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Love is analogous to money in human brain: Coordinate-based and functional connectivity meta-analyses of social and monetary reward anticipation

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Abstract

Both social and material rewards play a crucial role in daily life and function as strong incentives for various goal-directed behaviors. However, it remains unclear whether the incentive effects of social and material reward are supported by common or distinct neural circuits. Here, we have addressed this issue by quantitatively synthesizing and comparing neural signatures underlying social (21 contrasts, 207 foci, 696 subjects) and monetary (94 contrasts, 1083 foci, 2060 subjects) reward anticipation. We demonstrated that social and monetary reward anticipation engaged a common neural circuit consisting of the ventral tegmental area, ventral striatum, anterior insula, and supplementary motor area, which are intensively connected during both task and resting states. Functional decoding findings indicate that this generic neural pathway mediates positive value, motivational relevance, and action preparation during reward anticipation, which together motivate individuals to prepare well for the response to the upcoming target. Our findings support the

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The authors are unaware of any conflicts of interest, financial or otherwise.

Appendix A. Supplementary data
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common neural currency hypothesis by providing the first meta-analytic evidence to quantitatively show the common involvement of brain regions in both social and material reward anticipation.

Keywords

Social reward; Reward anticipation; Monetary incentive delay task; Meta-analysis; Functional decoding; Meta-analytic connectivity modeling; Resting-state functional connectivity

1. Introduction

As social beings, human behavior is strongly motivated by social rewards, i.e., desirable outcomes that are social in nature without material payoff. It is common for adults to purchase luxurious products to draw attention and admiration of others, adolescents to devote a lot of time in video games for higher virtual social status, and children to finish their homework with the expectation of being praised. Indeed, our anticipation of social rewards is such a powerful incentive that most of us (if not all) are motivated by it and employ it to motivate other people. Although the importance of social rewards in goal-directed behaviors has long been recognized (Fehr and Schmidt, 1999; Zajonc, 1965), investigations on neural underpinnings of social reward anticipation only emerged in the past decade. A key question addressed in recent neuroimaging studies is whether social rewards are represented in a specific neural circuit or in an analogue manner to the neural encoding of material rewards (e.g., money).

A growing body of studies has compared the neural signatures of social and material rewards with a variety of paradigms (Dvash et al., 2010; Izuma et al., 2008; Rilling et al., 2002; Spreckelmeyer et al., 2009; Tabibnia et al., 2008; Wake and Izuma, 2017; Zink et al., 2008). Among them, the monetary incentive delay (MID) task is one of the most reliable and widely-used paradigms (Knutson et al., 2001a, b; Knutson et al., 2003, 2000; Oldham et al., 2018; Rademacher et al., 2010; Spreckelmeyer et al., 2009; Wilson et al., 2018). In the classic MID, participants are first presented with an incentive cue (e.g., circle) indicating reward information of successfully responding to a target. The cue is followed by a short period of delay (i.e., anticipation phase), after which a target is presented, and participants need to respond to it. Finally, outcome is revealed based on participants' performance (Knutson, Adams, Fong, & Hommer, 2001; Knutson et al., 2000). In this way, the MID paradigm offers several important advantages. First, this task allows for assessing neural signatures of anticipatory reward processing and separating them from those of consummatory reward processing (Knutson et al., 2001b; Rademacher et al., 2010). Second, the separation between anticipation and outcome phases enables elegant comparisons between anticipation of different types of rewards (e.g., money and smiling faces) by using simple shapes as cue stimuli that are well controlled for non-relevant attributes (e.g., physical properties, familiarity, and self-relevance).

Combining the MID task with functional magnetic resonance imaging (fMRI), previous studies have demonstrated consistent engagement of the ventral striatum (VS) in monetary reward anticipation. In particular, the VS plays a key role in encoding expected positive incentive value (Abler et al., 2006; Bjork et al., 2010a, 2008a; Knutson et al., 2001a; Mucci et al., 2015). Moreover, monetary reward anticipation further engages the anterior insula (AI) and dorsal anterior cingulate cortex/supplementary motor area (dACC/SMA), which are implicated in signaling salience of an upcoming event (Funayama et al., 2014; Kirk et al., 2015; Kollmann et al., 2017; Oldham et al., 2018; Wilson et al., 2018).

Building on previous findings, many recent studies have employed a social variant of the MID (here forth social incentive delay [SID]) task to examine neural signatures of social reward anticipation. In the SID task, social stimuli that are intrinsically rewarding, such as smiling faces, “thumbs-up” gestures, positive verbal messages, were employed as incentives (Goerlich et al., 2017; Kollmann et al., 2017; Spreckelmeyer et al., 2009). Evidence has shown that social reward anticipation recruits both overlapping and distinct neural circuits compared to monetary reward anticipation. On one hand, there is considerable evidence that both social and monetary reward anticipation frequently evoke the activity of VS (Barman et al., 2015; Carter et al., 2009; Kirsch et al., 2003; Rademacher et al., 2014; Spreckelmeyer et al., 2009), supporting the role of the VS as the generic mediator of reward prediction. On the other hand, several studies have shown that social reward anticipation also engages the temporoparietal junction (TPJ), dorsomedial prefrontal cortex (dmPFC), precuneus, and superior temporal gyrus (STG), brain regions that are critical for social-cognitive processes (Barman et al., 2015; Goerlich et al., 2017; Spreckelmeyer et al., 2013). Likewise, electroencephalographic evidence has shown that social and monetary incentive cues evoke differential event-related potential patterns at both early and late temporal stages (Flores et al., 2015). Moreover, neural activation induced by social and monetary reward anticipation are differentially modulated by age (Rademacher et al., 2013), sex (Greimel et al., 2018; Spreckelmeyer et al., 2009; Wang et al., 2017), and social proficiency (Gossen et al., 2014). Taken together, recent evidence suggests a hypothesis that social reward anticipation engages a more complex neural circuit than monetary reward anticipation, consisting of not only reward-related regions (e.g., VS) but also social-cognitive related regions (e.g., dmPFC, TPJ).

Our study examined this hypothesis with a meta-analytic approach to quantitatively synthesize and compare previous brain imaging findings on social and monetary reward anticipation. Meta-analysis is an increasingly popular method to overcome the heterogeneity and divergence of previous results and assess the consistency of previous findings (Gurevitch et al., 2018; Kotov et al., 2010; Müller et al., 2018). Specifically, we first utilized a coordinate-based meta-analysis to quantitatively synthesize previous neuroimaging findings on social and monetary reward anticipation. Second, we examined the correspondence between social and monetary reward anticipation to determine the common and distinct neural circuits underlying different types of rewards. Third, psychological functions of identified brain regions were decoded based on large-scale database, implementing a data-driven quantitative inference on mental processes associated with identified regions (Laird et al., 2009). Finally, the functional profiles of revealed brain regions were characterized by both task-dependent and task-independent functional connectivity. In short, these approaches aim to achieve a more fine-grained characterization of the neural signatures implicated in social and monetary reward anticipation.

2. Materials and methods

2.1. Meta-analysis

2.1.1. Literature search and selection—A systematic online database search was performed in May 2018 using PubMed, ISI Web of Science, and Google Scholar by entering various combinations of relevant search items (e.g., [“monetary incentive delay” OR “MID task” OR “anticipation of reward” OR “reward anticipation” OR “social incentive delay” OR “SID task” OR “incentive delay task”] AND [“functional magnetic resonance imaging” OR “fMRI” OR “positron emission tomography” OR “PET”]). In addition, we have explored several other sources, including: (i) the bibliography and citation indices of the pre-selected papers, and (ii) direct searches on the names of frequently occurring authors.

The identified papers were further assessed according to the following criteria (Fig. 1): (i) subjects were free from psychiatric or neurological diagnoses; (ii) the paper reported a SID task, a MID task, or both; (iii) fMRI or PET was used as the imaging modality; (iv) whole-brain general-linear-model-based analyses (rather than region of interest [ROI] analyses) were applied; (v) results were derived from a general linear model based on either a binary contrast (e.g., anticipation of reward > anticipation of no reward) or continuous parametric analyses; and (vi) activations were presented in a standardized stereotaxic space (Talairach or Montreal Neurological Institute, MNI). Note that for the papers reporting Talairach coordinates, a conversion to the MNI coordinates was employed using an icbm2tal algorithm (Lancaster et al., 2007). Filtering search results according to the inclusion/exclusion criteria yielded a total of 21 experiments (207 foci, 696 subjects) for the anticipation of social reward and 94 experiments (1083 foci, 2060 subjects) for the anticipation of monetary reward (Table 1). Notably, the sample in Gossen et al. study (2014: n = 35) overlapped with that in Goerlich et al. (2017: n = 45). Accordingly, we conducted a robust test by excluding the data by Gossen et al. (2014) from the meta-analysis, and the results were essentially same as those of the primary analysis (Fig. S1 and S2).

In light of recent studies on lesion network mapping (Darby et al., 2018a, b), we performed additional literature search and selection to include potentially relevant lesion studies. Specifically, we searched PubMed by entering the following keywords: (“monetary incentive delay” OR “MID task” OR “anticipation of reward” OR “expect of reward” OR “reward anticipation” OR “social incentive delay” OR “SID task” OR “incentive delay task”) AND (“MRI” OR “CT” OR “neuroimaging” OR “lesion”) AND (“damage” OR “stroke” OR “hemorrhage” OR “tumor” OR “lesion”). The search resulted in 10 papers in total, but none of them met the criteria to conduct following-up lesion network mapping.

2.1.2. Activation likelihood estimation (ALE) analysis—A coordinate-based meta-analysis of reported fMRI experiments was conducted, employing the ALE algorithm (in-house MATLAB scripts) (Eickhoff et al., 2009). ALE determines the convergence of foci reported from different functional (e.g., blood-oxygen-level dependent [BOLD] contrast imaging) or structural (e.g., voxel-based morphometry) neuroimaging experiments, with published foci in Talairach or MNI space (Laird et al., 2005; Turkeltaub et al., 2002). In addition, ALE interprets reported foci as spatial probability distributions, of which the widths are based on empirical estimates of the spatial uncertainty due to the between-subject and between-template variability of the neuroimaging data (Eickhoff et al., 2009). The ALE algorithm weighs the between-subject variability based on the number of subjects analyzed in the experiments, modeling larger sample sizes with smaller Gaussian distributions and, thus, presupposing more reliable approximations of the "true" activation for larger sample sizes (Eickhoff et al., 2009).

The union of the individual modulated activation maps, firstly created from the maximum probability associated with any one focus (always the closest one) for each voxel (Turkeltaub et al., 2002), was then calculated to obtain an ALE map across experiments. This ALE map was assessed against a null-distribution of random spatial association between the experiments using a non-linear histogram integration algorithm (Eickhoff et al., 2012, 2009). In addition, the average non-linear contribution of each experiment for each cluster was calculated from the fraction of the ALE values at the cluster, with and without the experiment in question (Eickhoff et al., 2017). Based on the calculated contribution, we employed two additional criteria to select significant clusters: (i) the contributions for one cluster were from at least two experiments so that the findings would not be merely driven by one single experiment; and (ii) the average contribution of the most dominant experiment (MDE) shall not exceed 50% and the average contribution of the two most dominant experiments (2MDEs) shall not exceed 80% (Eickhoff et al., 2017). All ALE maps were thresholded using a cluster-level family-wise error (cFWE) correction ($P < 0.05$) with a cluster-forming threshold of $P < 0.001$ using 10,000 permutations for correcting multiple comparisons (Eickhoff et al., 2017).

2.1.3. Conjunction and contrast analyses—

After obtaining the consistent maxima separately for the anticipation of social reward and monetary reward, a conjunction analysis between them was conducted to assess the correspondence. This was implemented by using the conservative minimum statistic (Nichols et al., 2005), which is equivalent to identification of the intersection between two corrected ALE results. In addition, differences between the anticipation of social reward and monetary reward were tested by first performing separate ALE analyses for each task and computing the voxel-wise difference between the ensuing ALE maps (Eickhoff et al., 2011). Afterwards, all experiments contributing to either analysis were then pooled and randomly divided into two groups, whose sizes were the same as that in the two original sets of experiments, reflecting the contrasted ALE analyses (Langner et al., 2018). The ALE values for these two randomly assembled groups were calculated, and the differences between the ALE values were recorded for each voxel of the brain. Repeating this process for 25,000 times yielded a null-distribution of differences in ALE values between two tasks. The true difference in the ALE values was then tested against the voxel-wise null-distribution of label-exchangeability, and thresholded at a probability of $P > 95\%$ for true differences.

2.2. Task-based connectivity: meta-analytic connectivity modeling (MACM) analyses

To examine the co-activation patterns of the bilateral VS, ventral tegmental area (VTA), SMA, and left AI, which are commonly recruited by social and monetary reward anticipation (see the Results section), we conducted MACM analyses — with these regions as ROIs — using the BrainMap Database (http://www.brainmap.org/) (Laird et al., 2009).

