Hogan
352 et al., 2019; Westbrook et al., 2019).

353 The current study has some limitations. First, the sample size of the net value analysis is
354 relatively small. Although the inclusion of statistical images partly offsets this issue, the number of
355 included studies still limited our ability to further explore the effects of potential moderators, such as
356 effort type (i.e., physical vs. cognitive), parameter type (i.e., difference in SV vs. SV of one option), effort
357 execution requirement (i.e., real vs. hypothetical), and reward probability (i.e., cumulative vs. random
358 payout). Because effort-based decision-making is sensitive to reward probability (Barch et al., 2014;
359 Soder et al., 2020; Treadway et al., 2012) and opportunity costs (Otto and Daw, 2019), future research
360 should directly explore the interaction between effort demand and other cost domains and/or task

361 features. Second, the majority of the included studies focused on physical effort measured by handgrip
362 devices. These findings should be treated cautiously when generalizing to other formats of effort.
363 Finally, the meta-analytic results reflected consistent regional activations across studies. Although our
364 study identified critical brain regions related to effort-related value integration or cost encoding, how
365 these regions interact with each other to achieve the dynamic valuation process remains to be
366 elucidated by studies using task-based connectivity technique (Hauser et al., 2017) or imaging methods
367 with higher temporal resolution (e.g., magnetoencephalography).

368 In conclusion, this study is the first to use combined image- and coordinate-based meta-analyses
369 to examine neural activity related to effort-related costs and net value. The results showed the pre-SMA
370 is involved in cost representation of prospective effort independent of rewards. In contrast, the vmPFC
371 and VS, which have been implicated in value integration in other cost domains, are also involved in
372 effort-reward integration. These findings further clarify the neural mechanisms underlying effort-related
373 valuation and may provide candidate intervention targets for patients with decreased motivation to
374 exert effort to obtain rewards.

375

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384

385 **Declarations of interest:**

386 None

387

388 Table 1. Summary of Included Studies

Study	N	Task Type	Effort Type (Description)	Analysis	Data Type	Parameter
Aridan 2019	40	Choice	Physical (Handgrip)	Net Value	Map	P(yes)
				Effort	Map	Parametric effort demand
Arulpragasam 2018	28	Choice	Physical (Key press)	Net Value	Map	SV of Chosen Option
				Effort	Map	Effort demand of the variable option (at Cue 1)
Bernacer 2019	24	Choice	Physical (Running)	Net Value	Map	SV Difference
				Effort	Map	Max > no effort
Bonnelle 2016	37	Choice	Physical (Handgrip)	Net Value	Coordinates	“Expected Reward”
Chong 2017*	34	Choice	Physical (Handgrip) + Cognitive (RSVP)	Net Value	Map	SV Difference
				Effort	Map	Parametric effort demand
Croxson 2009	16	No choice	Physical (Trackball)	Net Value	Coordinates	Log (reward/effort)
				Effort	Coordinates	Increasing effort level
Hogan 2019	34	Choice	Physical (Handgrip)	Net Value	Map	SV of chosen option
Gaillard 2019	23	No Choice	Cognitive (Spatial WM)	Effort	Map	Categorical High vs Low WM Load
Grodin 2016	17	No Choice	Physical (Key press)	Effort	Map	Categorical High vs Low effort
Hauser 2017	28	Reward/effort learning	Physical (Handgrip)	Effort	Map	Parametric expected effort demand
Klein-Flügge 2016	21	Choice	Physical (Handgrip)	Net Value	Map	SV difference
				Effort	Map	Parametric Effort Difference
Kurniawan 2010	17	Choice	Physical (Handgrip)	Net Value**	Coordinates	Reward X [choice to grip > choice to hold]
				Effort	Coordinates	High > low effort of chosen option
Kurniawan 2013	19	No Choice	Physical (Handgrip)	Effort	Map	High > low effort demand
Massar 2015	23	Choice	Cognitive (Backwards typing)	Net Value	Map	SV of chosen option
				Effort	Map	Parametric effort level
Nagase 2018	33	Reward/effort learning	Cognitive (Arithmetic)	Effort	Map	Expected effort demand of chosen option
Park 2017	30	No Choice	Physical (Mouse click)	Effort	Coordinates	High vs low effort demand
Prévost 2010	16	Choice	Physical (Handgrip)	Net Value	Coordinates	SV of variable option
				Effort	Coordinates	Parametric Effort Demand

