nature human behaviour

SUPPLEMENTARY INFORMATION

https://doi.org/10.1038/s41562-018-0440-2

In the format provided by the authors and unedited.

Choice overload reduces neural signatures of choice set value in dorsal striatum and anterior cingulate cortex

Elena Reutskaja[1,8], Axel Lindner[2,3,4,8]*, Rosemarie Nagel[5], Richard A. Andersen[4,6] and Colin F. Camerer[7]

[1]Marketing Department, IESE Business School, Barcelona, Spain. [2]Department of Psychiatry and Psychotherapy, University Hospital Tübingen, Tübingen, Germany. [3]Department of Cognitive Neurology, Hertie-Institute for Clinical Brain Research, Tübingen, Germany. [4]Division of Biology and Biological Engineering, California Institute of Technology, Pasadena, CA, USA. [5]Institució Catalana de Recerca i Estudis Avançats, Barcelona Graduate School of Economics, Department of Economics and Business, Universitat Pompeu Fabra, Barcelona, Spain. [6]The Tianqiao and Chrissy Chen Brain-Machine Interface Center, California Institute of Technology, Pasadena, CA, USA. [7]Division of the Humanities and Social Sciences and Computation and Neural Systems, California Institute of Technology, Pasadena, CA, USA. [8]These authors contributed equally: Elena Reutskaja, Axel Lindner.
*e-mail: a.lindner@medizin.uni-tuebingen.de

Supplementary Discussion

In this supplementary discussion we first consider alternative task designs before we discuss possible confounding variables that could have influenced our fMRI results.

In this study we used post-choice self-reported subjective ratings of the subjects to determine the value of the set (see main manuscript). The exact question we asked was thereby borrowed from the seminal paper on choice overload[1]. We relied on post-choice measures because the integrated value of a set (i.e., the related benefits and costs of choosing between items of a given set) might only become apparent during the ultimate process of choosing from the set. We also opted for this measure because many studies in domains similar to ours have shown that subjective liking ratings of individual goods are highly correlated with inferred utility or monetary value (measured by incentive-compatible Becker-DeGroot-Marschak procedures; e.g. see [2], which shows parallel results from predicting ratings and inferred utility rankings). Another study showed strong correlation between liking ratings and BDM bids[3]. See also[4] which found strong correlations between ratings of health and taste, and choices of foods. We, however, recognize that there are other methods to elicit the estimation of the set value and each method has its own merits and drawbacks. One possible way to determine set value in future research is to have subjects pay in an incentivize-compatible way to be allowed to make choices from that set, or to make subjects select which of the three set sizes they prefer to choose from.

As we already discuss in the main manuscript, it would be especially interesting to know whether neural activity in dorsal striatum and ACC might also account for inter-individual differences in perceived set value. An alternative way to exhibit such an

interrelation would be to correlate individual amount ratings with fMRI activity. Moreover, such approach could also be considered as an alternative means to exhibit areas representing set-value (instead of modelling the inverted-u shaped profile of set-value of the overall subject group by a quadratic predictor). While our study was not designed for such an analysis, we still have implemented it as per reviewer request. But it did not show any correlations that survive our statistical threshold (a second-level regression analysis was performed on the beta estimates of model 2 for the pooled choice conditions of the exposure period and on individual subject estimates of choice set value; $P < 0.05$ FDR-corrected for multiple comparisons).

This outcome is not particularly surprising as neither our design nor our data set were created to perform such analysis on the individual level. We did not sample subjects' set-value curves in a way that could estimate inter-individual differences. Before and during the scanning, the subjects were not told the number of different choice sets or the number of items included. This information was only provided as they learned, and was explicitly told to them afterwards. Hence, subjects would have to provide post-hoc ratings about three choice sets (small, medium, and large) which they did not necessarily notice during the experiment. In fact, we do have some evidence about what subjects noticed during the scanning. Before telling subjects about the different choice sets they had just seen, they guessed how many choice set sizes were used and how large they were. The mean estimate for the number of different choice set sizes was 5.0 (standard deviation SD=3.2). The average estimate of the number of images in the smallest and largest set was 6.4 (SD=4.0) and 24.5 (SD=8.7), respectively. The latter set size estimates are accurate on average but highly variable across subjects. It is likely that even after knowing the actual sizes, their subjective estimates had some influence on their ratings and made them noisy.

Having noisier individual estimates could simply explain the null result of this alternative analysis.

One future way could be to design an experiment with a larger range of choice set sizes, in which subjects are asked, after each choice, how they felt about the particular choice set encountered before. We did not implement such a design for two reasons. First, we did not intend to study inter-individual differences. This is a pioneering exploratory study of this complicated phenomenon and estimating inter-individual differences is too challenging at this point (and also requires a larger sample size of people if one plans, for example, to classify people into clusters, as would be sensible). A group analysis ignoring individual differences has often been a good starting point in decision neuroscience and was sufficient to get information about our research questions. Second, the measurement time necessary to perform an fMRI experiment like the one described before—asking about set liking in several trials-- would be way too long to comply with our recommended institutional scanning time guidelines (and people get tired). Finally, we did not want to bias our subjects' responses: if subjects had to answer such questions after each choice, they would alter the focus of their attention also on the attributes under investigation, which, in turn, could change their behaviour and our fMRI results. Instead, we here particularly tried to avoid such biases by asking subjects about their perceived value of the sets only after the fMRI experiment.

Next, we will discuss why the inverted-u shaped activity profile, supposedly representing choice set value, is unlikely to be explained by a number of potential confounding factors:

First, it seems unlikely that this pattern emerged simply because subjects would have "given up" earlier in case of the largest choice sets. This is because the number of

saccades steadily increased up to the largest choice set (Fig. 3b) and irrespective of the choice condition (NF vs. CF). This is likewise documented by the distribution of large, re-fixating saccades across the exposure period (Supplementary Fig. 2). If subjects would have given up early, we would have expected to observe a correlated drop in saccade frequency for the largest choice set. This was not the case. Moreover, if subjects had aborted the decision process at an earlier point in time for the larger sets, the time-courses of fMRI-activity would have reflected that drop (Fig. 4c). In fact, visual inspection of the time-courses of fMRI-activity does not reveal any obvious earlier drop in exposure-related fMRI activity for the largest choice sets. In these and in all other trials subjects seemingly “worked” on the choice sets until the end of the exposure period and only then the fMRI-signal dropped rapidly and simultaneously for all choice set sizes (Fig. 4c).

Second, the inverted u-shaped pattern also cannot be directly explained by decision confidence: confidence should steadily decrease with S as the both the difference in liking between the best and the second-best item in a set and the variance in the liking of individual choice options decreased numerically with S in both free choice conditions (Supplementary Fig. 1d and 1b, respectively) while, as visual inspection of Supplementary Fig.1c suggests, the rating of the best image within CF and NF sets was rather constant. Note that this theoretical consideration thereby assumes that decision confidence is separable from choice satisfaction, as is captured by our amount rating. The assumed interrelation between set size and decision confidence is also suggested by our measures of choice performance, which likewise decreased with set size (Fig. 3d,e).

Finally, we'd like to discuss whether the inverted u-shaped pattern could arise from eye movements or visual search. In fact, the number of saccades rises with choice-set size (Fig. 3b) while, at the same time, saccade amplitudes get smaller (Fig. 3c). Could it be that the interplay of increasing saccade frequency and decreasing saccade size (and a growing ease to find the next saccade target) explain the inverted u-shaped activity profile? For the following reasons, we do think that such a scenario is rather unlikely: (i) Neither the right ACC nor the left dorsal striatum did exhibit a correlation of activity with the frequency of saccades across subjects (Supplementary table 1). If the sheer number of saccades would contribute to the observed signal pattern, at least a hint for such interrelation should be present. (ii) It is also questionable whether smaller saccade amplitudes *per se* would lead to significant signal reductions for larger sets. In fact, saccade amplitude is chiefly topologically coded in saccade-related areas above the brainstem level, and this coding scheme results in saccade-related fMRI-signals, which are hardly influenced by saccade amplitude but which do almost exclusively reflect saccade frequency[5]. Accordingly, we'd rather expect a linear signal increase in saccade-related areas and, in fact, several of the 'linear areas' that were revealed by our study are also engaged in the control of saccadic eye movements. (iii) Finally, it is questionable whether the ease of the visual search problem, i.e. finding the next saccade target, truly grows with the number of options available in a choice set. To come up with a decision a subject has to search all options (and not simply saccade to the nearest target) and this search space is increasing with choice set size. Accordingly, reaction times do increase for larger sets in visual search while performance decreases. This effect is also referred to as "set-size effect" in visual search. Moreover, brain activity typically increases (rather than decreases) with larger sets in visual search[6]. Future

research should include a ‘neutral’ control condition that mimics visual search and saccadic performance in our experimental conditions. Yet, in conclusion, we do think that saccades and visual search are at least highly unlikely to explain the observed pattern of results in our current study.

The observed shift from a quadratic to a linear response profile in right ACC and left dorsal striatum is also clearly consistent with the predictions of our simple model on choice set value (Fig. 1a; compare green vs. blue curve, respectively). It is important to stress, however, that there are multiple factors that could give rise to the observed difference in activity between CF and NF. This difference is consistent with a set-value interpretation. It could, however, also refer to differences in decision difficulty, in decision confidence, or in the value of the chosen item across conditions (Fig. 3d). Yet, the latter interpretation is unlikely, because hardly any of the ROIs associated with set value showed a dependency of their (residual) activity on the value of the chosen item at least during the exposure stage (Fig. 4e). Also, the factor decision difficulty seems ineligible as fMRI activity was greater in CF than in NF while difficulty should lead to the exact opposite, namely higher activity in NF than in CF. Ultimately, decision confidence could likewise – besides choice set value - explain the difference between CF and NF. As was pointed out above, however, decision confidence seems unable to explain our primary marker of choice set-value – namely the inverted-u shaped activity profile as a function of set size S.

In summary, we are convinced that explaining the overall pattern of activity in right ACC and the left dorsal striatum within the framework of choice set-value is the most parsimonious interpretation of our data.