MACM delineates patterns of co-activation across thousands of studies using neuroimaging databases and produces data-driven functional connectivity maps based on pre-defined ROIs (Langner et al., 2014). For our analysis, only whole-brain neuroimaging studies reporting activation in standard stereotaxic space in a healthy population were included, while other studies investigating differences in age, sex, handedness, and training effects or clinical populations were excluded. First, whole-brain peak coordinates of all those studies from BrainMap were downloaded if the study reported at least one focus of activation within each ROI. Next, coordinates were analyzed using the ALE algorithm (as described above) to detect areas of convergence of coactivation with each seed. Finally, the ALE maps were thresholded using a cFWE correction ($P < 0.05$) with a cluster-forming threshold of $P < 0.001$ using 10,000 permutations for correcting multiple comparisons.

2.3. Task-free connectivity: resting-state functional connectivity (RSFC) analyses

To complement task-based connectivity derived from MACM analyses, whole-brain RSFC of the bilateral VS, VTA, SMA, and left AI as ROIs was assessed. The analysis was based on resting-state fMRI images of 192 healthy volunteers obtained from the enhanced Nathan Kline Institute-Rockland Sample (NKI-RS: http://fcon_1000.projects.nitrc.org/indi/enhanced/) (Nooner et al., 2012). The enhanced NKI-RS is a community-ascertained, lifespan sample in which age, ethnicity, and socioeconomic status are representative of the general population (Horn and Blankenburg, 2016) (see also supplementary methods for details). The enhanced NKI-RS dataset, similar to other open datasets such as Human Connectome Project (HCP, Van Essen et al., 2013), has been widely used in previous studies including those conducting meta-analysis (Krall et al., 2015; Wong et al., 2018). Notably, previous studies that employed both these databases have found that the results derived from these databases were highly similar (Fukushima et al., 2018). In the same vein, one of our recent studies showed that the RSFC results were essentially the same across different datasets (Bellucci et al., 2018), although these data were from (i) different sites and participant populations (Europe vs. China), (ii) different machines (7 T vs. 3 T), and (iii) different scanning parameters. Although validation using different datasets is an intriguing and important topic, this is beyond the scope of the current study.

Implementing a seed-based analysis, the functional connectivity (bivariate correction) between the average BOLD signals from given seed regions (bilateral VS, VTA, SMA, and left AI) and all other voxels in the brain was computed. The voxel-wise correlation coefficients were then transformed into Fisher’s Z-scores and tested for consistency across subjects (see also supplementary methods for details).

2.4. Hierarchical clustering on resting-state functional connectivity of brain regions identified in the contrast analysis

To further reveal potential functions of those regions that were observed in the contrast analyses (i.e., social > monetary or monetary > social), we implemented hierarchical clustering based on RSFC of these regions. As such, we aimed to examine whether regions showing differential activation to social and monetary reward anticipation could also be distinguished by their RSFC patterns (Amft et al., 2015; Camilleri et al., 2018). RSFC analysis was conducted between all identified regions (see also supplementary methods for details). Using the singular value decomposition (SVD) function implemented in MATLAB/ SPM8, the time-course of each seed (i.e., each identified region) was extracted per subject by computing the first eigenvariate of the time-series of all voxels within the seed. Employing the first eigenvariate is a common practice as this approach — compared to using mean time-series — is less likely to be influenced disproportionally by potential outliers when using large and inhomogeneous regional templates (Friston et al., 2006). However, both approaches (i.e., first eigenvariate and mean) will lead to reliable and highly similar results when ROIs are relatively small (as those in the current study) (see also Braun et al., 2012). To reduce spurious correlations, variance explained by the mean white matter and cerebral spinal fluid signal were removed from the time series, which was subsequently band-pass filtered to preserve the frequencies between 0.01 and 0.08 Hz. RSFC between all regions of the contrast analysis was computed using the FSLNets toolbox (http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FSLNets). Partial temporal correlations between time series data of all regions were computed to estimate pairwise functional connectivity (Marrelec et al., 2006). For each pairwise connection, Fisher's Z-transformed functional connectivity values were submitted to one-sample t-tests. The resulting t values, reflecting connection strength as well as consistency across the sample, were z-transformed (i.e., into units of the standard normal distribution). This connectivity matrix was then fed into the Ward clustering, which is a commonly used method for hierarchical cluster analysis (Murtagh and Legendre, 2014).

The key concept of Ward/hierarchical clustering is to group the initial elements (regions) in a stepwise fashion such that the elements within a cluster have features that are as homogeneous as possible, while different clusters are distinct from each other as far as possible. This is achieved through an agglomerative approach in which clusters initially formed by individual regions are subsequently merged according to their similarity using standardized Euclidean distances and Ward's incremental sum of squares method (Eickhoff et al., 2011; Timm and Kruse, 2002). This hierarchical approach then reveals cliques of all identified regions at different level of granularity based on resting-state connectivity. In particular, the distance between two clusters is defined as the increase in variance for the cluster being merged (Ward, 1963). Based on this understanding, Ward clustering forms clusters by minimizing the total within-cluster variation, which is measured as the sum of squares of the Euclidean distances between each point in the cluster and the cluster centroid. In each step, the two clusters with the lowest intracluster variation would be joined (Danielsson et al., 1999). According to Sharma and Sharma (1996), Ward's method is superior in giving a larger amount of correct classified observations.

2.5. Functional decoding

Based on the BrainMap database (http://www.brainmap.org/), functional decoding was implemented for each region identified in the conjunction analysis and for each subcluster of brain regions derived from contrast analysis (see also the Results section). In particular, we performed the functional characterization based on the behavioral domain meta-data categories available for each neuroimaging experiment included in the BrainMap database (Turner and Laird, 2012) (see http://brainmap.org/scribe/). We determined the individual functional profile corresponding to each region/subcluster by using forward and reverse inference approaches. Forward inference refers to the probability of identifying activity in a region/subcluster, given the knowledge of the psychological process, whereas reverse inference refers to the probability of a psychological process being present, given the knowledge of a particular region/subcluster (for details, see also Bzdok et al., 2013; Chen et al., 2018; Genon et al., 2017). Significance was obtained at $P < 0.05$, corrected for multiple comparisons using the false discovery rate (FDR) method.

2.6. Validation analysis

We implemented additional analyses to validate findings derived from conventional ALE meta-analysis. First, we implemented a leave-one-experiment-out (LOEO) analysis for the ALE meta-analyses on the anticipation of social reward or monetary reward. On each fold, one experiment was excluded, and the ALE meta-analysis was conducted on the remaining N-1 experiments. Afterwards, we conducted a conjunction analysis on the ALE results of all folds to identify the brain regions that were robustly engaged in social/monetary reward anticipation. These analyses were employed to validate our main ALE meta-analysis findings on social or monetary reward anticipation.

Second, the unbalanced number of experiments between social and monetary reward anticipation (21 vs. 94) could lead to differences in statistical power for the experiments to be compared. To address this issue, we implemented an additional re-subsampling approach for the conjunction and contrast analyses. The re-subsampling was repeated for 1000 rounds. During each round, 19 experiments were randomly selected from datasets of social and monetary reward anticipation. The conjunction and contrast analyses were then conducted for the selected experiments of each dataset. Afterwards, conjunction and contrast results of all rounds were averaged to represent the re-subsampling findings. These analyses were employed to validate our main conjunction and contrast findings.

Third, the ALE approach treats different experiments within a paper as distinct experiments (Laird et al., 2009). This approach (i) ensures that all relevant information in a paper is represented in the meta-analysis, and (ii) avoids selection of a single experiment based on subjective and inconsistent criteria across publications. However, an issue with this approach is that multiple experiments from a single study might be related. Although this issue could be partly addressed by the LOEO and resampling methods mentioned above, we further implemented a supplementary analysis by combining different experiments from the same paper into a single experiment. As such, multiple experiments from a single paper would not independently influence the results of meta-analyses (Turkeltaub et al., 2012). Combining within-paper experiments resulted in 18 experiments for social reward anticipation and 75 experiments for monetary reward anticipation.

All ALE maps were thresholded using a cFWE correction ($P < 0.05$) with a cluster-forming threshold of $P < 0.001$ using 10,000 permutations for correcting multiple comparisons.

3. Results

3.1. ALE findings

For social reward anticipation, the ALE meta-analysis revealed significant convergence of activity in the bilateral VS, dACC/SMA, AI, VTA, and middle occipital gyrus (MOG) (Fig. 2a and Table 2). Twelve out of 21 contrasts (reward vs. no reward) contributed to the cluster in the left VS (MDE = 11.6%; 2MDE = 22.92%, Table 3). Fifteen out of 21 contrasts contributed to the cluster in the right VS (MDE = 16.02%; 2MDE = 28.61%, Table 3). Seven out of 21 contrasts contributed to the cluster in the dACC/SMA (MDE = 18.46%; 2MDE = 35.75%, Table 3). Five out of 21 contrasts contributed to the cluster in the left AI (MDE = 31.64%; 2MDE = 60.69%, Table 3). Seven out of 21 contrasts contributed to the cluster in the right AI (MDE = 25.99%; 2MDE = 49.93%, Table 3). Seven out of 21 contrasts contributed to the cluster in the midbrain (MDE = 28.92%; 2MDE = 56.83%, Table 3). Seven out of 21 contrasts contributed to the cluster in the MOG (MDE = 26.94%; 2MDE = 47.77%, Table 3).

The ALE meta-analysis on monetary reward anticipation revealed significant convergence of activity in the VS, dACC, dACC/SMA, postcentral gyrus, precentral gyrus, MOG, and cuneus (Fig. 2b and Table 2). Eighty-eight out of 94 contrasts (reward vs. no reward) contributed to the cluster in the VS (MDE = 3.25%; 2MDE = 6.39%, Table 4). Thirteen out of 94 contrasts contributed to the cluster in the dACC (MDE = 14.84%; 2MDE = 27.55%, Table 4). Forty-two out of 94 contrasts contributed to the cluster in the dACC/SMA (MDE = 7.01%; 2MDE = 12.82%, Table 4). Twenty-one out of 94 contrasts contributed to the cluster in the postcentral gyrus (MDE = 8.01%; 2MDE = 15.83%, Table 4). Fourteen out of 94 contrasts contributed to the first cluster in the precentral gyrus (MDE = 13.73%; 2MDE = 27.33%, Table 4). Twenty-two out of 94 contrasts contributed to the second cluster in the MOG (MDE = 11.65%; 2MDE = 21.81%, Table 4). Twenty-one out of 94 contrasts contributed to the cluster in the cuneus (MDE = 10.2%; 2MDE = 9.89%, Table 4).

3.2. Conjunction findings

3.2.1. Conjunction analysis—The conjunction analysis revealed a common activation maximum in the bilateral VS, VTA, SMA, and left AI, for both social and monetary reward anticipation (Fig. 2c and Table 2).

3.2.2. Quantitative functional profiling of conjunction regions—Results regarding functional decoding for each subcluster are illustrated in Fig. 3. For the left VS (Fig. 3A), forward and reverse inference alike indicated an association with reward, reasoning, and attention. For the right VS (Fig. 3B), an association with reward, reasoning, action execution, pain, and sexuality was revealed. For the VTA (Fig. 3C), the decoding analysis revealed an association with reward and pain. For the left AI (Fig. 3D), an association with phonology and pain was indicated. For the SMA (Fig. 3E), the results indicated an association with music, action execution, action imagination, and visual motion.

3.2.3. Functional connectivity profiles—These overlapping regions were commonly connected to brain regions important for reward and salience processing during both resting and task states (Fig. 4), including VS, AI, SMA, and dACC.

3.3. Contrast findings

3.3.1. Contrast analysis—Results of contrast analysis (social vs. monetary; Table 2) showed that the dorsal caudate, SMA, dorsal AI, putamen, thalamus, midbrain, and MOG were more activated for social reward anticipation than monetary reward anticipation (Fig. 2D). In contrast, the VS, dorsal caudate, dACC, right ventral AI, and left thalamus were more activated for monetary reward anticipation than social reward anticipation (Fig. 2D). Notably, however, brain regions revealed in two directions of contrast analyses were adjacent to each other.