Sayali & Badre 2019	50	Choice	Cognitive (Cued task switching)	Effort	Map	Expected effort demand of chosen option
Scholl 2015	20	Reward/effort learning	Physical (Trackball)	Net Value	Map	Decision value difference
				Effort	Map	Effort demand difference
Seaman 2018	75	Choice	Physical (Keyboard)	Net Value	Map	SV of chosen option
Skvortsova 2014	20	Reward/effort learning	Physical (Handgrip)	Net Value	Map	Expected value demand of chosen option
				Effort	Map	Effort Q
Stoppel 2011	18	No Choice	Cognitive (Line tracing)	Net Value**	Coordinates	Reward X Difficulty
				Effort	Coordinates	Hard > easy effort
Suzuki 2020	19	Choice	Physical (Keypress)	Net Value	Coordinates	SV of chosen option
		No Choice	Physical (Maze Navigation)	Effort	Coordinates	High > low effort
Vassena 2014	22	No Choice	Cognitive (Arithmetic)	Effort	Coordinates	High > low effort
Westbrook 2019	21	Choice	Cognitive (N-back)	Net Value	Map	SV of the more effortful option
				Effort	Map	Effort demand

389 *Maps from separate tasks were combined for all analyses. Abbreviation: RSVP, rapid serial visual presentation.

390 **Only included in supplementary Net Value analysis.

391 Table 2. Results of ROI analyses

ROI	MNI coordinate	Analysis	Hedge's <i>g</i>	<i>Z</i>	<i>p</i>	<i>I</i> ² (in %)	Egger's <i>p</i>
vmPFC	(2, 46, -8)	Net value	0.332	5.861	< 0.001	0.007	0.393
		Raw effort	-0.167	-2.482	0.013	39.381	0.678
rVS	(12, 10, -6)	Net value	0.167	2.334	0.020	35.404	0.420
		Raw effort	-0.061	-1.170	0.242	< 0.001	0.286
lVS	(-12, 12, -6)	Net value	0.132	1.779	0.075	40.289	0.559
		Raw effort	-0.082	-1.565	0.118	< 0.001	0.879
Pre-SMA	(-2, 16, 46)	Net value	-0.290	-2.255	0.024	78.669	0.130
		Raw effort	0.187	2.142	0.032	63.161	0.726
ACC	(-2, 28, 28)	Net value	-0.088	-0.792	0.429	72.962	0.735
		Raw effort	0.083	1.163	0.245	47.311	0.764
rAI	(32, 20, -6)	Net value	-0.151	-1.474	0.141	68.130	0.131
		Raw effort	0.109	1.751	0.080	31.031	0.195
lAI	(-30, 22, -6)	Net value	-0.090	-0.787	0.431	74.025	0.107
		Raw effort	0.055	0.894	0.371	29.295	0.388

392 Abbreviations: vm, ventromedial; r, right; l, left; PFC, prefrontal cortex; VS, ventral striatum; ACC, anterior cingulate cortex; AI, anterior insula.