Supplementary Methods

Sample Size

Sample size was guided by our previous behavioural study on choice overload[7] and built on a power-analysis (alpha=0.05, power=0.8) performed on amount rating data obtained on a scale equivalent to ours (Fig. 1c). Namely, it builds on the results from a previously published study which found that satisfaction from choice followed an inverted-U shape pattern with the highest satisfaction experienced by subjects when choosing from intermediate-sized sets (vs larger or smaller sets[7]). In that study 120 subjects were choosing a gift box to pack a present for their friends from different sized sets of boxes containing either 5, 10, 15 or 30 alternatives. Specifically, in our power-analysis we considered the rating difference between the small choice set [5 items, M = 4.17, SD = 1.80, N=30] and an intermediate choice set [10 items = twice the size of the small set, M = 5.53, SD = 1.57, N=30] and the difference between an intermediate choice set [15 items, M = 4.90, SD = 2.25, N=30] and the large choice set [30 items = twice the size of the intermediate set, M = 6.77, SD = 1.87, N=30] (results from[7]). Note that the effective sensitivity of the current study should be even higher due to our within-subject design and due to task repetitions (as compared to the between-subjects design and the lack of repetitions[7]). Both our current study and study[7] used visual stimuli. However, as study[7] suggests, the definition of “optimal”, “too small”, and “too large” choice set should depend on the costs and benefits of each choice setting and is different in varying environments.

Task 1 - Liking Rating. Participants were shown 312 landscape images one by one on a computer screen. All the images were obtained from www.terragalleria.com with the permission from the website. Subjects stated how much they wanted to have each of those pictures printed on the product of their choice by setting a bar on a 11-point scale (with “0” stating “I would not like at all to have the picture on my selected item” and “10” stating “I would like to have the picture on my selected item very much.”; step size: 0.2), a procedure adopted from[8] and adjusted to the stimuli of our study. Landscape images were assigned to 6 categories: mountains, lakes, dunes, waterfalls, forests and beaches. Each category included 52 pictures. All 312 images were presented in a random order within a round and subjects had to rate each image twice in two successive rounds. The final rating of each image was determined by the average rating calculated across the two rounds. Subjects had stable preferences for a particular picture and rated the same image similarly in both rounds: the individual linear correlation of ratings of the first and second round revealed high correlation coefficients, ranging from 0.37 [CI 95%: 0.270, 0.462] to 0.84 [0.804, 0.870] (0.6 on average). Moreover, liking ratings did not differ significantly in the first and second round (2-way repeated measures ANOVA with the factor ‘round’ [1 vs. 2] and the factor ‘image’ [1-312]; round: $F(1,18)= 2.726$, $p=0.116$; η^2p [$CI_{95\%}$]= 0.132 [0.000, 0.357]; image: $F(311,5598)= 3.504$, $p<0.001$, η^2p [$CI_{95\%}$]= 0.163 [0.024, 0.025]; interaction: $F(311,5598)= 0.962$, $p=0.673$, η^2p [$CI_{95\%}$]= 0.051 [0.000, 0.006]).

Task 2 – fMRI Experiment/Choice Task. During the choice task of the experiment participants examined the sets of images and decided which of the landscape pictures they wanted to have printed on the product of their choice. The choice sets differed on

two dimensions: the number of alternatives and the availability of a clear favourite item in the set. Choice sets included 6, 12, or 24 landscape images of the same category (Fig. 2b). In 2/3 of the randomly interleaved trials subjects could select a photograph by themselves (“free” choice trials, CF and NF). In the remaining 1/3 of trials, a landscape picture from a particular set was selected for the participant by the computer (“forced” choice trials, FO). Within a FO trial the computer would always select a highly valued picture, ranked by the subject in task 1 either as 1st or 2nd best. All forced choice sets were sets without a clear favourite picture, and were therefore similar to NF sets, without clear favourite item.

To create CF, NF and FO sets we used the subjective ratings of images made by participants in the liking rating task of the experiment. Choice sets were always composed of images from the same landscape category. Specifically, to create within-category choice sets with 6, 12 and 24 items, respectively, we first selected images from the 42 lower-rated pictures within each of our six landscape categories (each category had a total of 52 images). Then we assigned the resulting sets to the CF, NF and FO condition in a way that should minimize differences in the overall mean and variance of ratings across all NF and FO sets (and the prototypes for the final CF sets) (see Supplementary Figs 1a and 1b). In CF sets we additionally replaced the best-rated image out of the sub-selection of the 42 lower-rated images of a respective category with either the best or the 2nd-best rated image from the overall sample of 52 pictures within that category. These replacements guaranteed that maximal image rating (Supplementary Fig. 1c) as well as the difference in rating between the first and second best image (Supplementary Fig. 1d) were numerically larger in CF than in the NF and FO sets. No choice set included identical alternatives. Moreover, within each

experimental run an item was shown once, only, and, across sessions, choice sets would always comprise different items.

Visual stimuli were back-projected onto a translucent screen (22° x 16° visual angle) by using a video projector (800x600 pixels, 60 Hz). Subjects viewed the visual stimuli via a mirror that was mounted on the head coil of the MRI scanner (viewing distance 1150mm). Stimuli were generated on a windows PC using “Cogent Graphics” developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience and in combination with Matlab 7.5. Choice sets were presented on an otherwise black screen with a central, white fixation cross (Fig. 2b). Items of the choice sets could be randomly placed at 15 possible positions to each side of the fixation cross. On both sides these positions were arranged in five rows and three columns. Depending on the condition, a certain number of landscape images were placed at these positions (with an equal number placed to the right and to the left sides of the fixation cross). Scrambled images were presented at the remaining locations in order to diminish global visual differences between sets of different size (luminance, colour, image density, etc.). Individual image size was 3.5° x 2.6° visual angle.

Each trial in the choice task consisted of three main stages: an exposure stage (10s+0.5s mask), a delay stage (13-14s), and a response stage (3s, Fig. 2c). During the latter stage, subjects had to indicate the chosen item using the thumb of their right hand on an MRI-compatible button-box. In contrast to the free choice conditions CF and NF, in FO, subjects had to select an object that was chosen by the computer and highlighted by a yellow frame during the response stage. To distinguish the FO from free choice trials, the forced choice trials were cued during the exposure stage by brackets around the fixation cross (“[+]” instead of “+”; Fig. 2c). The response time in the exposure

phase of all conditions was very short (3 sec) in order to prevent subjects from delaying their decision in CF and NF trials to the response stage. This was confirmed by our analysis of reaction times. Before each trial, subjects had to maintain fixation on a central white cross, presented on an otherwise dark background (duration: 13 s). This initial fixation period served as a baseline for our fMRI analysis.

The choice task of the experiment consisted of four runs with short breaks between runs (< 5 min). Each participant went through 72 trials (3 conditions x 3 set sizes x 8 repetitions) with 18 trials in each run (3 conditions x 3 set sizes x 2 repetitions). All trials were presented to each participant in randomized order. To familiarize themselves with the task, subjects went through a training run (18 trials) in which we presented only choice sets that were not used in the actual experiment.

Task 3 – Questionnaire task. After scanning, participants filled in a paper-based questionnaire. Participants reported whether they felt that each choice set size contained the "right" amount of alternatives (on a 9-point scale centred at 5 "Yes, I had just the right amount of choice options", with lower numbers meaning too few options and higher numbers meaning too many; also see Fig. 1c), the measure borrowed from[1]. Based on this estimate we derived the normalized set value as

1 - | 5 – Average Amount Rating | / 4

In other words, a set size is perceived as optimal if this index is 1 while a set size is perceived as least optimal if this index is 0 (Figure 1d). Subjects also reported their difficulty of choosing from each set size (from 1 "Not difficult at all" to 10 "Extremely difficult"; see Fig.1b). Questionnaires further revealed that subjects liked the selection of images that they were choosing from (mean = 7.16, SD = 1.57; range: 1 = not at all – 10

= very much) and found the process of choosing enjoyable (mean = 7.32, SD = 1.33; range: 1 = not at all – 10 = very much). Several subjects also indicated verbally or in written comments that the experiment was “engaging”, “cool”, and “interesting”. These data confirm that subjects were not indifferent to the images they were exposed to, and that the choice task was engaging.

Analysis of the post-scanning questionnaire further revealed that our subjects generally preferred to choose by themselves (n = 14). The remaining five subjects (out of the 19 subjects that were included in our analysis) sometimes preferred the computer to choose for them. Four of these subjects stated (without being explicitly asked) that they wanted the computer to choose for them when the set size was large or whenever they had no clear favourite image. This implies that when subjects experience choice overload, they might prefer the computer to select for them (as in FO trials).

Performance Monitoring. Eye movements of participants were monitored during fMRI using an MRI-compatible eye-camera and the ViewPoint Eye Tracker software. Our procedure was identical to that applied in earlier studies[9]. Eye position was sampled at a frequency of 60Hz. Further processing of the behaviour was performed off-line using Matlab 7.5. Eye position samples were filtered using a 10Hz low-pass filter. Saccades were detected using an absolute velocity threshold (20deg/s), while blinks were identified as gaps in the eye position records due to lid closure.

Image selection was realized by moving a button-controlled cursor on top of the item of choice within the 3s time limit of the response stage. Subjects used the thumb of their right hand on a MRI-compatible diamond-shaped four-button response-box (Current Designs Inc., Philadelphia, USA). Subjects could move the cursor (i.e., the

green frame; see Figure 2c) up, down, left or right by pressing the corresponding buttons. Reaction time was defined by the amount of time that elapsed from the appearance of the response screen until subjects first started to move the cursor towards the item choice (i.e., until the time of the first button press).