3.3.2. Clustering on RSFC between regions identified in the contrast analysis—The hierarchical clustering based on RSFC patterns between all regions identified in the contrast analysis (social vs. monetary) grouped these regions into subclusters with strong within-cluster similarity (Fig. 5). Importantly, this data-driven grouping did not separate regions activated more in social reward anticipation from those activated more in monetary reward anticipation. Instead, most subclusters (3 of 4) included regions from both directions of contrast analyses. Specifically, cluster 1 consisted of the bilateral AI, SMA, and dACC (three regions from the contrast of social > monetary and two regions from the contrast of monetary > social); cluster 2 consisted of the bilateral midbrain and thalamus (three regions from the contrast of social > monetary and one region from the contrast of monetary > social); cluster 3 comprised of the bilateral caudate and putamen (three regions from the contrast of social > monetary and two regions from the contrast of monetary > social); finally, cluster 4 included the MOG (one region from the contrast of social > monetary). These results indicate that the regions derived from two directions of contrast analyses (social > monetary or monetary > social) could not be separated according to their functional connectivity profiles. Instead, these regions belonged to similar subclusters.

3.3.3. Quantitative functional profiling of subclusters—Results of functional decoding for each subcluster are illustrated in Fig. 6. For subcluster 1 (Fig. 6A), forward and reverse inference alike indicated a significant association of the subcluster with action (especially learning and execution) and music-related cognition. Reverse inference additionally revealed an association with pain, speech action, and action imagination. For subcluster 2 (Fig. 6B), both forward and reverse inference indicated an association with pain perception, while reverse inference also indicated an association with speech action. For subcluster 3 (Fig. 6C), an association of this subcluster was found with reward, reasoning, attention, and sexuality in both forward and reverse inference. Forward inference further revealed an association with gustation. For subcluster 4 (Fig. 6D), forward and reverse inference identified an association with semantics, and reverse inference further revealed an association with sexuality.

3.4. Validation analyses

3.4.1. LOEO findings of social reward anticipation—Consistent activation maxima for social reward anticipation were found in the bilateral caudate/putamen, thalamus, and dACC/SMA (Fig. S3 and Table S1). That is to say, the results of the LOEO approach corroborated the findings of the standard ALE meta-analysis.

3.4.2. LOEO findings of monetary reward anticipation—The LOEOALE meta-analysis on monetary reward anticipation revealed consistent maxima in the bilateral caudate, dACC/SMA, posterior cingulate cortex, precentral gyrus, cuneus, MOG, cerebellum, left middle frontal gyrus, and inferior parietal lobule (Fig. S4 and Table S1). These results confirmed the main findings derived from conventional ALE meta-analysis.

3.4.3. Re-subsampling findings—The re-subsampling analyses revealed results largely overlapping with those of main conjunction and contrast analyses (Fig. S5–S7).

3.4.4. Within-paper experiments combined—This analysis revealed essentially the same findings as those from main ALE meta-analyses, conjunction, and contrast analyses (Figure S8–S12 and Tables S2–S4), thus further validating our findings.

4. Discussion

The power of social incentives on human goal-directed behaviors has been a long-standing topic in multiple disciplines (Fehr and Schmidt, 1999; Zajonc, 1965), with well-known examples showing that the mere presence of others could facilitate individual performance (Zajonc, 1965). With the advent of human brain imaging techniques (e.g., fMRI), the past decade has witnessed a surge of interest in delineating neural underpinning of social reward processing (Báez-Mendoza and Schultz, 2013; Ruff and Fehr, 2014). Neuroscience studies have employed various experimental designs and stimuli, and have identified heterogeneous findings, making it difficult to capture a clear picture of social reward circuitry in human brain. In this regard, the SID/MID task represents an ideal paradigm to unveil neural signatures of social reward anticipation and to compare with those of material reward anticipation, since these tasks share all elements but the nature of the reward.

Based on previous fMRI studies employing MID/SID task, this study quantitatively synthesized and compared neuroimaging findings on social and monetary reward anticipation. Our results identified a convergence of reported activation foci in neural circuits important in reward and salience processing for both social and monetary reward anticipation. Specifically, consistent involvements of the VS, VTA, AI, and SMA were identified in the anticipation of both social and monetary rewards. These meta-analytic findings were validated with additional validation analyses (e.g., LOEO). Further, our findings also identified several regions showing differences between social and monetary reward anticipation. However, social-reward sensitive and monetary-reward sensitive regions were adjacent to each other, and clustering findings indicated that these regions belonged to four subclusters, such that regions within each subcluster exhibited similar functional connectivity profiles. These findings together suggest that anticipation of social and monetary rewards engages an overlapping neural circuit in human brain, mainly consisting of the VS, VTA, AI, and SMA.

Among these regions, the VTA and VS are key regions in the dopaminergic system. The VTA is a core node of the dopaminergic projection system that produces dopamine and transmits it to other regions (e.g., VS) in the mesocorticolimbic neurocircuitry (Kalivas, 1993). Both single-unit recording and human brain imaging studies have detected the activity of VTA in response to reward-predicting cues and during anticipation of reward (Haber and Knutson, 2010; Ikemoto, 2010; Schultz et al., 1997). The VS is a primary target region of dopaminergic projections from the VTA, such that reward-related neural responses in the VS are well linked with dopamine release in the VTA (Buckholtz et al., 2010; Schott et al., 2008). Similar to the VTA, VS is consistently activated during anticipation of reward (Knutson and Cooper, 2005; Oldham et al., 2018; Plichta and Scheres, 2014). Notably, VS activity is proportional with magnitude of anticipated reward (Bjork et al., 2004, 2008a; Knutson et al., 2001a) and correlates with self-reported pleasure induced by the upcoming reward (Bjork et al., 2008a; Knutson et al., 2001a). Moreover, although there is evidence showing that the VS is engaged by anticipation of both reward and loss (Carter et al., 2009; Oldham et al., 2018), this region usually exhibits stronger activity during reward compared to loss anticipation (Carter et al., 2009; Cooper and Knutson, 2008; Juckel et al., 2006). Finally, our functional decoding findings indicate that the VS and VTA are most strongly associated with reward processing. Taken together, these findings suggest that the VS works together with VTA to code for expected positive incentive value during reward anticipation.

Notably, our findings indicate that the positive valence conveyed by the activity of VS and VTA might generalize across material and social rewards. In line with our findings, many studies have shown that VS and VTA are frequently engaged by reward processing and reward-related behaviors in the social domain (Báez-Mendoza and Schultz, 2013), such as social status (Zink et al., 2008), social acceptance (Izuma et al., 2008), fairness (Tabibnia et al., 2008), and cooperation (Rilling et al., 2002). Likewise, there is also evidence showing that the VS and VTA are involved in social learning (Diaconescu et al., 2017; Klucharev et al., 2009), such as learning the trustworthiness of others (Fareri et al., 2012; Krueger et al., 2007). These findings, thus, support the common-currency hypothesis, holding that a common neural network is engaged by a variety of reward processing (Levy and Glimcher, 2012; McNamara and Houston, 1986; Ruff and Fehr, 2014). In other words, the activity of VS and VTA may reflect a generic mediator of positive valence associated with expected rewards.

The AI constitutes a key node in the salience network implicated in detecting the motivational salience of events (Seeley et al., 2007). Specifically, the AI receives input from multiple regions such as the VTA, VS, and amygdala (Cauda et al., 2012) and integrates this information to represent the reward or loss saliency of the stimuli (Critchley et al., 2013; Pizzagalli et al., 2009). Accordingly, the AI is consistently involved in the anticipation of both reward and loss (Bjork et al., 2010b; Enzi et al., 2012a, b; Funayama et al., 2014; Van Duin et al., 2016). In addition, the AI has been frequently involved in detecting the salience of social stimuli or events (Feng et al., 2015; Luo et al., 2018). For instance, the activity of AI is induced by both positive and negative facial expressions (Chen et al., 2009), social interactions that are both better or worse than expectations (Feng et al., 2018; Xiang et al., 2013; Yu et al., 2014), or behaviors/opinions deviated from group norms (Wu et al., 2016). Considering the role of AI in both social and nonsocial context, it is plausible that this region may act as a universal mediator of motivational salience. In line with this conjecture, our functional decoding results suggest that the AI is mainly involved in cognition and pain processing that engage in the detection of salience.

The SMA plays a critical role in movement control (Picard and Strick, 1996), such as the preparation and execution of externally-triggered movement (Cunnington et al., 2002). Specifically, the SMA contributes to planning and elaboration of actions and action sequences by mediating between medial limbic cortex and primary motor cortex (Goldberg, 1985). Thus, the involvement of the SMA has been widely observed in various cognitive tasks that require motor operations, including word production and response inhibition (Alario et al., 2006; Hu et al., 2014). Indeed, our functional characterization findings indicate that the SMA is associated with action execution in a variety of tasks. Notably, the SMA activity is modulated by reward expectancy, such that the saccades associated with upcoming reward evoke bursting activity in the SMA neurons, whereas the activity diminishes when the saccades and reward are no longer associated (Campos et al., 2005). In the context of SID/MID task, the activity of the SMA might reflect the preparation of action in response to reward cues.

In short, our meta-analytic study identified a series of brain regions in response to both social and material incentive cues, which mediates positive value, motivational salience, and action preparation during reward anticipation. In light of previous research on the brain reward network in humans (Doya, 2008; Frank et al., 2009), we propose a domain-general neural circuitry responsible for encoding social and monetary reward anticipation. First, the presentation of reward cue (either social or material) evokes expectancy of a positive outcome, which induces dopamine release and neural activity in the VTA. Changes in dopamine release are projected to the VS, where activity represents positive value and/or motivational salience of expected positive outcome. Furthermore, the AI integrates information from the VS, VTA, and other regions to represent motivational relevance of the reward cue. Finally, the positive value encoded in the VS/VTA and motivational significance encoded in the AI motivate individuals to better prepare for the adequate action, manifested as neural activity in the SMA, to enhance the chance of obtaining actual reward. This conjecture is consistent with functional profiles of these regions, such that they are connected with each other and with other regions in the brain associated with reward and salience processing. However, it should be noted that the above hypothesis of how brain regions interact is tentative, and empirical studies combining SID/MID task with effective connectivity analysis are needed to address this issue.

In addition to common neural circuits recruited by both social and monetary reward anticipation, previous findings suggest that social reward anticipation specifically engages the brain regions important for social-cognitive processes, such as the STG, TPJ, and dmPFC (Barman et al., 2015; Goerlich et al., 2017; Spreckelmeyer et al., 2013). However, neither the current main ALE analysis nor contrast analyses (social vs. monetary) revealed consistent involvement of these “social brain regions” in the anticipation of social reward.

Instead, our contrast analyses revealed that the brain regions showing differences in social and monetary reward anticipation were adjacent to each other and to those regions consistently engaged across both domains (i.e., conjunction analysis). Furthermore, hierarchical clustering findings indicate that social-sensitive and monetary-sensitive regions exhibit similar functional profiles within four subclusters. Lastly, functional decoding results indicate that these subclusters are associated with similar functions with those of conjunction regions, including action, salience, and reward. These findings, thus, provide convergent evidence that social and monetary reward anticipation engage similar regions but only to different extents.

However, this conclusion should be considered with caution due to several reasons. First, the current common neural circuit was revealed with SID/MID, which represents a simplified but elegant paradigm to specifically probe anticipation processes. Therefore, one may not generalize the current conclusion to other tasks involving complex decision-making. Indeed, by using more complicated task designs associated with social interaction, previous studies have detected the involvement of social brain regions, such as the dmPFC and TPJ (Carter et al., 2012; Feng et al., 2016). Second, it is noteworthy that adjacent or overlapping brain activation does not necessarily imply identical functions for all neurons within these regions (Haxby et al., 2001). Follow-up studies are needed to examine the functions of the adjacent/overlapping regions with more fine-grained techniques (e.g., multivoxel pattern analysis) or specifically designed task paradigms (e.g., repetition suppression paradigm), which allow for comparison of the neural patterns of adjacent/overlapping regions at the sub-voxel level (Norman et al., 2006; Peelen and Downing, 2007; Wake and Izuma, 2017). Likewise, the independent component analysis (ICA) might be employed to investigate whether social and monetary reward anticipation engage networks that are similar in terms of both spatial distribution and neural response function. For example, Zhang and Li (2012) using ICA identified sub-networks for error processing, attentional monitoring, and response inhibition, which otherwise seemingly engage a common cognitive control network. Similarly, Xu et al. (2013) revealed with ICA that multiple networks commonly engaged by attention and working memory exhibit distinct neural response functions.

Several limitations related to the current study should be noted. First, the limited number of studies in the social domain did not allow us to synthesize and compare neural mechanisms associated with consummatory reward or anticipatory and consummatory loss. Preliminary evidence has shown that social and material reward consumption engages distinct neural circuits (Rademacher et al., 2010), which requires systematic investigation in future meta-analytic studies with more publications on social reward. Second, the current study did not examine aberrant brain functions of reward anticipation across mental disorders, which are closely related to dysfunctions of reward-related processing (Hanewald et al., 2017; Husain and Roiser, 2018; Knutson and Heinz, 2015). Future studies in this line might reveal common neural circuit disruptions in reward anticipation across psychiatric disorders. Finally, as noted in the Materials and Methods section, a recently validated lesion network mapping approach investigates whether cognitive and behavioral abnormalities are a result of dysfunction of brain regions connected to a lesion location besides the lesion itself (Darby et al., 2018a, b). This technique may allow us to make causal inference about the functional networks underlying reward anticipation, an important topic to consider with growing number of lesion studies of reward processing in the future.