393 Table 3. Results of whole-brain analyses

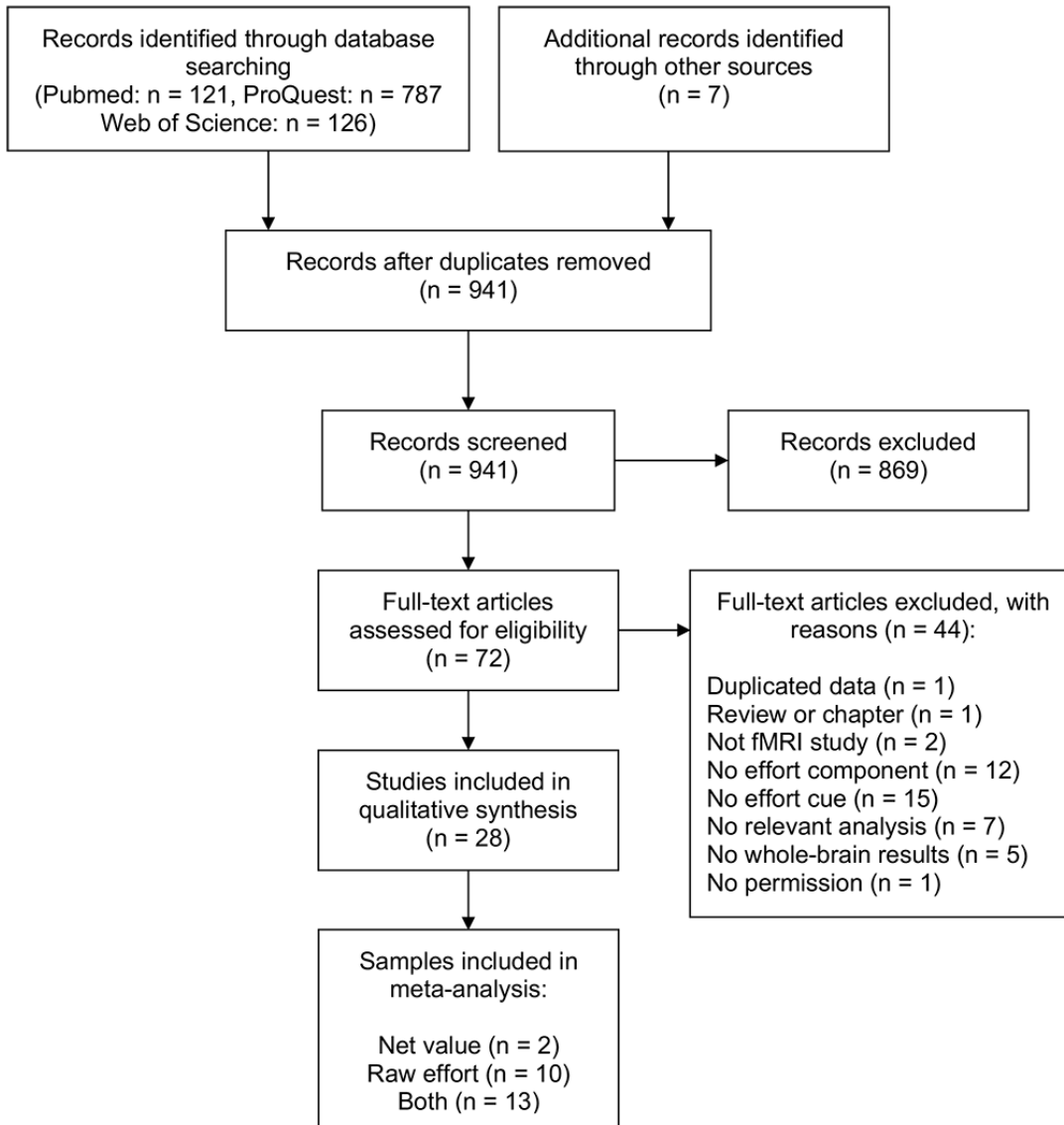
Analysis	Cluster	Voxels	Peak MNI coordinates	BA	Regions	SDM-Z	I^2 (in %)	Egger's p					
Net value	1*	23918	-4, 52, -8	10	Left vmPFC	7.052	0.208	0.702					
			2, 52, -8	11	Right vmPFC	6.473							
			8, 10, -8		Right NAc	6.417							
			30, -6, -4		Right putamen	5.782							
			-32, -16, 4		Left putamen	5.546							
			-22, -6, -14	34	Left amygdala	5.398							
			24, 0, -16	34	Right amygdala	5.372							
			-50, -62, 14	37	Left temporal gyrus	5.335							
			-6, 14, -8		Left NAc	5.255							
	2*	3821	-6, 38, 0	11	Left ACC	5.170	6.332	0.444					
			-52, -50, 2	21	Left middle temporal gyrus	5.145							
			24, 14, -16	48	Right insula	5.131							
			-14, -38, 40	23	Left PCC	5.592							
			-12, -40, 44		Left precuneus	5.446							
			0, -8, 42	23	Dorsal ACC	5.003							
			-16, -34, 40		Left superior parietal gyrus	4.879							
			-26, 28, 38	9	Left dlPFC	4.245							
			Prospective effort	1*	112	-8, 16, 52			6	Left SMA	-3.718	3.266	0.594
						44, 38, 24			8	Right dlPFC	-4.263	64.089	0.085
16, 20, 58	8	Right superior frontal gyrus				-3.797	50.050	0.186					
8, 16, 64	6	Right SMA				3.966	24.707	0.249					
-8, 8, 52	6	Left SMA				3.922	1.069	0.494					
14, -66, 38	7	Right precuneus				3.615	0.161	0.684					
-28, -6, 50	6	Left middle frontal gyrus				3.505	59.40	0.111					
-8, 56, -8	11	Left vmPFC				-4.264	0.162	0.933					
Prospective effort	1*	112	-42, 30, -14	47	Left OFC	-4.037	5.901	0.634					
			6, 54, -14	11	Right vmPFC	-3.798	0.002	0.947					
			-56, -6, -18	21	Left middle temporal gyrus	-4.385	15.71	0.936					
							7.473	0.724					

394 All results survived a statistical threshold of voxel-level uncorrected $p < 0.001$ and cluster size > 20 .

395 * Regions survived a statistical threshold of TFCE-corrected $p < 0.025$.