Statistical analyses. Analyses were performed using Matlab 7.5 and the Measures of Effect Size (MES) Toolbox V1.6, SPM 5 and SPSS 24. Subjects ratings (Task 3) were analysed by means of one-way repeated measures ANOVAs with the factor set size. Additional post-hoc comparisons directly contrasted the effects for sets of different size S (6 vs. 12; 12 vs. 24; 6 vs 24; Bonferroni-corrected for multiple comparisons). Behavioural performance (i.e. reaction time, saccade frequency, value of the chosen item, and percentage of trials with best image chosen) was analysed by means of 2-way repeated measures ANOVAs to reveal the influence of the factors choice set size S and task condition. Separate ANOVAs were performed for conditions CF vs. NF, which only differed with respect to the availability of a dominant option, and for conditions NF vs. FO, which only varied in terms of subjects' decision intent, namely "choosing" vs. "browsing", respectively. We tested for sphericity (Mauchly's test) and adjusted the F statistic according to the procedure of Greenhouse and Geyser whenever the assumption of sphericity was not met.

In all aforementioned cases the assumption of normality was confirmed by Shapiro-Wilk tests ($p>0.01$; no correction for multiple comparisons). Please note that in case of our fMRI-data we used a canonical analytical approach in SPM 5, which assumes normality.

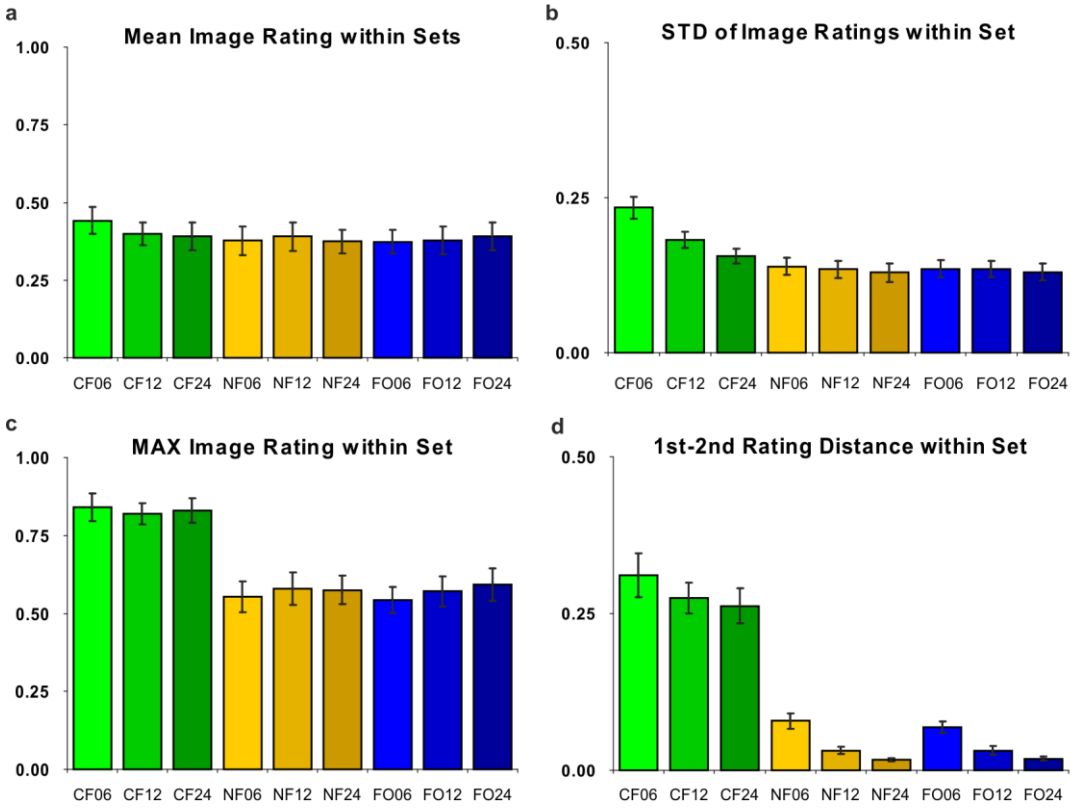
fMRI Image Volume Coverage. The EPI volume provided an almost entire coverage of the cerebral cortex and of most sub-cortical structures: only the posterior part of the cerebellum was not covered, and there were signal dropouts in orbito-frontal cortex and inferior aspects of temporal cortex (see Fig. 4 for additional information about the actual volume covered). While the orbito-frontal cortex is often a region of interest in studies of valuation, partial dropout had to be tolerated because the imaging sequence was optimized to cover the whole brain.

Interrelation of main GLM regressors, subjective difficulty and performance. While there was obviously no correlation between our main GLM regressors of interest, namely the linear predictor and the orthogonalized quadratic predictor in model 1, both correlated to different extend with subjective ratings of perceived difficulty and average saccade frequency. Significant positive correlation with the linear predictor was obtained for both subjects' difficulty ratings ($F(1,55)=22.792$, $p<0.001$, r [95% CI]=0.541 [0.326, 0.703]) and subjects' average number of saccades per second in choice trials ($F(1,112)=41.656$, $p<0.001$, r [95% CI]=0.521 [0.373, 0.643]). Importantly, these correlations demonstrate that the "linear predictor" is a good description of the objective and subjective costs of choosing, namely the number of saccades and perceived difficulty, respectively. In addition, the number of saccades and the difficulty ratings were also positively correlated ($F(1,112)=9.028$, $p=0.003$, r [95% CI]=0.273 [0.094, 0.435]). In contrast, the orthogonalized quadratic predictor was neither correlated with the number of saccades ($F(1,112)=3.451$, $p=0.066$, r [95% CI]= 0.173 [-0.011, 0.346]) nor with the difficulty ratings ($F(1,55)=0.178$, $p=0.675$, r [95% CI]= 0.057 [-0.207, 0.313]).

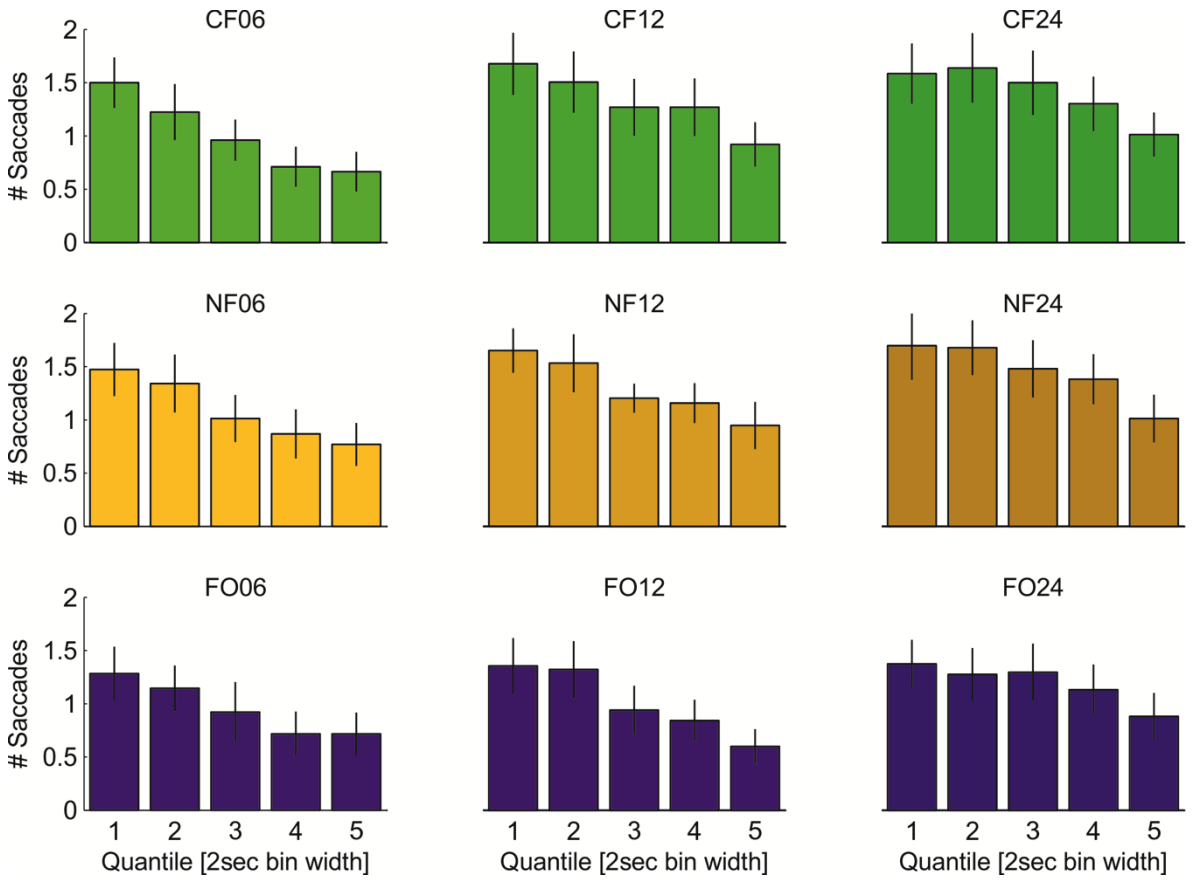
Supplementary References

1. Iyengar, S. S. & Lepper, M. R. When choice is demotivating: can one desire too much of a good thing?. *J. Pers. Soc. Psychol.* **79,** 995-1006 (2000).
2. Smith, A., Bernheim, B. D., Camerer, C. F., & Rangel, A. Neural activity reveals preferences without choices. *Am Econ J-Microecon* **6** (2), 1-36 (2014).
3. Harris, A., Adolphs, R., Camerer C.F. & Rangel A. Dynamic construction of stimulus values in the ventromedial prefrontal cortex. *PLoS One* **6** (6) e21074 (2011).
4. Hare, T. A., Camerer, C. F., & Rangel, A. Self-Control in Decision-Making Involves Modulation of the vmPFC Valuation System. *Science* **324,** 646-648 (2009).
5. Kimmig, H. et al. Relationship between saccadic eye movements and cortical activity as measured by fMRI: quantitative and qualitative aspects. *Exp. Brain Res.* **141,** 184–194 (2001). 5
6. Jerde, T. A., Ikkai, A. & Curtis, C. E. The search for the neural mechanisms of the set size effect. *E. J. Neurosci.*, **33,** 2028-2034 (2011). 6
7. Reutskaja, E., & Hogarth, R. M. Satisfaction in choice as a function of the number of alternatives: When ‘goods satiate. *Psychol. Market.* **26,** 197-203 (2009).
8. Reutskaja, E., Camerer, C., Nagel, R. & Rangel, A. Search dynamics in consumer choice under time pressure: an eye-tracking study. *Am. Econ. Rev.* **101,** 900-926 (2011).
9. Lindner, A., Iyer, A., Kagan, I. & Andersen, R. A. Human posterior parietal cortex plans where to reach and what to avoid. *J. Neurosci.* **30,** 11715-11725 (2010).
10. Masson, M. E. & Loftus G. R. Using confidence intervals for graphically based data interpretation. *Can. J. Exp. Psychol.* **57,** 203-220 (2003).