To sum up, the current results indicate that social and monetary reward anticipation engage a common neural circuit consisting of the VTA, VS, AI, and SMA, regions connected with each other during both task and resting states (see also Lin et al., 2011; Rademacher et al., 2015). This generic neural pathway might mediate positive value, motivational relevance, and action preparation during reward anticipation, which together motivate individuals to prepare well for the response to the upcoming target. Therefore, our findings provide the first meta-analytic evidence to quantitatively show the common involvement of brain regions in both social and non-social reward anticipation. These results are consistent with the common-currency hypothesis that a shared neural circuit is responsible for encoding different types of rewards (Berridge and Kringelbach, 2013). The development of a common reward neural circuit makes it possible for disparate categories of rewards to be compared in a common currency of utility (Berridge and Robinson, 2003; Lebreton et al., 2009), and thus facilitates decision-making between incommensurable options (e.g., love vs. money) when necessary.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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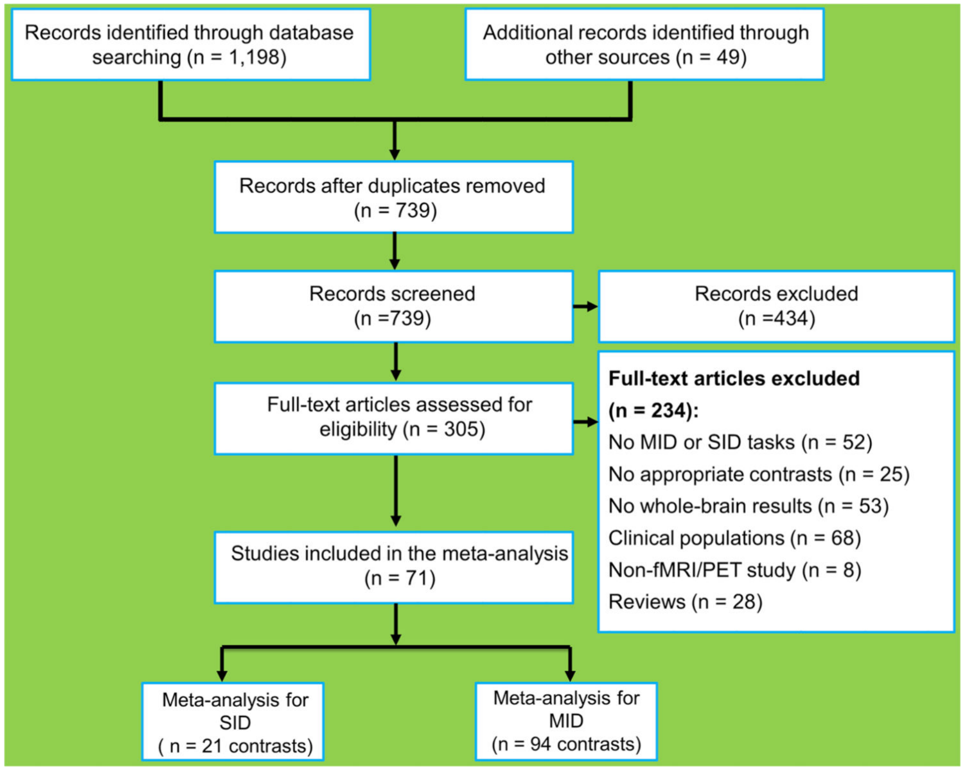

Fig. 1.

Flow chart of the study selection process for the meta-analysis. SID, social incentive delay task; MID, monetary incentive delay task; fMRI, functional magnetic resonance imaging; PET, positron emission tomography.

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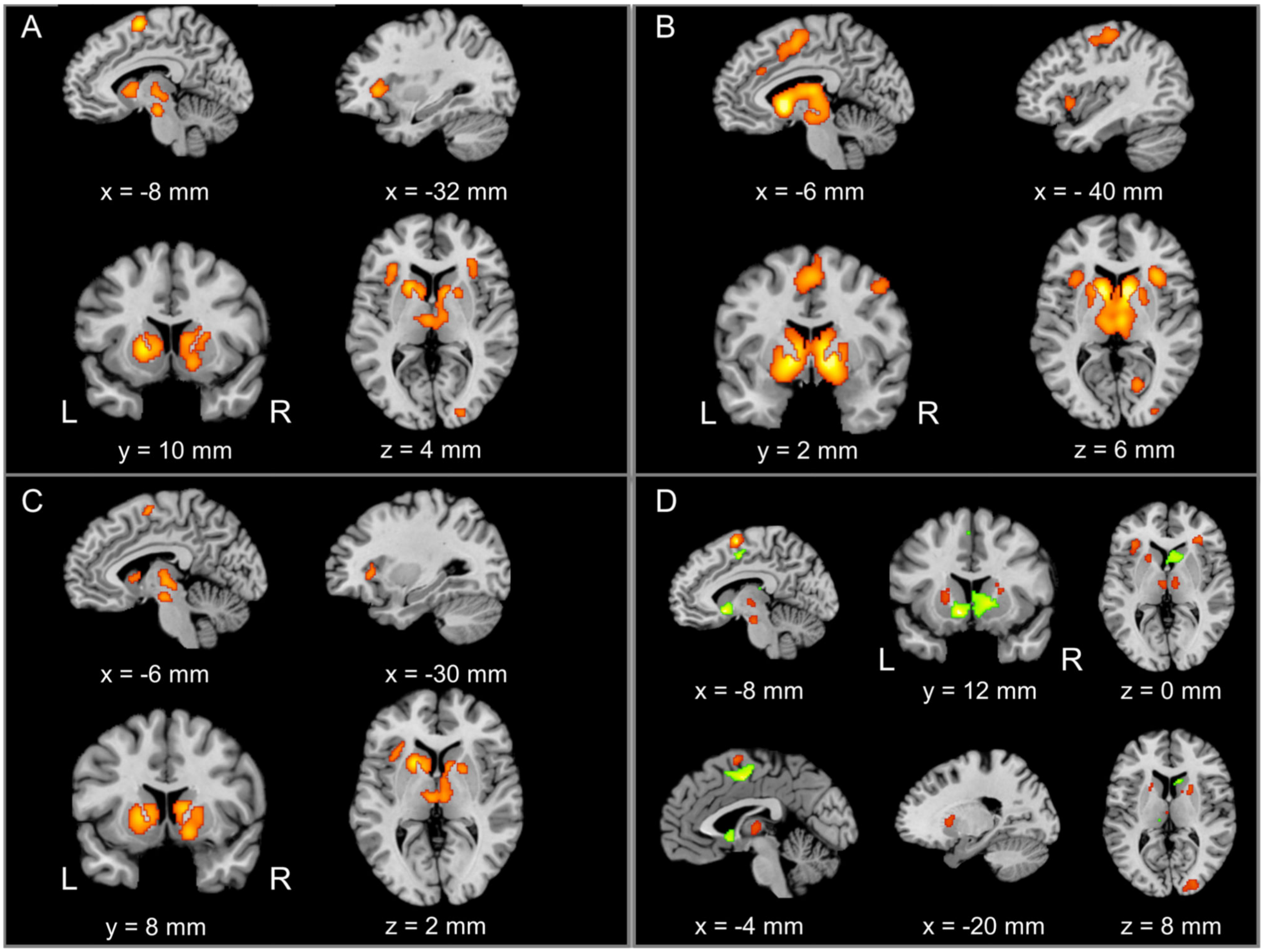

Fig. 2.

Significant clusters from the main coordinate-based activation likelihood estimation meta-analysis (cluster-level family-wise error correction [$P < 0.05$] with a cluster-forming threshold of $P < 0.001$ using 10,000 permutations) for social reward anticipation, monetary reward anticipation, and their conjunction and contrasts. Consistent maximum for: (A) social reward anticipatation; (B) monetary reward anticipation; (C) the conjunction of social and monetary reward anticipation; (D) the contrasts of social and monetary reward anticipation. Brain regions showing higher activation in the anticipation of social reward are illustrated in red, whereas regions showing higher activation in the anticipation of monetary reward are illustrated in green. L, left; R, right.

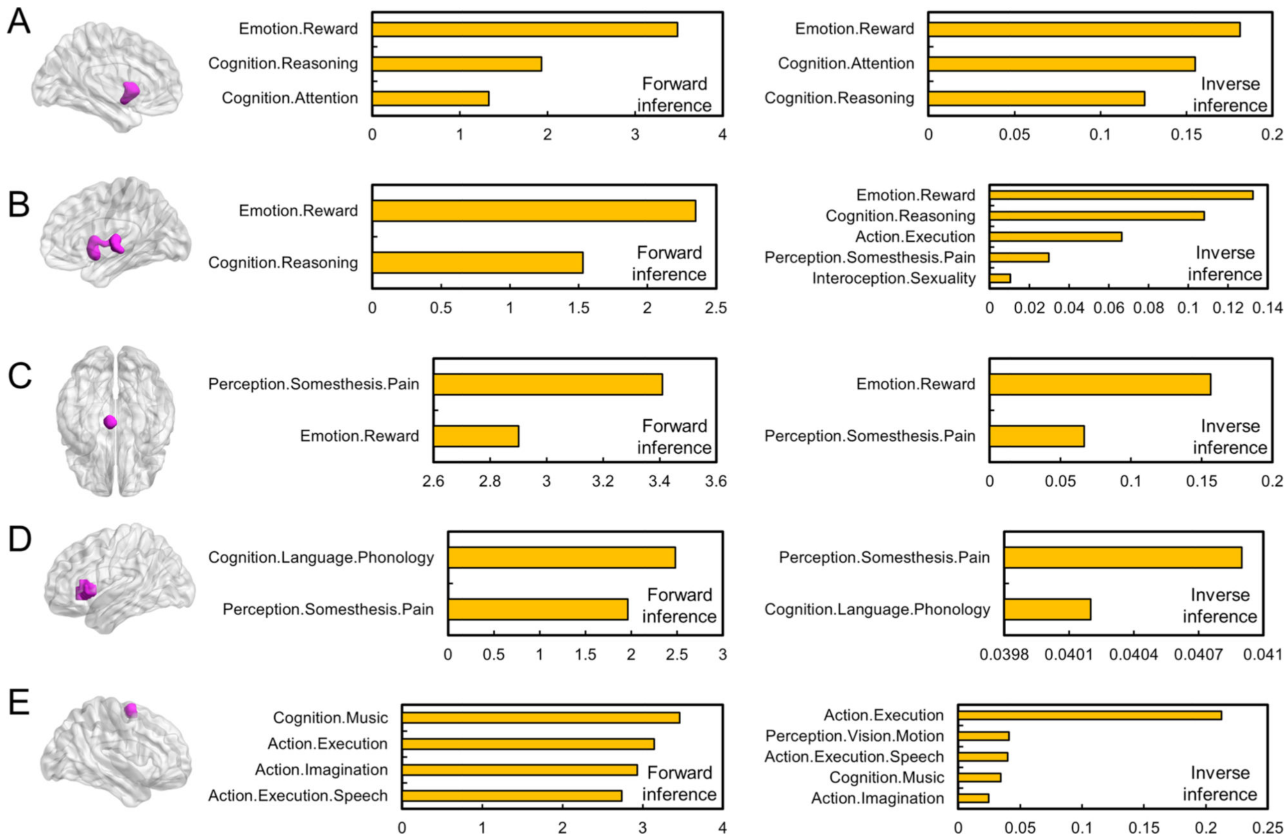

Fig. 3.

Quantitative forward and reverse inference on each region identified in the conjunction analysis. Quantitative forward and reverse inference for: (A) left VS; (B) right VS; (C) VTA; (D) left AI; and (E) SMA.