396 Abbreviations: BA, Brodmann areas; vm, ventromedial; dl, dorsolateral; d, dorsal; r, rostral; PFC, prefrontal cortex; NAc, nucleus accumbens; ACC, anterior
397 cingulate cortex; PCC, posterior cingulate cortex; SMA, supplementary motor area; OFC, orbitofrontal cortex.

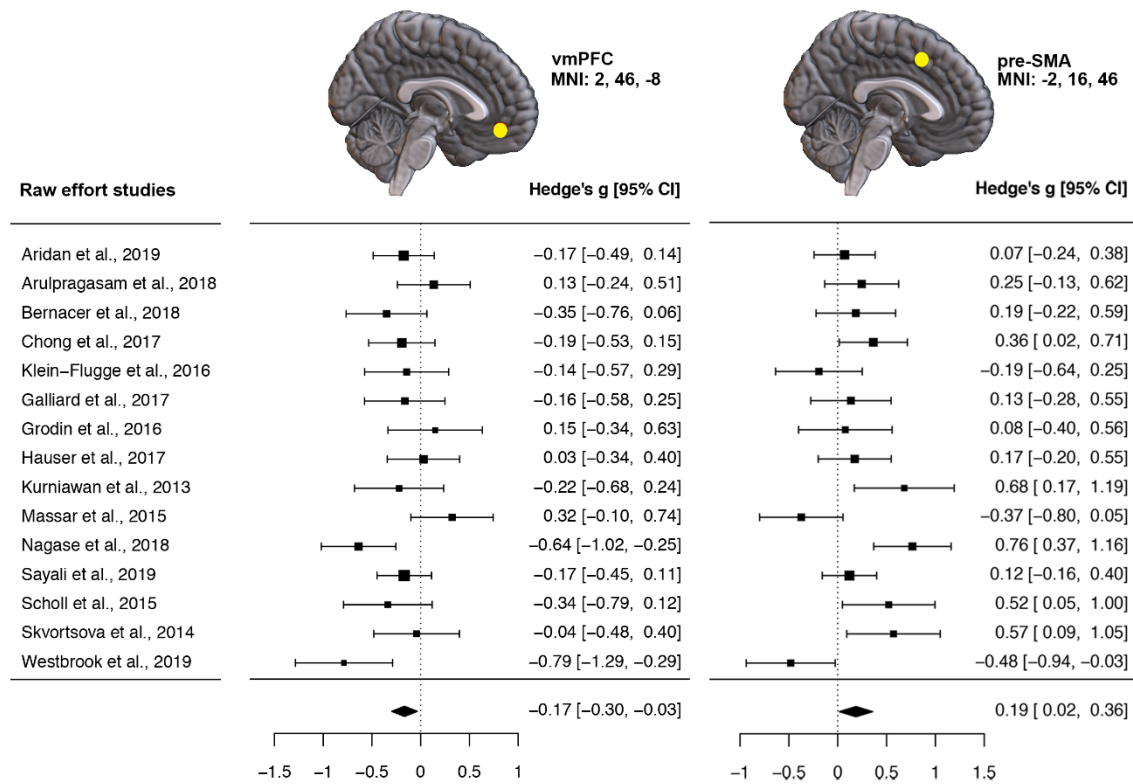
398 **Figure legend**



399

400 Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram.

401



402

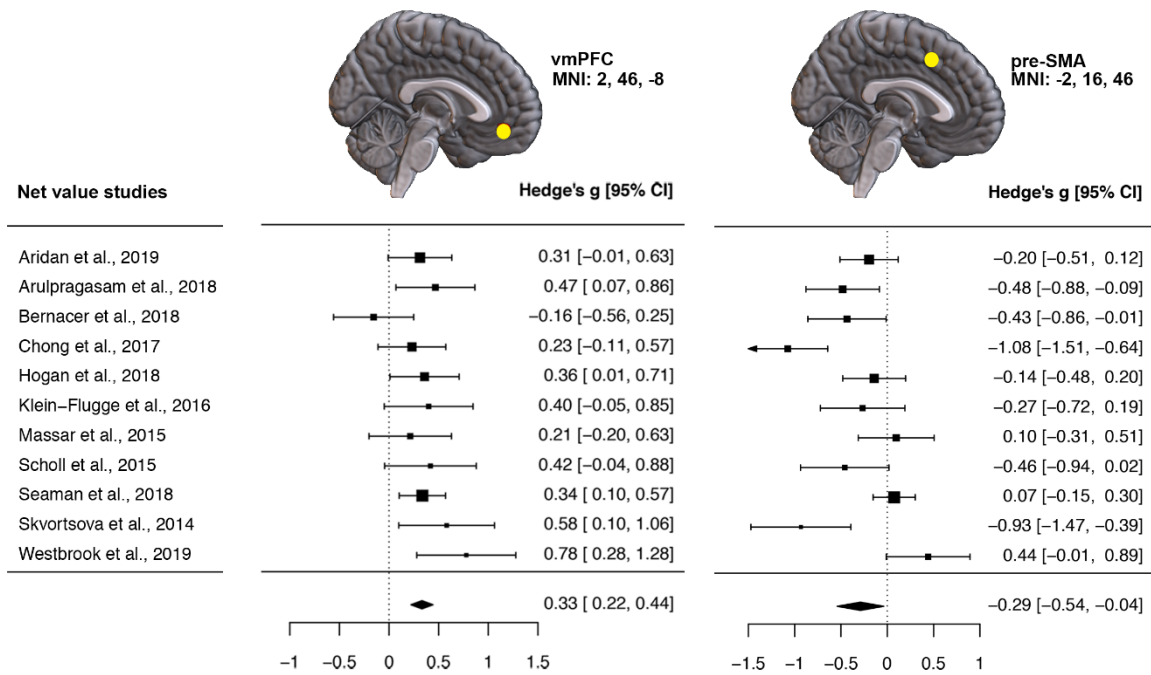
403 Figure 2. Forest plot illustrating activation related to effort demand in the vmPFC and pre-SMA ROIs in