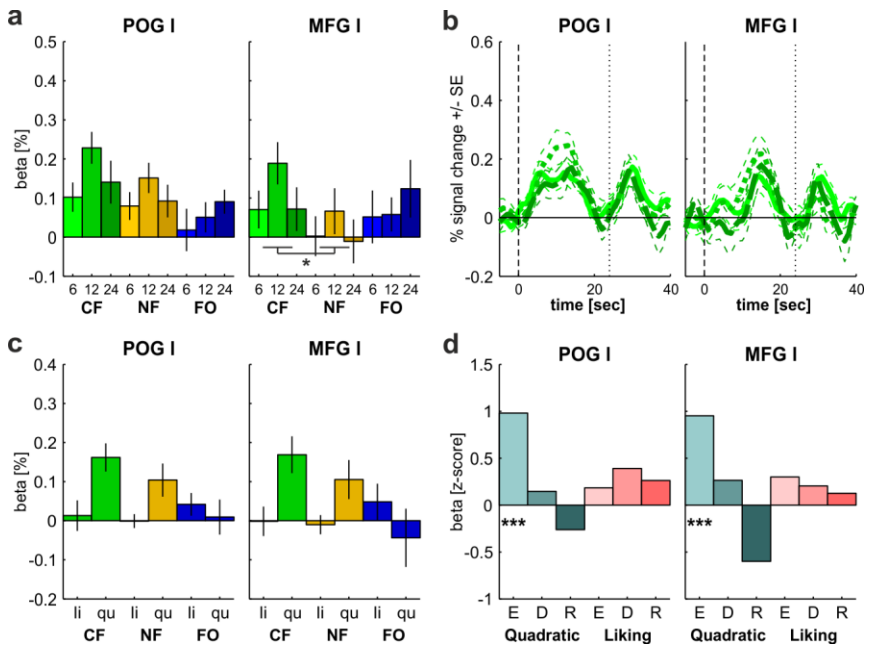
Supplementary Figures



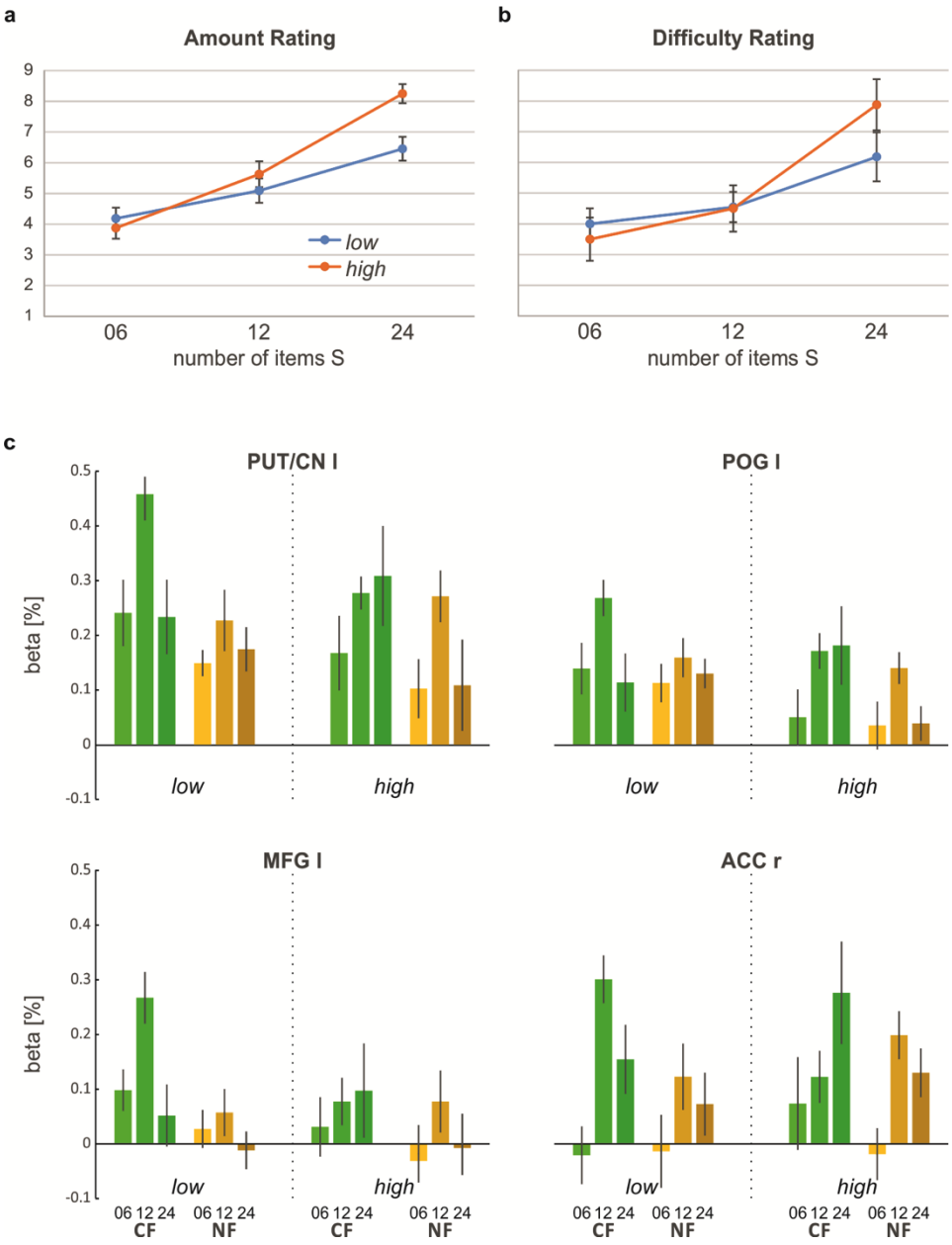
Supplementary Fig. 1 | Descriptive Statistics of Choice sets (N=19). In this figure the attributes of the choice sets for the different conditions are depicted, averaged across 19 subjects (+/- 95% confidence intervals): **a** shows the mean image rating of each set, **b** the standard deviation of image ratings within a set, **c** the rating of the best image within the set, and **d** the difference in rating between the first and second best image in the set. Note that this distance was always >0 in all subjects and in all conditions. Please refer to the paragraph on 'Task 2 – fMRI Experiment/Choice Task' in our supplementary methods for further details.



Supplementary Fig. 2 | Distribution of re-fixating saccades across the exposure phase (N=19). The nine histograms show the mean number (+/- 95% confidence intervals) of large, re-fixating saccades (amplitude larger than image width, i.e. >3.5deg visual angle) throughout the 10s exposure phase of the fMRI task for each condition (CF, NF, FO) and for each set size (bin width: 2s). As is obvious when visually inspecting the figure, subjects use the full length of the exposure period to explore the choice sets not only in free choice but also in FO conditions (all bins >0). Importantly, the way that the number of re-fixating saccades decreases across the exposure phase is indistinguishable between conditions. Specifically, three-way repeated measures ANOVAs with factors condition [CF vs. NF or NF vs. FO], set size [S], and quantile [bins 1-5], which were calculated across the free choice conditions, revealed no significant influence of the relevant effects of interest, namely the interaction between quantile and condition (CF vs NF: $F(4,72)= 0.139$, $p=0.967$; η^2p [CI95%]= 0.0 [0.0, 0.0]; NF vs FO: $F(4,72)= 0.409$, $p=0.801$; η^2p [CI95%]= 0.0 [0.0, 0.0]) and the interaction between quantile, condition and set size (CF vs NF: $F(8,144)= 0.286$, $p=0.970$; η^2p [CI95%]= 0.0 [0.0, 0.0]; NF vs FO: $F(8,144)= 0.422$, $p=0.906$; η^2p [CI95%]= 0.0 [0.0, 0.0]).



Supplementary Fig. 3 | Additional quadratic ROIs. Figure **a** depicts the mean beta estimates of choice-related fMRI activity in the exposure phase for each experimental condition as a function of set size S (6, 12, and 24). Error bars denote SE. The asterisk indicates a significant difference in the betas between CF and NF for left MFG, as was revealed by a 2-way repeated measures ANOVA with the factors condition ($F(1,18)=6.290$, $p=0.022$*, η^2p [95% CI]=0.259 [0.136, 0.386]) and set size (factor of no interest). A trend for the same effect was present in left POG ($F(1,18)=4.233$, $p=0.054$, η^2p [95% CI]=0.190 [0.000, 0.415]). Each ROI's corresponding fMRI-signal time-courses (subjects' average % signal change +/- SE), calculated across the pooled free choice conditions, are depicted in **b.** Separate curves represent different choice set sizes. Bar graphs in **c** exhibit the beta estimates for the linear (li) and quadratic (qu) predictor of each condition during the exposure stage. In both ROIs there was a tendency for a reduction of the quadratic signal component in FO as compared to NF (one-tailed paired t-tests; POG l: $t(18)=1.532$; $p=0.071$; g_1[95% CI]=0.351 [-0.117, 0.811]; MFG l: $t(18)=1.485$; $p=0.077$; g_1[95% CI]=0.341 [-0.127, 0.799]). The subjects' z-scored average beta values of the quadratic predictor and the chosen-value regressor of the pooled free choice conditions are shown separately for each task stage in **d** (E: exposure; D: delay; R: response). Beta-values significantly larger than 0 are indicated (one-tailed t-tests; *** $P < 0.001$; detailed statistics are provided in supplementary table 2). N=19.