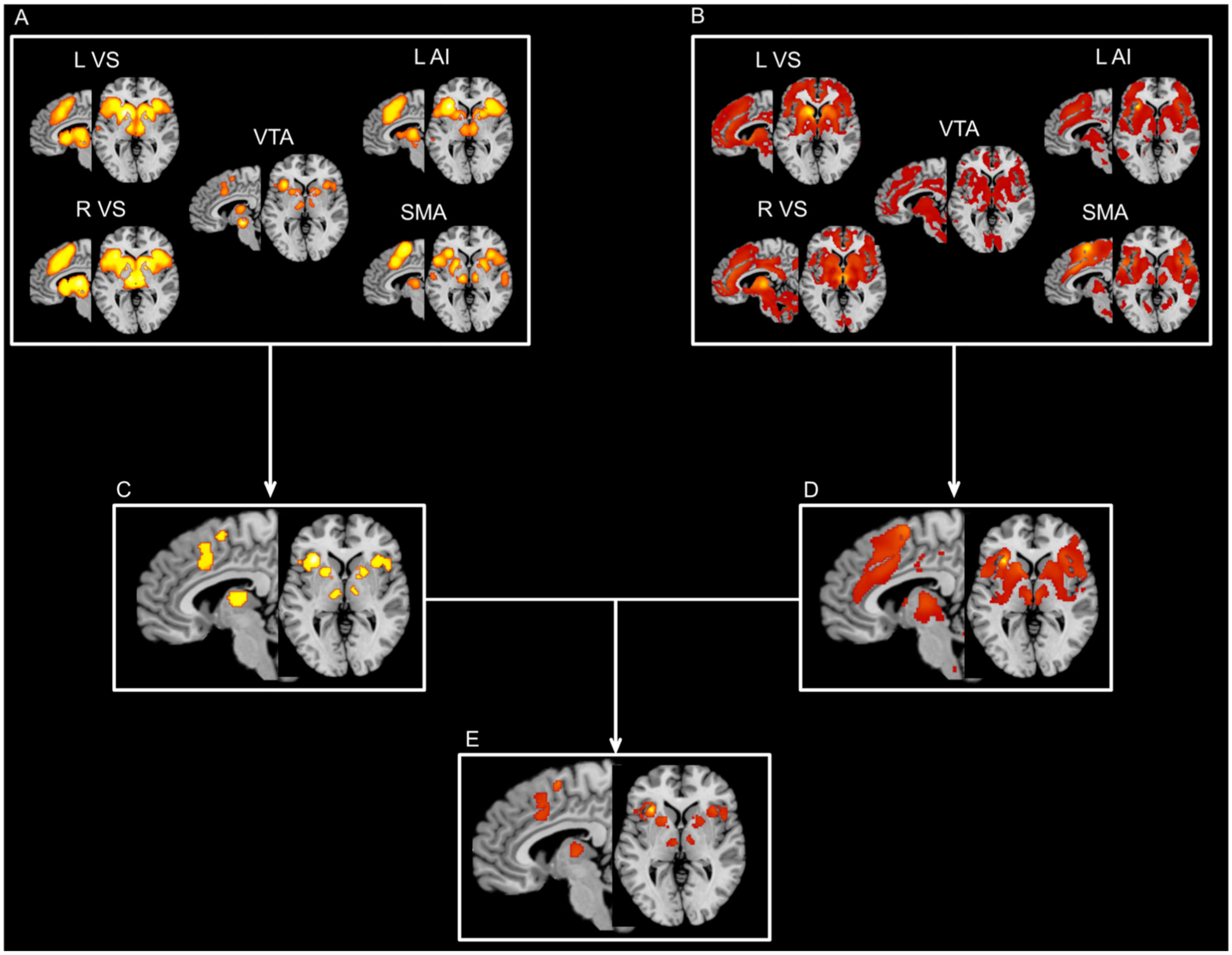

Fig. 4.

Results for the task-based meta-analytic connectivity modeling (MACM) analyses, task-free resting-state functional connectivity (RSFC) analyses, and their conjunctions for the regions commonly involved in the social and monetary reward anticipation. (A) task-based connectivity; (B) task-free connectivity; (C) conjunction across all MACM maps; (D) conjunction across all RSFC maps; (E) conjunction across all MACM and RSFC maps. L, left; R, right; VS, ventral striatum; AI, anterior insula; VTA, ventral tegmental area; SMA, supplementary motor area.

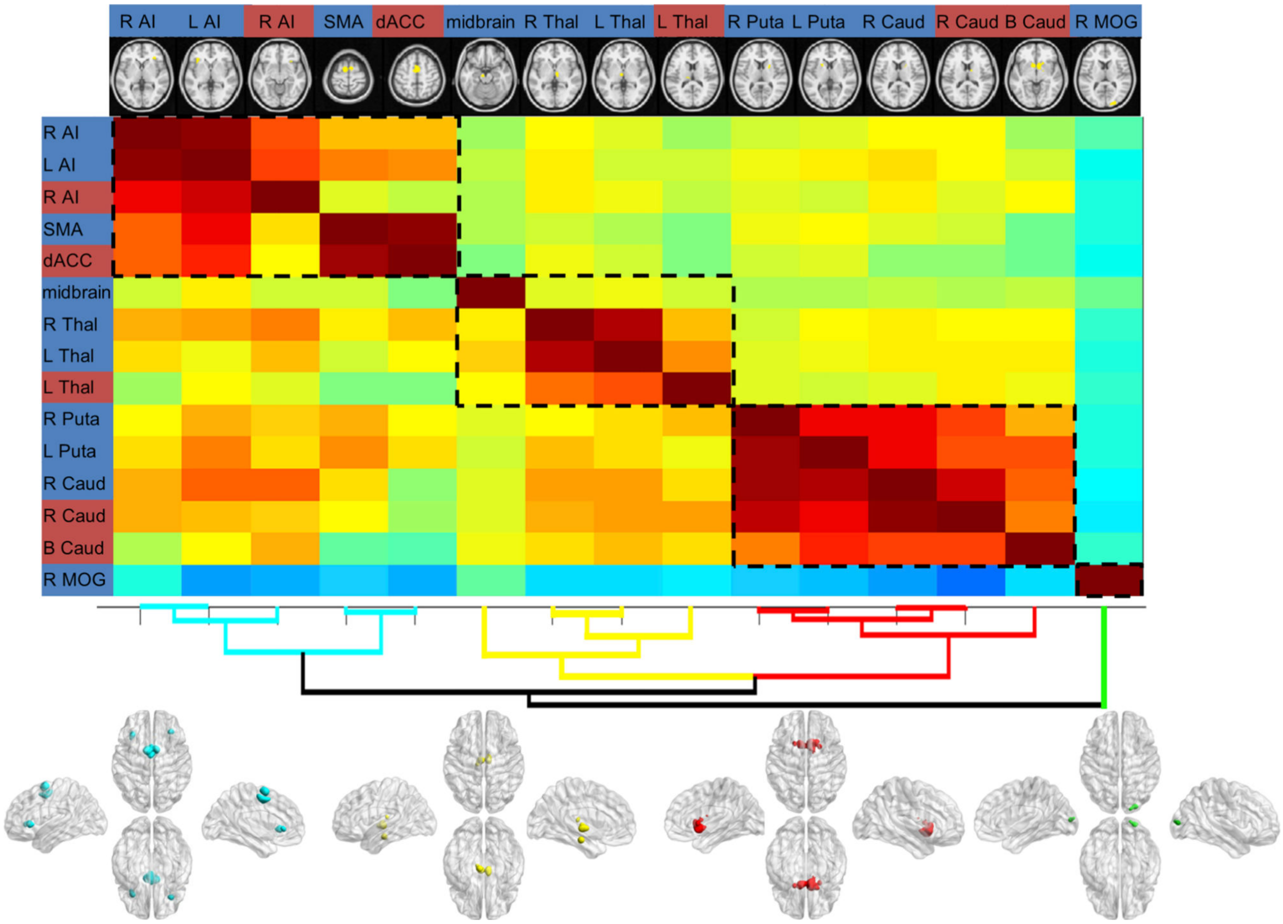

Fig. 5.

Clustering on functional connectivity between regions identified in the contrast analyses. Full (below the diagonal) and partial (above the diagonal) correlation matrices were illustrated, with warmer colors denoting positive correlations and cooler colors denoting negative correlations. The location of each region was displayed at the top of each column. The background color of region label indicates the contrast of each region (blue = social > monetary; red = monetary > social). The spatial map of each subcluster is illustrated at the bottom. L, left; R, right; AI, anterior insula; SMA, supplementary motor area; dACC, dorsal anterior cingulate cortex; Thal, thalamus; Puta, putamen; Caud, caudate; MOG, middle occipital gyrus.

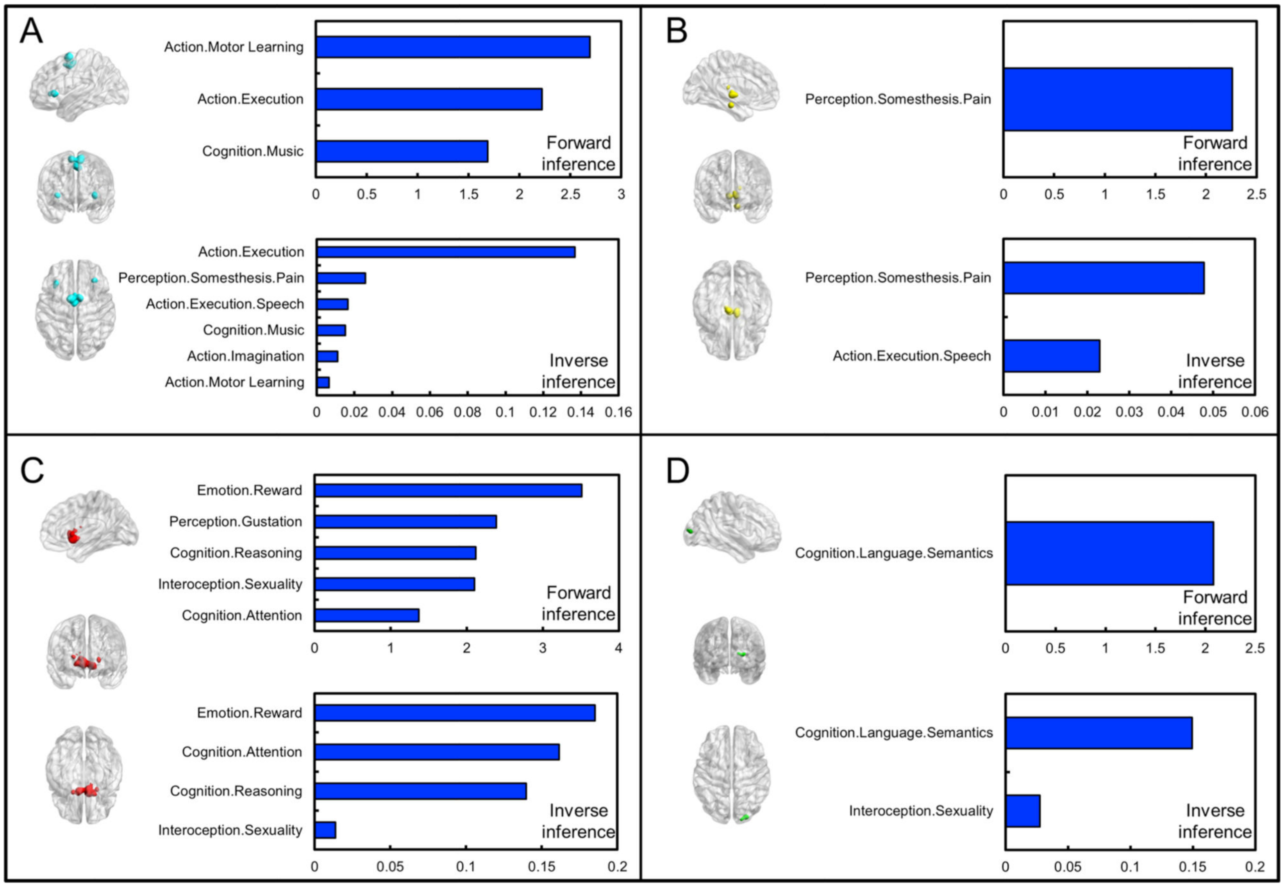

Fig. 6.

Quantitative forward and reverse inference on each subcluster identified in the hierarchical clustering. Quantitative forward and reverse inference for: (A) subcluster 1; (B) subcluster 2; (C) subcluster 3; and (D) subcluster 4.

Table 1

Summary of studies included for the meta-analysis of social and monetary reward.