404 studies with statistical maps. Contrary to our findings for net value signaling, the pre-SMA is activated

405 (Hedge's $g = 0.20$, 95% CI [0.02, 0.37]) and the vmPFC is deactivated (Hedge's $g = -0.17$, 95% CI [-0.30, -

406 0.03]) when tracking pure prospective effort.

407



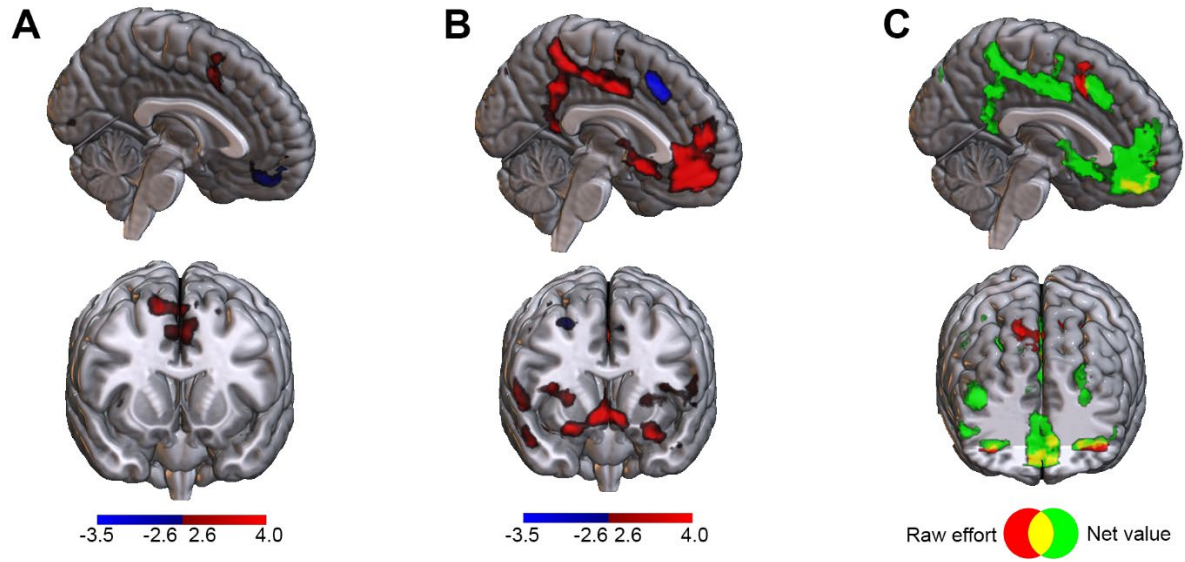
408

409 Figure 3. Forest plot illustrating activation related to net value in the vmPFC and pre-SMA ROIs in studies

410 with statistical maps. The vmPFC is activated (Hedge's $g=0.22$, 95% CI [0.22, 0.44]) and the pre-SMA is

411 deactivated (Hedge's $g=-0.28$, 95% CI [-0.52, -0.03]) during effort-reward integration.

412



413

414 Figure 4. Whole-brain meta-analytic results. A: neural activity related to pure effort cost representation;

415 B: neural activity related to net value; and C: their conjunction based on absolute values. Display

416 threshold: uncorrected $p < 0.005$ at voxel level.

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