Supplementary Fig. 4 | Inter-individual differences in brain activity. Based on the individual amount ratings (Figure 1c) we split our subjects into two groups that exhibited a weaker modulation of the amount rating as a function of set size (low slope group, N=11) vs. a stronger modulation (high slope group, N=8), respectively. **a** Mean amount rating of low vs. high slope group (+/-SE). We performed a 2-way mixed model ANOVA with the between-subject factor slope (high vs. low slope) and the within-subject factor set size (S) for descriptive purposes: in agreement with our splitting criterion, we revealed a significant effect for the factor set size ($F(2,34)=103.936$, $p<0.001$***, η^2p [95% CI]=0.859 [0.766 0.894]) and its interaction with the factor slope ($F(2,34)=10.394$, $p<0.001$***, η^2p [95% CI]=0.379 [0.144 0.519]). The interaction effect is chiefly driven by a higher amount rating for large choice sets in the high slope group. The overall amount rating does, however, not statistically differ between both sub-groups ($F(1,17)=2.043$, $p=0.171$, η^2p [95% CI]=0.107 [0.00 0.336]). **b** Mean difficulty rating of low vs. high slope group (+/-SE). A corresponding 2-way mixed model

ANOVA revealed a significant effect of the within-subject factor set size ($F(1.387,23.581)=18.1$, $p<0.001$***, η^2p [95% CI]=0.516 [0.242 0.652]) while the between-subject factor slope ($F(1,17)=0.286$, $p=0.600$, η^2p [95% CI]= 0.017 [0.000 0.194]) and its interaction with set size ($F(1.387,23.581)=2.064$, $p=0.160$, η^2p [95% CI]= 0.108 [0.000 0.294]) were not significant. Yet, there was a trend for a higher difficulty rating of the larger sets in the high slope group. Please note that the two sub-groups did not differ in any of the additional measures that were obtained in our study. **c** Mean beta estimates of choice-related fMRI activity in the exposure phase for CF and NF as a function of set size S (6, 12, and 24; error bars denote SE; between subject variance was removed[10]). The same representative subset of ROIs is shown as in Figure 4 and supplementary Fig. 3. To reveal any putative change in the quadratic response profile (as a function of set size) with either group or with group and condition, we calculated a three-way mixed model ANOVA with the between-subjects factor group (high vs. low slope) and the within-subject factors set size (S) and condition (CF vs. NF). When considering the relevant effects of interest, we could not reveal any interaction of the quadratic set size effect with group in either ROI (PUT/CN l: $F(1,17)=0.415$, $p=0.528$, η^2p [95% CI]= 0.024 [0.000 0.203]; ACC r: $F(1,17)= 2.349$, $p=0.144$, η^2p [95% CI]= 0.121 [0.000 0.352]; POG l: $F(1,17)= 0.047$, $p=0.832$, η^2p [95% CI]= 0.003 [0.000 0.096]; MFG l: $F(1,17)= 1.368$, $p=0.258$, η^2p [95% CI]= 0.074 [0.000 0.296]).Yet, the change in the activity profile between the high- and the low- slope group in NF and its absence in CF was captured by a significant interaction of the quadratic set size effect with group and condition in all ROIs (PUT/CN l: $F(1,17)= 6.428$, $p=0.021$*, η^2p [95% CI]= 0.274 [0.025 0.492]; ACC r: $F(1,17)= 6.048$, $p=0.025$, η^2p [95% CI]= 0.262 [0.020 0.483]; POG l: $F(1,17)= 4.513$, $p=0.049$, η^2p [95% CI]= 0.210 [0.001 0.438]; MFG l: $F(1,17)= 5.870$, $p=0.027$, η^2p [95% CI]= 0.257 [0.017 0.478]).

Supplementary Table 1 | Detailed Results of ROI analyses (Part 1). This table summarizes all areas that exhibited a correlation of fMRI-activity with the orthogonalised quadratic predictor during the exposure phase of pooled choice trials (CF & NF). The respective t- and p- values of the underlying group analysis based on model 1 are provided along with their anatomical location (specified in MNI coordinates). For estimates of effect size of the quadratic predictor in each of these areas, please consult supplementary table 2. The ROIs displayed in Figure 4b-e and in Supplementary Figure 3 are highlighted light grey. In the subsequent columns of the table, the results of the additional statistical ROI-analyses are depicted. We probed for a linear signal increase with set size in choice conditions in the exposure stage. To this end we performed one-tailed t-tests on the individually averaged beta estimates of CF & NF conditions, namely for the linear predictor in the exposure stage (N=19; H0: beta>0; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). We also performed a 2-way repeated measures ANOVA with the factors condition [CF vs. NF] and set size [S=6, 12, or 24; factor of no interest] on subjects' average beta estimates of the exposure period that were revealed by model 2. The respective results for the factor of interest (condition) are indicated (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). A significant influence of factor condition thereby allowed to exhibit those signal changes that were due to the availability of a dominant option (present in CF but not in NF). In the following column we indicate the results of paired t-tests performed on the beta estimates capturing the quadratic signal component in NF vs. FO (model 1; N=19). This analysis specifically probed for reductions of this signal component due to diminished decision costs in FO (one-tailed paired t-test; H0: $Qu_{NF}>Qu_{FO}$). Finally, in the last two columns of the table we report the results of regression analyses that were performed on the pooled beta values of the choice conditions (CF and NF) of varying set size (model 2) and (i) subjects' difficulty ratings and (ii) the number of saccades (between subject variance was removed[10]).