Study	Task	Methodology	N(male)	Age(sd)	Software	Tesla
Abler et al. (2005)	monetary incentive delay task	fMRI	12(6)	21–33	BrainVoyager 4.9	1.5
Adcock et al. (2006)	monetary incentive delay task	fMRI	12(9)	18–35	SPM2	3
Arrondo et al. (2015)	monetary incentive delay task	fMRI	21(17)	34.33(10.11)	FSL	3
Balodis et al. (2012)	monetary incentive delay task	fMRI	14(10)	37.1(11.3)	SPM5	3
Barman et al. (2015)	monetary incentive delay task/social incentive delay task	fMRI	63(32)	24.56	SPM8	3
Beck et al. (2009)	monetary incentive delay task	fMRI	19(19)	41.68(8.97)	SPM5	1.5
Behan et al. (2015)	monetary incentive delay task	fMRI	20(9)	23.05	AFNI	3
Bjork et al. (2004)	monetary incentive delay task	fMRI	24(12)	19.27	AFNI	3
Bjork et al. (2008a)	monetary incentive delay task	fMRI	13(8)	13.8(0.4)	AFNI	3
Bjork et al. (2008b)	monetary incentive delay task	fMRI	23(12)	32.0(8.0)	AFNI	3
Bjork et al. (2010b)	monetary incentive delay task	fMRI	48(24)	22.05	AFNI	3
Bjork et al. (2010a)	monetary incentive delay task	fMRI	12(9)	15.3(1.4)	AFNI	3
Bjork et al. (2012)	monetary incentive delay task	fMRI	23(12)	30.1(5.9)	AFNI	3
Bustamante et al. (2014)	monetary incentive delay task	fMRI	18(18)	37.44(8.15)	SPM8	1.5
Carl et al. (2016)	monetary incentive delay task	fMRI	31(8.8)	20(6)	FSL 5.0.1	3
Carter et al. (2009)	monetary incentive delay task/social incentive delay task	fMRI	17(N)	24	FEAT(FSL)	3
Costumero et al. (2013)	monetary incentive delay task	fMRI	44(44)	23.4(4.1)	SPM5	1.5
Cremers et al. (2015)	social incentive delay task	fMRI	20(11)	27.7(7.7)	FSL Version 4.1.3	3
Damiano et al. (2014)	monetary incentive delay task	fMRI	31(14)	23.58(3.15)	FEAT(FSL)	3
Dillon et al. (2010)	monetary incentive delay task	fMRI	32(18)	21.68(3.35)	FS-FAST and FreeSurfer	1.5
Enzi et al. (2012a)	monetary incentive delay task	fMRI	19(10)	29.6	SPM5	3
Enzi et al. (2012b)	monetary incentive delay task	fMRI	15(8)	34.73(8.29)	SPM5	1.5
Figee et al. (2011)	monetary incentive delay task	fMRI	19(6)	32(6.6)	SPM2	1.5
Funayama et al. (2014)	monetary incentive delay task	fMRI	20(12)	29.9	SPM8	1.5
Goerlich et al. (2017)	monetary incentive delay task/social incentive delay task	fMRI	45(45)	24.1(3.2)	SPM8	3
Gossen et al. (2014)	monetary incentive delay task/social incentive delay task	fMRI	35(35)	24.17	SPM8	3
Herbort et al. (2016)	monetary incentive delay task	fMRI	23(0)	23.78(5.75)	SPM8	3
Juckel et al. (2006)	monetary incentive delay task	fMRI	10(10)	31.7(8.4)	SPM2	1.5

Study	Task	Methodology	N(male)	Age(sd)	Software	Tesla
Juckel et al. (2012)	monetary incentive delay task	fMRI	13(11)	25.69(4.84)	SPM5	1.5
Kappel et al. (2013)	monetary incentive delay task	fMRI	30(28)	20.13	SPM8	3
Kaufmann et al. (2013)	monetary incentive delay task	fMRI	19(8)	34.9(11.8)	SPM8	1.5
Kirk et al. (2015)	monetary incentive delay task	fMRI	44(20)	36.5(9.7)	SPM8	3
Kirsch et al. (2003)	monetary incentive delay task/social incentive delay task	fMRI	27(3)	23.3	SPM99	1.5
Knutson et al. (2001b)	monetary incentive delay task	fMRI	9(2)	26.45(5.85)	AFNI	1.5
Knutson et al. (2001a)	monetary incentive delay task	fMRI	8(4)	31	AFNI	1.5
Knutson et al. (2003)	monetary incentive delay task	fMRI	12(6)	31	AFNI	1.5
Knutson et al. (2008)	monetary incentive delay task	fMRI	12(4)	18–48	AFNI	1.5
Kocsel et al. (2017)	monetary incentive delay task	fMRI	37(15)	25.92(4.18)	SPM12	3
Kollmann et al. (2017)	monetary incentive delay task/social incentive delay task	fMRI	41(20)	40.2	SPM8	3
Maresh et al. (2014)	monetary incentive delay task	fMRI	84(42)	24.56(1.17)	FEAT6(FSL)	3
Mucci et al. (2015)	monetary incentive delay task	fMRI	22(10)	31.91(8.49)	SPM8	3
Nawijn et al. (2017)	social incentive delay task	fMRI	72(40)	40.12	SPM8	3
Ossewaarde et al. (2011)	monetary incentive delay task	fMRI	27(0)	20.51	SPM5	3
Pfabigan et al. (2014)	monetary incentive delay task	fMRI	25(12)	23.8(3.6)	SPM8	3
Plichta et al. (2013)	monetary incentive delay task	fMRI	14(8)	24(4.24)	SPM8	3
Pujara et al. (2016)	monetary incentive delay task	fMRI	14(9)	62.6(3.9)	AFNI & FSL	3
Rademacher et al. (2010)	monetary incentive delay task/social incentive delay task	fMRI	28(13)	28.26	SPM5	1.5
Rademacher et al. (2014)	social incentive delay task	fMRI	48(24)	23.4 / 66.2	SPM5	1.5
Romanczuk-Seiferth et al. (2015)	monetary incentive delay task	fMRI	17(17)	37.41(11.76)	SPM8	3
Samanez-Larkin et al. (2007)	monetary incentive delay task	fMRI	24(12)	23.75(2.05) / 72.92(5.50)	AFNI	1.5
Saji et al. (2013)	monetary incentive delay task	fMRI	18(10)	29.6(6.94)	SPM8	1.5
Schlagenhauf et al. (2008)	monetary incentive delay task	fMRI	10(9)	31.8(8.7)	SPM2	1.5
Schreiter et al. (2016)	monetary incentive delay task	fMRI	20(8)	41.45 (7.33)	SPM8	3
Simon et al. (2010)	monetary incentive delay task	fMRI	24(11)	24.8(3.2)	SPM5	3
Spreckelmeyer et al. (2009)	monetary incentive delay task/social incentive delay task	fMRI	32(16)	28.9	SPM5	1.5
Spreckelmeyer et al. (2013)	social incentive delay task	fMRI	30(17)	22.72	SPM5	3
Stark et al. (2011)	monetary incentive delay task/social incentive delay task	fMRI	31(0)	23(2.9)	SPM8	1.5
Staudinger et al. (2011)	monetary incentive delay task	fMRI	24(11)	25.05(2.79)	SPM5	3
Stoy et al. (2011)	monetary incentive delay task	fMRI	12(12)	28.08(6.2)	SPM5	1.5

Study	Task	Methodology	N(male)	Age(sd)	Software	Tesla
Stoy et al. (2012)	monetary incentive delay task	fMRI	15(10)	39.5(11.9)	SPM5	1.5
Ströhle et al. (2008)	monetary incentive delay task	fMRI	10(10)	31.9(9.9)	SPM2	1.5
Treadway et al. (2013)	monetary incentive delay task	fMRI	38(20)	22	SPM5	3
Van Duin et al. (2016)	monetary incentive delay task	fMRI	12(8)	29(9.6)	SPM8	3
Weiland et al. (2014)	monetary incentive delay task	fMRI	12(0)	30.9(9)	SPM8	3
Wittmann et al. (2005)	monetary incentive delay task	fMRI	16(8)	22.9(3)	SPM2	1.5
Wrase et al. (2007b)	monetary incentive delay task	fMRI	16(16)	39.9(8.6)	SPM2	1.5
Wrase et al. (2007a)	monetary incentive delay task	fMRI	14(14)	39.9(10.3)	SPM2	1.5
Wu et al. (2014)	monetary incentive delay task	fMRI	52(23)	50(16.5)	AFNI	1.5
Yan et al. (2016a)	monetary incentive delay task	fMRI	23(12)	19.78(0.8)	SPM8	3
Yan et al. (2016b)	monetary incentive delay task	fMRI	22(11)	19.78(0.8)	SPM8	3
Yau et al. (2012)	monetary incentive delay task	fMRI	20(12)	20.1(1.3)	FSL 4.0	3

Table 2

ALE meta-analysis results for anticipation of social reward, monetary reward, their conjunction and contrasts.

Laterality	Brain Regions	Brodmann Area	MNI Coordinates (mm)			peak Z score	Cluster Size (mm^3)
			x	y	z		
Social reward anticipation							
L	VS	/	−18	12	0	7.43	3672
R	VS	/	16	6	−10	6.14	6872
L/R	dACC/SMA	6	−8	0	64	7.03	2608
L	anterior insula	13/47	−32	26	0	5.47	1208
R	anterior insula	13/47	30	34	0	4.89	768
L	ventral tegmental area	/	−8	−18	−18	5.25	736
R	middle occipital gyrus	18/19	26	−92	8	4.6	960
Monetary reward anticipation							
L/R	VS	/	−12	10	−2	8.5	46296
L/R	dACC	32/24	0	32	26	5.01	872
L/R	dACC/SMA	6/32/24/8	0	−2	54	6.7	7560
L	postcentral gyrus	4/6/3	−40	−22	56	4.74	1824
R	precentral gyrus	6	46	0	46	4.93	1096
R	middle occipital gyrus	18/19	32	−88	−6	5.03	1608
R	cuneus	31/23/17	16	−70	10	5.93	1440
Conjunction							
L	VS	/	−18	12	0	7.43	3664
R	VS	/	16	6	−10	6.14	6136
L/R	SMA	6	−6	−2	60	4.66	616
L	anterior insula	13/47	−30	24	0	3.97	608
L	ventral tegmental area	/	−6	−16	−16	4.57	480
Social reward > Monetary reward							
R	dorsal caudate	/	18	8	12	2.75	96
L/R	SMA	6	−8	0	64	7.03	2344
L	dorsal anterior insula	47/13/45	−36	28	2	3.02	720

Laterality	Brain Regions	Brodmann Area	MNI Coordinates (mm)			peak Z score	Cluster Size (mm^3)
			x	y	z		
R	dorsal anterior insula	/	34	32	4	3.06	416
L	putamen	/	−18	12	4	2.31	320
R	putamen	/	22	6	10	2.62	240
L	thalamus	/	−4	−14	4	2.42	536
R	thalamus	/	8	−10	−2	3.14	592
L	midbrain	/	−6	−18	−22	2.67	368
R	middle occipital gyrus	18	26	−90	8	2.67	840
Monetary reward > Social reward							
L	VS	/	−8	12	−10	3.24	4464
R	dorsal caudate	/	12	−2	16	1.93	88
L/R	dACC	6/24/32	0	−4	48	3.2	1872
R	ventral anterior insula	47/13	28	20	−8	1.98	72
L	thalamus	/	−10	−24	12	2.01	112

VS, ventral striatum; dACC, dorsal anterior cingulate cortex; SMA, supplementary motor area.

Table 3

Average contribution of each experimental contrast for significant clusters identified for the meta-analysis of social reward anticipation.

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
left VS	Spreckelmeyer et al. (2009)	32	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	6	11.6
	Rademacher et al. (2014)	48	social incentive delay task	social reward > no reward	8	11.32
	Spreckelmeyer et al. (2009)	16	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	11	11.21
	Spreckelmeyer et al. (2009)	32	social incentive delay task	social reward > no reward	9	10.99
	Carter et al. (2009)	17	social incentive delay task	social reward > no reward	10	9.83
	Goerlich et al. (2017)	45	social incentive delay task	social reward > no reward	20	8.96
	Rademacher et al. (2010)	28	social incentive delay task	social reward > no reward	13	7.62
	Spreckelmeyer et al. (2009)	16	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	3	6.93
	Gossen et al. (2014)	15	social incentive delay task	social reward > no reward	25	5.99
	Cremers et al. (2015)	40	social incentive delay task	social reward > no reward	4	5.91
	Kollmann et al. (2017)	41	social incentive delay task	social reward > no reward	11	4.83
	Kirsch et al. (2003)	27	social incentive delay task	social reward > no reward	18	4.76
right VS	Spreckelmeyer et al. (2013)	30	social incentive delay task	high social reward > low social reward	20	16.02
	Gossen et al. (2014)	15	social incentive delay task	social reward > no reward	25	12.59
	Gossen et al. (2014)	35	social incentive delay task	social reward > no reward	10	11.34
	Carter et al.(2009)	17	social incentive delay task	social reward > no reward	10	10.61
	Kirsch et al. (2003)	27	social incentive delay task	social reward > no reward	18	8.51
	Spreckelmeyer et al. (2009)	32	social incentive delay task	social reward > no reward	9	8.45
	Goerlich et al. (2017)	45	social incentive delay task	social reward > no reward	20	7.64
	Spreckelmeyer et al. (2009)	16	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	11	6.43
	Rademacher et al. (2014)	48	social incentive delay task	social reward > no reward	8	4.92
	Kollmann et al. (2017)	41	social incentive delay task	social reward > no reward	11	3.22
	Spreckelmeyer et al. (2013)	30	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	6	3.2
	Spreckelmeyer et al. (2009)	32	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	6	1.99