Structure	x,y,z	t-value	p	t-test	2x3 rmANOVA [Task x S]	t-test	Regression	Regression
	{mm MNI}	*peak value*	*(uncorr.)*	*Linear > 0*	*F(1,18), p, η^2p [95% CI]*	*$Qu_{NF>FO}$*	*Difficulty*	*Saccades*
Frontal Lobe								
POG l	*-27 -27 -9*	4.41	0.000	- t(18)=0.256; p=0.401; g1[95% CI]=0.059 [-0.392, 0.508]	- F=4.233, p=0.054, η^2p [95% CI]=0.190 [0.000, 0.415]	- t(18)=1.532; p=0.071; g1[95% CI]=0.351 [-0.117, 0.811]	- F(1,112)=1.218, p=0.272, r[95% CI]=0.104 [-0.082, 0.282]	- F(1,112)=0.210, p=0.648, r[95% CI]=0.043 [-0.142, 0.225]
aINS / POG l	*-30 21 9*	4.61	0.000	- t(18)=1.018; p=0.161; g1[95% CI]=0.233 [-0.226, 0.686]	- F=1.910, p=0.184, η^2p [95% CI]=0.096 [0.046, 0.160]	- t(18)=0.729; p=0.238; g1[95% CI]=0.167 [-0.288, 0.618]	* F(1,112)=5.726, p=0.018, r[95% CI]=0.221 [0.038, 0.389]	- F(1,112)=1.778, p=0.185, r[95% CI]=0.125 [-0.060, 0.302]
aINS / POG l	*-30 12 3*	4.75	0.000	- t(18)=0.570; p=0.288; g1[95% CI]=0.131 [-0.323, 0.581]	* F=7.360, p=0.014, η^2p [95% CI]=0.290 [0.155, 0.424]	- t(18)=1.178; p=0.127; g1[95% CI]=0.270 [-0.191, 0.725]	- F(1,112)=3.064, p=0.083, r[95% CI]=0.163 [-0.021, 0.337]	- F(1,112)=0.257, p=0.613, r[95% CI]=0.048 [-0.137, 0.230]
aINS / POG r	*33 21 3*	4.31	0.000	* t(18)=1.858; p=0.040; g1[95% CI]=0.426 [-0.050, 0.891]	- F=2.499, p=0.131, η^2p [95% CI]=0.122 [0.059, 0.200]	* t(18)=1.783; p=0.046; g1[95% CI]=0.409 [-0.065, 0.873]	** F(1,112)=9.251, p=0.003, r[95% CI]=0.276 [0.097, 0.438]	- F(1,112)=2.876, p=0.093, r[95% CI]=0.158 [-0.026, 0.332]
ACC	*9 24 33*	5.14	0.000	- t(18)=1.678; p=0.055; g1[95% CI]=0.385 [-0.087, 0.847]	- F=3.756, p=0.068, η^2p [95% CI]=0.173 [0.086, 0.273]	- t(18)=1.389; p=0.091; g1[95% CI]=0.319 [-0.147, 0.776]	* F(1,112)=6.865, p=0.010, r[95% CI]=0.240 [0.059, 0.406]	- F(1,112)=2.380, p=0.126, r[95% CI]=0.144 [-0.041, 0.320]
ACC	*-6 30 33*	4.67	0.000	* t(18)=1.817; p=0.043; g1[95% CI]=0.417 [-0.058, 0.881]	** F=11.962, p=0.003, η^2p [95% CI]=0.399 [0.230, 0.545]	- t(18)=1.498; p=0.076; g1[95% CI]=0.344 [-0.124, 0.802]	* F(1,112)=4.167, p=0.044, r[95% CI]=0.189 [0.006, 0.361]	- F(1,112)=1.637, p=0.203, r[95% CI]=0.120 [-0.065, 0.297]
ACC	*6 33 27*	4.62	0.000	* t(18)=2.000; p=0.030; g1[95% CI]=0.459 [-0.021, 0.927]	* F=6.934, p=0.017, η^2p [95% CI]=0.278 [0.148, 0.409]	* t(18)=2.210; p=0.020; g1[95% CI]=0.507 [0.022, 0.980]	** F(1,112)=7.622, p=0.007, r[95% CI]=0.252 [0.072, 0.417]	- F(1,112)=2.642, p=0.107, r[95% CI]=0.152 [-0.033, 0.327]
MFG l	*-42 21 33*	4.34	0.000	- t(18)=1.165; p=0.130; g1[95% CI]=0.267 [-0.194, 0.722]	* F=5.370, p=0.032, η^2p [95% CI]=0.230 [0.118, 0.349]	- t(18)=1.004; p=0.164; g1[95% CI]=0.230 [-0.228, 0.683]	- F(1,112)=1.686, p=0.197, r[95% CI]=0.122 [-0.064, 0.299]	- F(1,112)=0.182, p=0.671, r[95% CI]=0.040 [-0.145, 0.223]
MFG l	*-39 36 15*	4.26	0.000	- t(18)=-0.214; p=0.583; g1[95% CI]=-0.049 [-0.498, 0.402]	* F=6.290, p=0.022, η^2p [95% CI]=0.259 [0.136, 0.386]	- t(18)=1.485; p=0.077; g1[95% CI]=0.341 [-0.127, 0.799]	- F(1,112)=0.464, p=0.497, r[95% CI]=0.064 [-0.121, 0.245]	- F(1,112)=0.038, p=0.847, r[95% CI]=-0.018 [-0.202, 0.166]
MFG l	*-27 36 27*	4.02	0.000	- t(18)=0.191; p=0.425; g1[95% CI]=0.044 [-0.407, 0.493]	- F=3.630, p=0.073, η^2p [95% CI]=0.168 [0.083, 0.266]	- t(18)=0.374; p=0.356; g1[95% CI]=0.086 [-0.366, 0.535]	- F(1,112)=1.353, p=0.247, r[95% CI]=0.109 [-0.076, 0.287]	- F(1,112)=0.011, p=0.917, r[95% CI]=0.010 [-0.174, 0.193]
MFG r	*48 36 18*	4.17	0.000	- t(18)=-0.438; p=0.667; g1[95% CI]=-0.101 [-0.550, 0.352]	- F=0.507, p=0.486, η^2p [95% CI]=0.027 [0.013, 0.048]	*** t(18)=3.625; p=0.001; g1[95% CI]=0.832 [0.299, 1.347]	- F(1,112)=0.594, p=0.442, r[95% CI]=0.073 [-0.113, 0.253]	- F(1,112)=0.245, p=0.622, r[95% CI]=-0.047 [-0.229, 0.138]
dPM l	*-30 -3 42*	4.49	0.000	* t(18)=1.931; p=0.035; g1[95% CI]=0.443 [-0.034, 0.910]	- F=3.758, p=0.068, η^2p [95% CI]=0.173 [0.086, 0.273]	- t(18)=0.897; p=0.191; g1[95% CI]=0.206 [-0.252, 0.658]	- F(1,112)=1.773, p=0.186, r[95% CI]=0.125 [-0.060, 0.302]	- F(1,112)=1.863, p=0.175, r[95% CI]=0.128 [-0.057, 0.305]
vPM l	*-42 -6 39*	4.45	0.000	* t(18)=2.118; p=0.024; g1[95% CI]=0.486 [0.003, 0.956]	** F=8.524, p=0.009, η^2p [95% CI]=0.321 [0.176, 0.460]	- t(18)=0.510; p=0.308; g1[95% CI]=0.117 [-0.336, 0.567]	* F(1,112)=5.897, p=0.017, r[95% CI]=0.224 [0.041, 0.391]	- F(1,112)=1.638, p=0.203, r[95% CI]=0.120 [-0.065, 0.297]
Basal Ganglia / Thalamus								
PUT / CN l	*-18 18 -3*	5.65	0.000	- t(18)=-0.292; p=0.613; g1[95% CI]=-0.067 [-0.516, 0.384]	** F=10.107, p=0.005, η^2p [95% CI]=0.360 [0.202, 0.503]	- t(18)=0.905; p=0.189; g1[95% CI]=0.208 [-0.250, 0.659]	- F(1,112)=0.519, p=0.473, r[95% CI]=0.068 [-0.117, 0.249]	- F(1,112)=0.014, p=0.905, r[95% CI]=0.011 [-0.173, 0.195]
PUT / CN l	*-18 9 6*	5.15	0.000	- t(18)=0.251; p=0.402; g1[95% CI]=0.058 [-0.393, 0.507]	** F=9.275, p=0.007, η^2p [95% CI]=0.340 [0.188, 0.481]	* t(18)=1.997; p=0.031; g1[95% CI]=0.458 [-0.021, 0.926]	- F(1,112)=0.576, p=0.449, r[95% CI]=0.072 [-0.114, 0.252]	- F(1,112)=0.131, p=0.718, r[95% CI]=0.034 [-0.151, 0.217]
PUT / CN l	*-30 12 3*	4.75	0.000	- t(18)=0.570; p=0.288; g1[95% CI]=0.131 [-0.323, 0.581]	* F=7.360, p=0.014, η^2p [95% CI]=0.290 [0.155, 0.424]	- t(18)=1.178; p=0.127; g1[95% CI]=0.270 [-0.191, 0.725]	- F(1,112)=3.064, p=0.083, r[95% CI]=0.163 [-0.021, 0.337]	- F(1,112)=0.257, p=0.613, r[95% CI]=0.048 [-0.137, 0.230]
CN r	*9 6 0*	5.94	0.000	- t(18)=0.261; p=0.399; g1[95% CI]=0.060 [-0.391, 0.509]	* F=4.729, p=0.043, η^2p [95% CI]=0.208 [0.106, 0.321]	- t(18)=1.124; p=0.138; g1[95% CI]=0.258 [-0.203, 0.712]	- F(1,112)=2.936, p=0.089, r[95% CI]=0.160 [-0.025, 0.334]	- F(1,112)=0.137, p=0.712, r[95% CI]=0.035 [-0.150, 0.217]
CN r (E)	*15 18 0*	4.73	0.000	- t(18)=-0.361; p=0.639; g1[95% CI]=-0.083 [-0.532, 0.369]	* F=6.079, p=0.024, η^2p [95% CI]=0.252 [0.132, 0.378]	- t(18)=1.224; p=0.118; g1[95% CI]=0.281 [-0.182, 0.736]	- F(1,112)=1.520, p=0.220, r[95% CI]=0.116 [-0.070, 0.293]	- F(1,112)=0.183, p=0.669, r[95% CI]=-0.040 [-0.223, 0.145]
Thal l	*-9 -18 3*	3.58	0.001	- t(18)=0.475; p=0.320; g1[95% CI]=0.109 [-0.344, 0.559]	* F=5.769, p=0.027, η^2p [95% CI]=0.243 [0.126, 0.366]	* t(18)=1.950; p=0.033; g1[95% CI]=0.447 [-0.031, 0.914]	- F(1,112)=3.249, p=0.074, r[95% CI]=0.168 [-0.017, 0.341]	- F(1,112)=0.304, p=0.582, r[95% CI]=0.052 [-0.133, 0.234]
Parietal Lobe								
pIPS r	*21 -75 36*	4.41	0.000	- t(18)=0.681; p=0.252; g1[95% CI]=0.156 [-0.298, 0.607]	- F=2.433, p=0.136, η^2p [95% CI]=0.119 [0.057, 0.196]	- t(18)=1.328; p=0.100; g1[95% CI]=0.305 [-0.160, 0.761]	- F(1,112)=1.014, p=0.316, r[95% CI]=0.095 [-0.091, 0.274]	- F(1,112)=0.738, p=0.392, r[95% CI]=0.081 [-0.105, 0.261]
pIPS r	*33 -84 33*	4.23	0.000	- t(18)=-0.404; p=0.655; g1[95% CI]=-0.093 [-0.542, 0.359]	- F=0.240, p=0.630, η^2p [95% CI]=0.013 [0.006, 0.023]	** t(18)=2.954; p=0.004; g1[95% CI]=0.678 [0.170, 1.171]	- F(1,112)=0.063, p=0.802, r[95% CI]=-0.024 [-0.207, 0.161]	- F(1,112)=0.155, p=0.695, r[95% CI]=-0.037 [-0.220, 0.148]
pIPS l	*-21 -75 30*	4.87	0.000	** t(18)=2.601; p=0.009; g1[95% CI]=0.597 [0.100, 1.079]	- F=0.622, p=0.441, η^2p [95% CI]=0.033 [0.015, 0.059]	* t(18)=2.116; p=0.024; g1[95% CI]=0.485 [0.003, 0.956]	* F(1,112)=4.923, p=0.029, r[95% CI]=0.205 [0.022, 0.375]	* F(1,112)=5.557, p=0.020, r[95% CI]=0.217 [0.035, 0.386]
pIPS l	*-15 -78 42*	3.7	0.001	- t(18)=1.212; p=0.121; g1[95% CI]=0.278 [-0.184, 0.733]	- F=0.796, p=0.384, η^2p [95% CI]=0.042 [0.020, 0.074]	* t(18)=1.764; p=0.047; g1[95% CI]=0.405 [-0.069, 0.868]	- F(1,112)=0.401, p=0.528, r[95% CI]=0.060 [-0.126, 0.241]	- F(1,112)=1.044, p=0.309, r[95% CI]=0.096 [-0.089, 0.275]
Occipital Lobe								
LG l	*-24 -60 -9*	5.23	0.000	** t(18)=2.656; p=0.008; g1[95% CI]=0.609 [0.111, 1.093]	- F=0.408, p=0.531, η^2p [95% CI]=0.022 [0.010, 0.039]	* t(18)=2.045; p=0.028; g1[95% CI]=0.469 [-0.011, 0.938]	* F(1,112)=6.554, p=0.012, r[95% CI]=0.235 [0.054, 0.402]	** F(1,112)=7.165, p=0.009, r[95% CI]=0.245 [0.064, 0.411]
LG l	*-18 -69 -3*	4.93	0.000	** t(18)=2.797; p=0.006; g1[95% CI]=0.642 [0.139, 1.130]	- F=0.167, p=0.688, η^2p [95% CI]=0.009 [0.004, 0.016]	* t(18)=2.171; p=0.022; g1[95% CI]=0.498 [0.014, 0.970]	* F(1,112)=4.558, p=0.035, r[95% CI]=0.198 [0.014, 0.368]	- F(1,112)=3.437, p=0.066, r[95% CI]=0.173 [-0.012, 0.345]
IOG	*-27 -81 -9*	4.31	0.000	** t(18)=2.797; p=0.006; g1[95% CI]=0.642 [0.139, 1.130]	- F=1.703, p=0.208, η^2p [95% CI]=0.086 [0.041, 0.146]	* t(18)=2.375; p=0.014; g1[95% CI]=0.545 [0.055, 1.021]	** F(1,112)=8.963, p=0.003, r[95% CI]=0.272 [0.093, 0.434]	** F(1,112)=7.385, p=0.008, r[95% CI]=0.249 [0.068, 0.414]
MOG r	*39 -81 21*	3.38	0.002	* t(18)=2.165; p=0.022; g1[95% CI]=0.497 [0.013, 0.968]	- F=3.060, p=0.097, η^2p [95% CI]=0.145 [0.071, 0.234]	* t(18)=2.144; p=0.023; g1[95% CI]=0.492 [0.009, 0.963]	- F(1,112)=2.516, p=0.116, r[95% CI]=0.148 [-0.037, 0.323]	- F(1,112)=2.587, p=0.111, r[95% CI]=0.150 [-0.035, 0.325]