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Spreckelmeyer et al. (2009)	16	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	3	1.88
	Cremers et al. (2015)	40	social incentive delay task	social reward > no reward	4	1.8
	Rademacher et al. (2010)	28	social incentive delay task	social reward > no reward	13	1.4
dACC/SMA	Goerlich et al. (2017)	45	social incentive delay task	social reward > no reward	20	18.46
	Gossen et al. (2014)	35	social incentive delay task	social reward > no reward	10	17.29
	Gossen et al. (2014)	20	social incentive delay task	social reward > no reward	11	16.6
	Spreckelmeyer et al. (2013)	30	social incentive delay task	high social reward > low social reward	20	15.93
	Gossen et al. (2014)	15	social incentive delay task	social reward > no reward	25	14.7
	Kollmann et al. (2017)	41	social incentive delay task	social reward > no reward	11	9.36
	Nawijn et al. (2017)	72	social incentive delay task	social reward > no reward	5	7.67
anterior insula	Gossen et al. (2014)	35	social incentive delay task	social reward > no reward	10	31.64
	Gossen et al. (2014)	20	social incentive delay task	social reward > no reward	11	29.05
	Goerlich et al. (2017)	45	social incentive delay task	social reward > no reward	20	20.11
	Kollmann et al. (2017)	41	social incentive delay task	social reward > no reward	11	17.73
	Kirsch et al. (2003)	27	social incentive delay task	social reward > no reward	18	1.41
anterior insula	Goerlich et al. (2017)	45	social incentive delay task	social reward > no reward	20	25.99
	Rademacher et al. (2010)	28	social incentive delay task	social reward > no reward	13	23.94
	Spreckelmeyer et al. (2009)	32	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	6	17.6
	Spreckelmeyer et al. (2009)	32	social incentive delay task	social reward > no reward	9	17.6
	Kirsch et al. (2003)	27	social incentive delay task	social reward > no reward	18	10.34
	Carter et al.(2009)	17	social incentive delay task	social reward > no reward	10	4.13
	Spreckelmeyer et al. (2009)	16	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	11	0.4
ventral tegmental area	Goerlich et al. (2017)	45	social incentive delay task	social reward > no reward	20	28.92
	Gossen et al. (2014)	35	social incentive delay task	social reward > no reward	10	27.91
	Gossen et al. (2014)	15	social incentive delay task	social reward > no reward	25	25.44
	Spreckelmeyer et al. (2013)	30	social incentive delay task	high social reward > low social reward	20	15.41

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Carter et al.(2009)	17	social incentive delay task	social reward > no reward	10	1.34
	Spreckelmeyer et al. (2013)	30	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	6	0.57
	Kirsch et al. (2003)	27	social incentive delay task	social reward > no reward	18	0.4
middle occipital gyrus	Spreckelmeyer et al. (2009)	16	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	11	26.94
	Spreckelmeyer et al. (2009)	16	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	3	20.83
	Spreckelmeyer et al. (2009)	32	social incentive delay task	social reward > no reward	9	19.86
	Spreckelmeyer et al. (2009)	32	social incentive delay task	brain regions showing proportional activation to increasing anticipated reward	6	18.46
	Spreckelmeyer et al. (2013)	30	social incentive delay task	high social reward > low social reward	20	13.14
	Rademacher et al. (2010)	28	social incentive delay task	social reward > no reward	13	0.52
	Goerlich et al. (2017)	45	Monetary incentive delay task/social incentive delay task	social reward > monetary reward	6	0.18

Table 4

Average contribution of each experimental contrast for significant clusters identified for the meta-analysis of monetary reward anticipation.

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
VS	Adcock et al. (2006)	12	monetary incentive delay task	monetary reward > no reward	17	3.25
	Adcock et al. (2006)	12	monetary incentive delay task	monetary reward > no reward	17	3.14
	Bjork et al. (2004)	12	monetary incentive delay task	monetary reward > no reward	13	2.9
	Treadway et al. (2013)	38	monetary incentive delay task	monetary reward > no reward	13	2.55
	Herbort et al. (2016)	23	monetary incentive delay task	monetary reward > no reward	25	2.5
	Samanez-Larkin et al. (2007)	12	monetary incentive delay task	monetary reward > no reward	21	2.38
	Kirsch et al. (2003)	27	monetary incentive delay task	monetary reward > no reward	26	2.2
	Enzi et al. (2012a)	19	monetary incentive delay task	monetary reward > no reward	15	2.17
	Kirsch et al. (2003)	27	monetary incentive delay task/social incentive delay task	monetary reward > social reward	12	2.13
	Saji et al. (2013)	18	monetary incentive delay task	monetary reward > no reward	22	2.07
	Wu et al. (2014)	52	monetary incentive delay task	monetary reward > no reward	20	2.05
	Kirk et al. (2015)	44	monetary incentive delay task	monetary reward > no reward	15	1.91
	Bjork et al. (2012)	23	monetary incentive delay task	monetary reward > no reward	19	1.85
	Stark et al. (2011)	31	monetary incentive delay task	monetary reward > no reward	14	1.82
	Knutson et al. (2001b)	9	monetary incentive delay task	monetary reward > no reward	13	1.68
	Samanez-Larkin et al. (2007)	12	monetary incentive delay task	monetary reward > no reward	43	1.61
	Wittmann et al. (2005)	16	monetary incentive delay task	monetary reward > no reward	22	1.6
	Bjork et al. (2004)	12	monetary incentive delay task	monetary reward > no reward	8	1.56
	Knutson et al. (2008)	12	monetary incentive delay task	monetary reward > no reward	8	1.54
	Adcock et al. (2006)	12	monetary incentive delay task	high monetary reward > low monetary reward	12	1.47
	Wrase et al. (2007a)	14	monetary incentive delay task	monetary reward > no reward	18	1.46
	Knutson et al. (2001a)	8	monetary incentive delay task	monetary reward > no reward	10	1.4
	Enzi et al. (2012b)	15	monetary incentive delay task	monetary reward > no reward	9	1.39
	Beck et al. (2009)	19	monetary incentive delay task	monetary reward > no reward	6	1.39
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	13	1.36
	Damiano et al. (2014)	31	monetary incentive delay task	monetary reward > no reward	15	1.35
	Costumero et al. (2013)	44	monetary incentive delay task	monetary reward > monetary punishment	18	1.34

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Juckel et al. (2012)	13	monetary incentive delay task	monetary reward > no reward	18	1.32
	Maresh et al. (2014)	84	monetary incentive delay task	monetary reward > no reward	18	1.32
	Knutson et al. (2001a)	8	monetary incentive delay task	high monetary reward > low monetary reward	12	1.31
	Knutson et al. (2003)	12	monetary incentive delay task	monetary reward > no reward	10	1.29
	Bjork et al. (2010b)	12	monetary incentive delay task	monetary reward > no reward	7	1.28
	Juckel et al. (2006)	10	monetary incentive delay task	monetary reward > no reward	9	1.26
	Rademacher et al. (2010)	28	monetary incentive delay task	monetary reward > no reward	36	1.23
	Bjork et al. (2008b)	23	monetary incentive delay task	monetary reward > no reward	17	1.22
	Kappel et al. (2013)	10	monetary incentive delay task	monetary reward > no reward	13	1.19
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	10	1.19
	Carl et al. (2016)	20	monetary incentive delay task	monetary reward > no reward	15	1.17
	Arrondo et al. (2015)	21	monetary incentive delay task	monetary reward > no reward	29	1.13
	Pfabigan et al. (2014)	25	monetary incentive delay task	monetary reward > no reward	12	1.13
	Carter et al. (2009)	17	monetary incentive delay task	monetary reward > no reward	10	1.12
	Ströhle et al. (2008)	10	monetary incentive delay task	monetary reward > no reward	7	1.04
	Yau et al. (2012)	20	monetary incentive delay task	monetary reward > no reward	6	1.03
	Costumero et al. (2013)	44	monetary incentive delay task	monetary reward > no reward	16	1.02
	Yan et al. (2016a)	23	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	15	0.99
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	12	0.98
	Figee et al. (2011)	19	monetary incentive delay task	monetary reward > no reward	7	0.97
	Spreckelmeyer et al. (2009)	32	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	7	0.96
	Staudinger et al. (2011)	24	monetary incentive delay task	high monetary reward > low monetary reward	6	0.91
	Romanczuk-Seiferth et al. (2015)	17	monetary incentive delay task	monetary reward > no reward	22	0.89
	Simon et al. (2010)	24	monetary incentive delay task	monetary reward > no reward	6	0.87
	Plichta et al. (2013)	14	monetary incentive delay task	monetary reward > no reward	6	0.87
	Spreckelmeyer et al. (2009)	32	monetary incentive delay task	monetary reward > no reward	8	0.87
	Stoy et al. (2012)	15	monetary incentive delay task	monetary reward > no reward	6	0.86
	Funayama et al. (2014)	20	monetary incentive delay task	monetary reward > no reward	17	0.85
	Schlagenhauf et al. (2008)	10	monetary incentive delay task	monetary reward > no reward	12	0.84

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Kappel et al. (2013)	20	monetary incentive delay task	monetary reward > no reward	6	0.83
	Kollmann et al. (2017)	41	monetary incentive delay task	monetary reward > no reward	17	0.82
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	8	0.82
	Stoy et al.(2011)	12	monetary incentive delay task	monetary reward > no reward	6	0.82
	Kocsel et al. (2017)	37	monetary incentive delay task	monetary reward > no reward	10	0.76
	Bjork et al. (2012)	23	monetary incentive delay task	monetary reward > no reward	7	0.75
	Abler et al. (2005)	12	monetary incentive delay task	monetary reward anticipation > target + outcome	3	0.74
	Schlagenhauf et al. (2008)	10	monetary incentive delay task	monetary reward > no reward	9	0.74
	Abler et al. (2005)	12	monetary incentive delay task	high monetary reward > low monetary reward	4	0.73
	Behan et al. (2015)	20	monetary incentive delay task	monetary reward > no reward	15	0.71
	Dillon et al. (2010)	32	monetary incentive delay task	monetary reward > no reward	7	0.71
	Yan et al. (2016a)	23	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	6	0.7
	Kappel et al. (2013)	20	monetary incentive delay task	monetary reward > no reward	7	0.66
	Yan et al. (2016b)	22	monetary incentive delay task	monetary reward > no reward	33	0.63
	Ossewaarde et al. (2011)	27	monetary incentive delay task	monetary reward > no reward	12	0.62
	Gossen et al. (2014)	20	monetary incentive delay task	monetary reward > no reward	8	0.62
	Gossen et al. (2014)	15	monetary incentive delay task	monetary reward > no reward	7	0.53
	Kaufmann et al. (2013)	19	monetary incentive delay task	monetary reward > no reward	15	0.51
	Kaufmann et al. (2013)	19	monetary incentive delay task	monetary reward > monetary punishment	3	0.48
	Stoy et al. (2012)	15	monetary incentive delay task	monetary reward > no reward	3	0.42
	Wrase et al. (2007b)	16	monetary incentive delay task	monetary reward > no reward	2	0.4
	Schreiter et al. (2016)	20	monetary incentive delay task	monetary reward > no reward	8	0.38
	Barman et al. (2015)	63	monetary incentive delay task/social incentive delay task	monetary reward > social reward	2	0.37
	Pujara et al. (2016)	14	monetary incentive delay task	monetary reward > no reward	6	0.32
	Bustamante et al. (2014)	18	monetary incentive delay task	monetary reward > no reward	3	0.28
	Mucci et al. (2015)	22	monetary incentive delay task	monetary reward > no reward	11	0.27
	Weiland et al. (2014)	12	monetary incentive delay task	monetary reward > no reward	4	0.26
	Abler et al. (2005)	12	monetary incentive delay task	monetary reward > no reward	1	0.25
	Bjork et al. (2008a)	13	monetary incentive delay task	monetary reward > no reward	1	0.2