Supplementary Table 2 | Detailed Results of ROI analyses (Part 2). This table summarizes all areas that exhibited a correlation of fMRI-activity with the orthogonalised quadratic predictor during the exposure phase of pooled choice trials (CF & NF) as in Supplementary Table 1. The ROIs displayed in Figure 4b-e and in Supplementary Figure 3 are highlighted light grey. The columns of the table depict the results of statistical ROI-analyses: We separately probed for a quadratic signal component as a function of set size in the pooled choice conditions for (i) the exposure stage, (ii) the delay stage, and (iii) the response stage. To this end we performed one-tailed t-tests on the individually averaged (across CF & NF) beta estimates for the quadratic predictor of the respective task stage (i-iii; N=19 each; H_0: beta>0; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). In addition, a corresponding set of t-test analyses was performed on the beta values for the GLM-predictor that captured the liking rating of the chosen item (separate tests for task stages i-iii; N=19 each; H_0: beta>0; * $p < 0.05$)

Structure	x,y,z	t-test [Quadratic > 0]	t-test [Quadratic > 0]	t-test [Quadratic > 0]	t-test [Liking of Chosen > 0]	t-test [Liking of Chosen > 0]	t-test [Liking of Chosen > 0]
	{mm MNI}	*Exposure*	*Delay*	*Response*	*Exposure*	*Delay*	*Response*
POG l	*-27 -27 -9*	*** t(18)=4.275; p=0.000; g1[95% CI]=0.981 [0.421, 1.522]	- t(18)=0.638; p=0.266; g1[95% CI]=0.146 [-0.308, 0.597]	- t(18)=-1.142; p=0.866; g1[95% CI]=-0.262 [-0.716, 0.199]	- t(18)=0.799; p=0.217; g1[95% CI]=0.183 [-0.273, 0.634]	- t(18)=1.696; p=0.054; g1[95% CI]=0.389 [-0.083, 0.851]	- t(18)=1.144; p=0.134; g1[95% CI]=0.263 [-0.199, 0.717]
aINS / POG l	*-30 21 9*	*** t(18)=4.583; p=0.000; g1[95% CI]=1.052 [0.478, 1.607]	- t(18)=0.895; p=0.191; g1[95% CI]=0.205 [-0.252, 0.657]	- t(18)=-1.362; p=0.905; g1[95% CI]=-0.313 [-0.769, 0.153]	- t(18)=1.013; p=0.162; g1[95% CI]=0.232 [-0.227, 0.685]	- t(18)=1.733; p=0.050; g1[95% CI]=0.398 [-0.075, 0.860]	- t(18)=1.447; p=0.082; g1[95% CI]=0.332 [-0.135, 0.790]
aINS / POG l	*-30 12 3*	*** t(18)=4.738; p=0.000; g1[95% CI]=1.087 [0.506, 1.649]	- t(18)=0.883; p=0.194; g1[95% CI]=0.203 [-0.255, 0.654]	- t(18)=-1.654; p=0.942; g1[95% CI]=-0.379 [-0.841, 0.092]	- t(18)=1.476; p=0.079; g1[95% CI]=0.339 [-0.129, 0.797]	- t(18)=1.622; p=0.061; g1[95% CI]=0.372 [-0.098, 0.833]	- t(18)=1.221; p=0.119; g1[95% CI]=0.280 [-0.182, 0.735]
aINS / POG r	*33 21 3*	*** t(18)=3.964; p=0.000; g1[95% CI]=0.909 [0.363, 1.438]	- t(18)=0.097; p=0.462; g1[95% CI]=0.022 [-0.428, 0.472]	- t(18)=-2.531; p=0.990; g1[95% CI]=-0.581 [-1.061, -0.086]	- t(18)=-0.232; p=0.590; g1[95% CI]=-0.053 [-0.502, 0.398]	- t(18)=1.137; p=0.135; g1[95% CI]=0.261 [-0.200, 0.715]	- t(18)=0.399; p=0.347; g1[95% CI]=0.092 [-0.360, 0.541]
ACC	*9 24 33*	*** t(18)=5.079; p=0.000; g1[95% CI]=1.165 [0.568, 1.743]	- t(18)=1.656; p=0.058; g1[95% CI]=0.380 [-0.091, 0.841]	- t(18)=-1.058; p=0.848; g1[95% CI]=-0.243 [-0.696, 0.217]	- t(18)=1.675; p=0.056; g1[95% CI]=0.384 [-0.087, 0.846]	- t(18)=1.476; p=0.079; g1[95% CI]=0.339 [-0.129, 0.797]	- t(18)=1.726; p=0.051; g1[95% CI]=0.396 [-0.077, 0.859]
ACC	*-6 30 33*	*** t(18)=4.393; p=0.000; g1[95% CI]=1.008 [0.443, 1.554]	- t(18)=1.172; p=0.128; g1[95% CI]=0.269 [-0.193, 0.723]	- t(18)=-2.441; p=0.987; g1[95% CI]=-0.560 [-1.038, -0.068]	* t(18)=2.263; p=0.018; g1[95% CI]=0.519 [0.033, 0.993]	* t(18)=2.180; p=0.021; g1[95% CI]=0.500 [0.016, 0.972]	* t(18)=1.961; p=0.033; g1[95% CI]=0.450 [-0.028, 0.917]
ACC	*6 33 27*	*** t(18)=4.236; p=0.000; g1[95% CI]=0.972 [0.414, 1.512]	- t(18)=1.510; p=0.074; g1[95% CI]=0.346 [-0.122, 0.805]	- t(18)=-2.300; p=0.983; g1[95% CI]=-0.528 [-1.002, -0.040]	- t(18)=1.645; p=0.059; g1[95% CI]=0.377 [-0.093, 0.839]	* t(18)=1.971; p=0.032; g1[95% CI]=0.452 [-0.026, 0.920]	- t(18)=1.060; p=0.152; g1[95% CI]=0.243 [-0.217, 0.697]
MFG l	*-42 21 33*	*** t(18)=4.130; p=0.000; g1[95% CI]=0.948 [0.394, 1.483]	- t(18)=1.602; p=0.063; g1[95% CI]=0.367 [-0.102, 0.828]	- t(18)=0.344; p=0.368; g1[95% CI]=0.079 [-0.373, 0.528]	- t(18)=0.223; p=0.413; g1[95% CI]=0.051 [-0.399, 0.501]	- t(18)=0.271; p=0.395; g1[95% CI]=0.062 [-0.389, 0.512]	- t(18)=0.754; p=0.230; g1[95% CI]=0.173 [-0.283, 0.624]
MFG l	*-39 36 15*	*** t(18)=4.147; p=0.000; g1[95% CI]=0.951 [0.397, 1.488]	- t(18)=1.153; p=0.132; g1[95% CI]=0.264 [-0.197, 0.719]	- t(18)=-2.615; p=0.991; g1[95% CI]=-0.600 [-1.083, -0.103]	- t(18)=1.304; p=0.104; g1[95% CI]=0.299 [-0.165, 0.755]	- t(18)=0.889; p=0.193; g1[95% CI]=0.204 [-0.253, 0.656]	- t(18)=0.546; p=0.296; g1[95% CI]=0.125 [-0.328, 0.575]
MFG l	*-27 36 27*	*** t(18)=3.845; p=0.001; g1[95% CI]=0.882 [0.340, 1.406]	- t(18)=1.410; p=0.088; g1[95% CI]=0.324 [-0.142, 0.781]	- t(18)=-2.586; p=0.991; g1[95% CI]=-0.593 [-1.075, -0.097]	- t(18)=0.493; p=0.314; g1[95% CI]=0.113 [-0.340, 0.563]	- t(18)=1.527; p=0.072; g1[95% CI]=0.350 [-0.118, 0.810]	- t(18)=1.272; p=0.110; g1[95% CI]=0.292 [-0.172, 0.747]
MFG r	*48 36 18*	*** t(18)=3.858; p=0.001; g1[95% CI]=0.885 [0.343, 1.410]	- t(18)=0.998; p=0.166; g1[95% CI]=0.229 [-0.230, 0.682]	- t(18)=-3.463; p=0.999; g1[95% CI]=-0.795 [-1.305, -0.268]	- t(18)=0.598; p=0.279; g1[95% CI]=0.137 [-0.317, 0.587]	- t(18)=1.687; p=0.054; g1[95% CI]=0.387 [-0.085, 0.849]	- t(18)=0.900; p=0.190; g1[95% CI]=0.207 [-0.251, 0.658]
dPM l	*-30 -3 42*	*** t(18)=4.205; p=0.000; g1[95% CI]=0.965 [0.408, 1.503]	- t(18)=1.523; p=0.073; g1[95% CI]=0.349 [-0.119, 0.809]	- t(18)=-0.956; p=0.824; g1[95% CI]=-0.219 [-0.672, 0.239]	- t(18)=1.101; p=0.143; g1[95% CI]=0.253 [-0.208, 0.706]	- t(18)=0.959; p=0.175; g1[95% CI]=0.220 [-0.238, 0.672]	- t(18)=0.315; p=0.378; g1[95% CI]=0.072 [-0.379, 0.522]