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Costumero et al. (2013)	44	monetary incentive delay task	high monetary reward > low monetary reward	2	0.19
	Simon et al. (2010)	24	monetary incentive delay task	monetary reward > no reward	1	0.15
	Balodis et al. (2012)	14	monetary incentive delay task	monetary reward > no reward	4	0.14
dACC	Treadway et al. (2013)	38	monetary incentive delay task	monetary reward > no reward	13	14.84
	Bjork et al. (2012)	23	monetary incentive delay task	monetary reward > no reward	19	12.71
	Adcock et al. (2006)	12	monetary incentive delay task	monetary reward > no reward	17	11.91
	Adcock et al. (2006)	12	monetary incentive delay task	high monetary reward > low monetary reward	12	11.91
	Adcock et al. (2006)	12	monetary incentive delay task	monetary reward > no reward	17	11.27
	Yan et al. (2016b)	22	monetary incentive delay task	monetary reward > no reward	33	9.47
	Arrondo et al. (2015)	21	monetary incentive delay task	monetary reward > no reward	29	7.85
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	12	7.35
	Knutson et al. (2001a)	8	monetary incentive delay task	high monetary reward > low monetary reward	12	5.06
	Rademacher et al. (2010)	28	monetary incentive delay task	monetary reward > no reward	36	2.85
	Enzi et al. (2012a)	19	monetary incentive delay task	monetary reward > no reward	15	2.3
	Simon et al. (2010)	24	monetary incentive delay task	monetary reward > no reward	6	1.29
	Carter et al. (2009)	17	monetary incentive delay task/social incentive delay task	monetary reward > social reward	7	0.88
dACC/ SMA	Maresh et al. (2014)	84	monetary incentive delay task	monetary reward > no reward	18	7.01
	Goerlich et al. (2017)	45	monetary incentive delay task	monetary reward > no reward	4	5.81
	Costumero et al. (2013)	44	monetary incentive delay task	monetary reward > no reward	16	5.13
	Knutson et al. (2001a)	8	monetary incentive delay task	monetary reward > no reward	10	4.32
	Funayama et al. (2014)	20	monetary incentive delay task	monetary reward > no reward	17	3.97
	Knutson et al. (2001b)	9	monetary incentive delay task	monetary reward > no reward	13	3.96
	Kirsch et al. (2003)	27	monetary incentive delay task	monetary reward > no reward	26	3.63
	Plichta et al. (2013)	14	monetary incentive delay task	monetary reward > no reward	6	2.78
	Herbort et al. (2016)	23	monetary incentive delay task	monetary reward > no reward	25	2.75
	Gossen et al. (2014)	35	monetary incentive delay task	monetary reward > no reward	3	2.74
	Ossewaarde et al. (2011)	27	monetary incentive delay task	monetary reward > no reward	12	2.72
	Knutson et al. (2001a)	8	monetary incentive delay task	high monetary reward > low monetary reward	12	2.67
	Kappel et al. (2013)	20	monetary incentive delay task	monetary reward > no reward	7	2.59

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Figee et al. (2011)	19	monetary incentive delay task	monetary reward > no reward	7	2.57
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	13	2.49
	Bjork et al. (2012)	23	monetary incentive delay task	monetary reward > no reward	19	2.49
	Wittmann et al. (2005)	16	monetary incentive delay task	monetary reward > no reward	22	2.46
	Dillon et al. (2010)	32	monetary incentive delay task	monetary reward > no reward	7	2.38
	Kollmann et al. (2017)	41	monetary incentive delay task	monetary reward > no reward	17	2.21
	Yan et al. (2016b)	22	monetary incentive delay task	monetary reward > no reward	33	2.21
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	10	2.2
	Kirk et al. (2015)	44	monetary incentive delay task	monetary reward > no reward	15	2.19
	Kappel et al. (2013)	20	monetary incentive delay task	monetary reward > no reward	6	2.16
	Knutson et al. (2003)	12	monetary incentive delay task	monetary reward > no reward	10	2.14
	Behan et al. (2015)	20	monetary incentive delay task	monetary reward > no reward	15	2.08
	Damiano et al. (2014)	31	monetary incentive delay task	monetary reward > no reward	15	2.08
	Bjork et al. (2008b)	23	monetary incentive delay task	monetary reward > no reward	17	1.96
	Samanez-Larkin et al. (2007)	12	monetary incentive delay task	monetary reward > no reward	43	1.85
	Gossen et al. (2014)	20	monetary incentive delay task	monetary reward > no reward	8	1.83
	Kaufmann et al. (2013)	19	monetary incentive delay task	monetary reward > monetary punishment	3	1.8
	Staudinger et al. (2011)	24	monetary incentive delay task	high monetary reward > low monetary reward	6	1.66
	Kaufmann et al. (2013)	19	monetary incentive delay task	monetary reward > no reward	15	1.57
	Stark et al. (2011)	31	monetary incentive delay task	monetary reward > no reward	14	1.5
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	12	1.5
	Saji et al. (2013)	18	monetary incentive delay task	monetary reward > no reward	22	1.26
	Pfabigan et al. (2014)	25	monetary incentive delay task	monetary reward > no reward	12	1.18
	Enzi et al. (2012a)	19	monetary incentive delay task	monetary reward > no reward	15	1.15
	Kirsch et al. (2003)	27	monetary incentive delay task/social incentive delay task	monetary reward > social reward	26	0.96
	Kappel et al. (2013)	10	monetary incentive delay task	monetary reward > no reward	13	0.86
	Arrondo et al. (2015)	21	monetary incentive delay task	monetary reward > no reward	29	0.64
	Romanczuk-Seiferth et al. (2015)	17	monetary incentive delay task	monetary reward > no reward	22	0.32
	Rademacher et al. (2010)	28	monetary incentive delay task	monetary reward > no reward	36	0.04

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
postcentral gyrus	Costumero et al. (2013)	44	monetary incentive delay task	monetary reward > no reward	16	8.01
	Stark et al. (2011)	31	monetary incentive delay task	monetary reward > no reward	14	7.82
	Knutson et al. (2001b)	9	monetary incentive delay task	monetary reward > no reward	13	7.61
	Bjork et al. (2012)	23	monetary incentive delay task	monetary reward > no reward	19	7.56
	Samanez-Larkin et al. (2007)	12	monetary incentive delay task	monetary reward > no reward	43	7.42
	Kappel et al. (2013)	20	monetary incentive delay task	monetary reward > no reward	6	6.95
	Behan et al. (2015)	20	monetary incentive delay task	monetary reward > no reward	15	6.91
	Kollmann et al. (2017)	41	monetary incentive delay task	monetary reward > no reward	17	6.77
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	10	6.38
	Pfabigan et al. (2014)	25	monetary incentive delay task	monetary reward > no reward	12	6.25
	Romanczuk-Seiferth et al. (2015)	17	monetary incentive delay task	monetary reward > no reward	22	5.07
	Kirsch et al. (2003)	27	monetary incentive delay task	monetary reward > no reward	26	4.12
	Arrondo et al. (2015)	21	monetary incentive delay task	monetary reward > no reward	29	3.68
	Herbort et al. (2016)	23	monetary incentive delay task	monetary reward > no reward	25	3.65
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	13	3.54
	Carl et al. (2016)	20	monetary incentive delay task	monetary reward > no reward	15	2.59
	Wittmann et al. (2005)	16	monetary incentive delay task	monetary reward > no reward	22	1.87
	Yan et al. (2016b)	22	monetary incentive delay task	monetary reward > no reward	33	1.63
	Bjork et al. (2008b)	23	monetary incentive delay task	monetary reward > no reward	17	0.87
	Ossewaarde et al. (2011)	27	monetary incentive delay task	monetary reward > no reward	12	0.79
	Samanez-Larkin et al. (2007)	12	monetary incentive delay task	monetary reward > no reward	43	0.31
precentral gyrus	Herbort et al. (2016)	23	monetary incentive delay task	monetary reward > no reward	25	13.73
	Arrondo et al. (2015)	21	monetary incentive delay task	monetary reward > no reward	29	13.6
	Kollmann et al. (2017)	41	monetary incentive delay task	monetary reward > no reward	17	12.89
	Kirsch et al. (2003)	27	monetary incentive delay task	monetary reward > no reward	26	12.54
	Damiano et al. (2014)	31	monetary incentive delay task	monetary reward > no reward	15	10.78
	Kirsch et al. (2003)	27	monetary incentive delay task/social incentive delay task	monetary reward > social reward	12	10.04
	Saji et al. (2013)	18	monetary incentive delay task	monetary reward > no reward	22	9.2

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Kaufmann et al. (2013)	19	monetary incentive delay task	monetary reward > no reward	15	6.63
	Yan et al. (2016b)	22	monetary incentive delay task	monetary reward > no reward	33	6.6
	Dillon et al. (2010)	32	monetary incentive delay task	monetary reward > no reward	7	1.45
	Wittmann et al. (2005)	16	monetary incentive delay task	monetary reward > no reward	22	0.86
	Pfabigan et al. (2014)	25	monetary incentive delay task	monetary reward > no reward	12	0.75
	Bjork et al. (2012)	23	monetary incentive delay task	monetary reward > no reward	19	0.69
	Rademacher et al. (2010)	28	monetary incentive delay task	monetary reward > no reward	36	0.12
middle occipital gyrus	Kocsel et al. (2017)	37	monetary incentive delay task	monetary reward > no reward	10	11.65
	Kirsch et al. (2003)	27	monetary incentive delay task	monetary reward > no reward	26	10.16
	Bjork et al. (2012)	23	monetary incentive delay task	monetary reward > no reward	19	9.41
	Juckel et al. (2012)	13	monetary incentive delay task	monetary reward > no reward	18	8.04
	Funayama et al. (2014)	20	monetary incentive delay task	monetary reward > no reward	17	7.96
	Van Duin et al. (2016)	12	monetary incentive delay task	monetary reward > no reward	13	7.65
	Yan et al. (2016b)	22	monetary incentive delay task	monetary reward > no reward	33	7.65
	Pfabigan et al. (2014)	25	monetary incentive delay task	monetary reward > no reward	12	7.11
	Samanez-Larkin et al. (2007)	12	monetary incentive delay task	monetary reward > no reward	21	6.88
	Maresh et al. (2014)	84	monetary incentive delay task	monetary reward > no reward	18	4.36
	Stoy et al. (2011)	12	monetary incentive delay task	monetary reward > no reward	6	3.96
	Dillon et al. (2010)	32	monetary incentive delay task	monetary reward > no reward	7	3.63
	Spreckelmeyer et al. (2009)	32	monetary incentive delay task	monetary reward > no reward	8	3.23
	Weiland et al. (2014)	12	monetary incentive delay task	monetary reward > no reward	4	3.11
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	12	2.02
	Behan et al. (2015)	20	monetary incentive delay task	monetary reward > no reward	15	0.95
	Kollmann et al. (2017)	41	monetary incentive delay task	monetary reward > no reward	17	0.74
	Damiano et al. (2014)	31	monetary incentive delay task	monetary reward > no reward	15	0.32
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	8	0.27
	Abler et al. (2005)	12	monetary incentive delay task	high monetary reward > low monetary reward	4	0.24
	Carter et al. (2009)	17	monetary incentive delay task	monetary reward > no reward	10	0.21

Cluster Name.	Study	N	Task	Contrast	No. of foci	Average contribution (%)
	Kappel et al. (2013)	10	monetary incentive delay task	monetary reward > no reward	13	0.17
cuneus	Damiano et al. (2014)	31	monetary incentive delay task	monetary reward > no reward	15	10.2
	Romanczuk-Seiferth et al. (2015)	17	monetary incentive delay task	monetary reward > no reward	11	9.89
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	8	9.08
	Spreckelmeyer et al. (2009)	32	monetary incentive delay task	monetary reward > no reward	8	8.69
	Adcock et al. (2006)	12	monetary incentive delay task	monetary reward > no reward	17	8.57
	Saji et al. (2013)	18	monetary incentive delay task	monetary reward > no reward	22	8.27
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	13	8.14
	Spreckelmeyer et al. (2009)	16	monetary incentive delay task	brain regions showing proportional activation to increasing anticipated monetary reward	12	8.04
	Adcock et al. (2006)	12	monetary incentive delay task	high monetary reward > low monetary reward	12	7.42
	Enzi et al. (2012b)	15	monetary incentive delay task	monetary reward > no reward	9	6.74
	Carl et al. (2016)	20	monetary incentive delay task	monetary reward > no reward	15	6.06
	Costumero et al. (2013)	44	monetary incentive delay task	monetary reward > no reward	16	4.28
	Bjork et al. (2008b)	23	monetary incentive delay task	monetary reward > no reward	17	2.51
	Samanez-Larkin et al. (2007)	12	monetary incentive delay task	monetary reward > no reward	43	0.33
	Bjork et al. (2004)	12	monetary incentive delay task	monetary reward > no reward	13	0.32
	Stoy et al. (2012)	15	monetary incentive delay task	monetary reward > no reward	6	0.31
	Kocsel et al. (2017)	37	monetary incentive delay task	monetary reward > no reward	10	0.29
	Carter et al. (2009)	17	monetary incentive delay task	monetary reward > no reward	10	0.23
	Stoy et al. (2012)	15	monetary incentive delay task	monetary reward > no reward	3	0.19
	Juckel et al. (2012)	13	monetary incentive delay task	monetary reward > no reward	18	0.16
	Bjork et al. (2010a)	24	monetary incentive delay task	monetary reward > no reward	10	0.15