vPM l	*-42 -6 39*	*** t(18)=4.163; p=0.000; g1[95% CI]=0.955 [0.400, 1.492]	- t(18)=0.588; p=0.282; g1[95% CI]=0.135 [-0.319, 0.585]	- t(18)=-0.631; p=0.732; g1[95% CI]=-0.145 [-0.595, 0.309]	- t(18)=0.755; p=0.230; g1[95% CI]=0.173 [-0.282, 0.624]	- t(18)=1.062; p=0.151; g1[95% CI]=0.244 [-0.216, 0.697]	* t(18)=1.787; p=0.045; g1[95% CI]=0.410 [-0.064, 0.874]
PUT / CN l	*-18 18 -3*	*** t(18)=5.002; p=0.000; g1[95% CI]=1.148 [0.555, 1.722]	- t(18)=1.121; p=0.139; g1[95% CI]=0.257 [-0.204, 0.711]	- t(18)=-1.684; p=0.945; g1[95% CI]=-0.386 [-0.848, 0.085]	- t(18)=0.491; p=0.315; g1[95% CI]=0.113 [-0.340, 0.562]	- t(18)=1.359; p=0.096; g1[95% CI]=0.312 [-0.153, 0.768]	* t(18)=2.217; p=0.020; g1[95% CI]=0.509 [0.023, 0.981]
PUT / CN l	*-18 9 6*	*** t(18)=5.127; p=0.000; g1[95% CI]=1.176 [0.577, 1.756]	- t(18)=0.583; p=0.283; g1[95% CI]=0.134 [-0.320, 0.584]	- t(18)=-2.032; p=0.971; g1[95% CI]=-0.466 [-0.935, 0.014]	- t(18)=1.181; p=0.126; g1[95% CI]=0.271 [-0.191, 0.725]	- t(18)=1.655; p=0.058; g1[95% CI]=0.380 [-0.091, 0.841]	* t(18)=2.230; p=0.019; g1[95% CI]=0.512 [0.026, 0.985]
PUT / CN l	*-30 12 3*	*** t(18)=4.738; p=0.000; g1[95% CI]=1.087 [0.506, 1.649]	- t(18)=0.883; p=0.194; g1[95% CI]=0.203 [-0.255, 0.654]	- t(18)=-1.654; p=0.942; g1[95% CI]=-0.379 [-0.841, 0.092]	- t(18)=1.476; p=0.079; g1[95% CI]=0.339 [-0.129, 0.797]	- t(18)=1.622; p=0.061; g1[95% CI]=0.372 [-0.098, 0.833]	- t(18)=1.221; p=0.119; g1[95% CI]=0.280 [-0.182, 0.735]
CN r	*9 6 0*	*** t(18)=5.455; p=0.000; g1[95% CI]=1.252 [0.636, 1.848]	- t(18)=1.491; p=0.077; g1[95% CI]=0.342 [-0.125, 0.801]	- t(18)=-0.645; p=0.737; g1[95% CI]=-0.148 [-0.598, 0.306]	- t(18)=1.433; p=0.084; g1[95% CI]=0.329 [-0.138, 0.787]	* t(18)=2.130; p=0.024; g1[95% CI]=0.489 [0.006, 0.959]	- t(18)=1.517; p=0.073; g1[95% CI]=0.348 [-0.120, 0.807]
CN r (E)	*15 18 0*	*** t(18)=4.478; p=0.000; g1[95% CI]=1.027 [0.459, 1.578]	- t(18)=0.578; p=0.285; g1[95% CI]=0.133 [-0.321, 0.582]	- t(18)=-0.486; p=0.684; g1[95% CI]=-0.111 [-0.561, 0.341]	- t(18)=0.849; p=0.203; g1[95% CI]=0.195 [-0.262, 0.646]	- t(18)=1.348; p=0.097; g1[95% CI]=0.309 [-0.156, 0.766]	- t(18)=0.433; p=0.335; g1[95% CI]=0.099 [-0.353, 0.549]
Thal l	*-9 -18 3*	** t(18)=3.300; p=0.002; g1[95% CI]=0.757 [0.237, 1.261]	- t(18)=1.015; p=0.162; g1[95% CI]=0.233 [-0.226, 0.686]	- t(18)=-1.554; p=0.931; g1[95% CI]=-0.357 [-0.816, 0.112]	- t(18)=1.369; p=0.094; g1[95% CI]=0.314 [-0.151, 0.771]	* t(18)=1.874; p=0.039; g1[95% CI]=0.430 [-0.046, 0.895]	- t(18)=0.536; p=0.299; g1[95% CI]=0.123 [-0.330, 0.573]
pIPS r	*21 -75 36*	*** t(18)=4.053; p=0.000; g1[95% CI]=0.930 [0.380, 1.462]	* t(18)=2.385; p=0.014; g1[95% CI]=0.547 [0.057, 1.024]	- t(18)=0.240; p=0.407; g1[95% CI]=0.055 [-0.396, 0.504]	- t(18)=-0.367; p=0.641; g1[95% CI]=-0.084 [-0.533, 0.368]	* t(18)=1.827; p=0.042; g1[95% CI]=0.419 [-0.056, 0.884]	- t(18)=1.129; p=0.137; g1[95% CI]=0.259 [-0.202, 0.713]
pIPS r	*33 -84 33*	*** t(18)=3.931; p=0.000; g1[95% CI]=0.902 [0.357, 1.429]	- t(18)=1.064; p=0.151; g1[95% CI]=0.244 [-0.216, 0.697]	- t(18)=-0.083; p=0.533; g1[95% CI]=-0.019 [-0.468, 0.431]	- t(18)=0.427; p=0.337; g1[95% CI]=0.098 [-0.354, 0.547]	- t(18)=1.236; p=0.116; g1[95% CI]=0.284 [-0.179, 0.739]	- t(18)=1.166; p=0.129; g1[95% CI]=0.268 [-0.194, 0.722]
pIPS l	*-21 -75 30*	*** t(18)=4.656; p=0.000; g1[95% CI]=1.068 [0.491, 1.626]	- t(18)=1.450; p=0.082; g1[95% CI]=0.333 [-0.134, 0.791]	- t(18)=-0.743; p=0.767; g1[95% CI]=-0.170 [-0.621, 0.285]	- t(18)=-0.179; p=0.570; g1[95% CI]=-0.041 [-0.490, 0.409]	- t(18)=1.634; p=0.060; g1[95% CI]=0.375 [-0.096, 0.836]	- t(18)=1.462; p=0.080; g1[95% CI]=0.335 [-0.132, 0.794]
pIPS l	*-15 -78 42*	*** t(18)=3.641; p=0.001; g1[95% CI]=0.835 [0.302, 1.352]	- t(18)=1.647; p=0.058; g1[95% CI]=0.378 [-0.093, 0.839]	- t(18)=0.071; p=0.472; g1[95% CI]=0.016 [-0.434, 0.466]	- t(18)=-0.480; p=0.681; g1[95% CI]=-0.110 [-0.560, 0.343]	- t(18)=0.468; p=0.323; g1[95% CI]=0.107 [-0.345, 0.557]	- t(18)=1.446; p=0.083; g1[95% CI]=0.332 [-0.135, 0.790]
LG l	*-24 -60 -9*	*** t(18)=4.963; p=0.000; g1[95% CI]=1.139 [0.547, 1.711]	* t(18)=2.216; p=0.020; g1[95% CI]=0.508 [0.023, 0.981]	- t(18)=0.341; p=0.368; g1[95% CI]=0.078 [-0.373, 0.528]	- t(18)=-0.224; p=0.588; g1[95% CI]=-0.051 [-0.501, 0.399]	- t(18)=1.323; p=0.101; g1[95% CI]=0.303 [-0.161, 0.760]	- t(18)=1.540; p=0.071; g1[95% CI]=0.353 [-0.115, 0.813]
LG l	*-18 -69 -3*	*** t(18)=4.740; p=0.000; g1[95% CI]=1.087 [0.507, 1.649]	* t(18)=2.049; p=0.028; g1[95% CI]=0.470 [-0.010, 0.939]	- t(18)=-0.066; p=0.526; g1[95% CI]=-0.015 [-0.465, 0.435]	- t(18)=-0.587; p=0.718; g1[95% CI]=-0.135 [-0.585, 0.319]	- t(18)=1.230; p=0.117; g1[95% CI]=0.282 [-0.180, 0.737]	- t(18)=1.133; p=0.136; g1[95% CI]=0.260 [-0.201, 0.714]
lOG	*-27 -81 -9*	*** t(18)=4.119; p=0.000; g1[95% CI]=0.945 [0.392, 1.480]	- t(18)=1.536; p=0.071; g1[95% CI]=0.352 [-0.116, 0.812]	- t(18)=0.075; p=0.471; g1[95% CI]=0.017 [-0.433, 0.467]	- t(18)=-1.779; p=0.954; g1[95% CI]=-0.408 [-0.872, 0.066]	- t(18)=1.166; p=0.130; g1[95% CI]=0.267 [-0.194, 0.722]	- t(18)=1.498; p=0.076; g1[95% CI]=0.344 [-0.124, 0.802]
MOG r	*39 -81 21*	** t(18)=3.086; p=0.003; g1[95% CI]=0.708 [0.195, 1.205]	- t(18)=1.564; p=0.068; g1[95% CI]=0.359 [-0.110, 0.819]	- t(18)=-1.213; p=0.880; g1[95% CI]=-0.278 [-0.733, 0.184]	- t(18)=0.925; p=0.184; g1[95% CI]=0.212 [-0.246, 0.664]	* t(18)=2.213; p=0.020; g1[95% CI]=0.508 [0.023, 0.980]	** t(18)=3.180; p=0.003; g1[95% CI]=0.730 [0.214, 1.230]