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Brain mechanisms underlying prospective thinking of sustainable behaviours

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The preservation of our environment requires sustainable ways of thinking and living. Here, we aimed to explore the core network of brain regions involved in the prospective thinking about (un)sustainable behaviours. Using a neuroimaging cue-exposure paradigm, we requested participants ($n = 86$) to report behaviours that were the most feasible for them to implement (sustainable behaviour) or diminish (unsustainable behaviour) in the future. We find that increasing sustainable behaviours was perceived to be more feasible than reducing unsustainable ones. Consistent with the role of the ventromedial prefrontal cortex and hippocampus in providing access to new representations of past behaviours, we observed stronger activation of these regions when picturing an increase in sustainable behaviours. Critically, simulating the reduction of unsustainable behaviours triggered activation within the right dorsolateral prefrontal cortex (a key region for inhibitory-control processes), which was negatively associated with hippocampal activation (a key region for memory). These findings suggest that the dorsolateral prefrontal cortex downregulates brain regions that support memory retrieval of unsustainable behaviours. This mechanism could inhibit the access to episodic details associated with unsustainable behaviours and in turn allow for prospective thinking of sustainable behaviours. These findings provide an initial step towards a better understanding of the brain networks that are involved in the adoption of sustainable habits.

In public campaigns and political narratives, pro-environmental daily-life behaviours are frequently framed in terms of either increasing sustainable behaviours (such as using public transportation) or reducing unsustainable behaviours (such as using a personal car)[1,2]. This duality is likely to play an important role for the capacity to project oneself toward the future adoption of pro-environmental behaviours. The ability to mentally simulate the future has been referred to as prospective thinking[3]. It involves the extraction of information that is stored in episodic and semantic memory (for example, details about previously encountered locations, objects and people), as well as more abstract, schematic and conceptual knowledge (such as envisioning general goals or events)[4]. There is convincing evidence supporting the notion that prospective thinking enables one to flexibly retrieve and recombine past information into simulation and mental imagery related to future events[3–6]. A central feature of prospective thinking is therefore that it binds memory to prospective processes[3].

In this Article, we assume that the prospective thinking framework is a sound starting point to gain knowledge about how individuals picture themselves in terms of either increasing future sustainable behaviours or decreasing unsustainable behaviours. We used functional magnetic resonance imaging (fMRI), which has been shown to be a sensitive technique for investigating the neural basis of prospective thinking. To date, the neural correlates of prospective thinking have mainly been inferred from studies on episodic future thinking (EFT; that is, a subdimension of prospective thinking that enables individuals to imagine themselves in a particular place at a specific time, bringing specific details to mind[3,7–10]). An important observation from this fMRI literature is that memory and EFT share a core network of brain regions, featuring the hippocampus (HC) and the ventromedial prefrontal cortex (vmPFC)[7]. The HC has a critical role in recombining memories to mentally simulate future events[11]. The vmPFC supports EFT by providing the contextual details that are relevant for the future imagined situation[12,13]. Critically, EFT is linked to activation of the right dorsolateral prefrontal cortex (rdlPFC) when individuals are instructed to suppress thinking about a future life event[9]. Accordingly, the rdlPFC is thought to downregulate vmPFC and HC activation to achieve control-oriented EFT[9,14–21].

On the basis of the EFT fMRI literature, we propose that comparable dlPFC inhibitory mechanism characterizes prospective thinking when individuals picture themselves reducing unsustainable behaviours. The rdlPFC is a key cerebral pathway for inhibitory control processes[22,23]. Thus, this region probably has a function in the inhibition of stored memories, triggered by HC and vmPFC activation (for example, past experiences of 'me using disposable cups'), to create alternative prospective thinking (for example, 'imagining myself reducing my use of disposable cups'). By contrast, the HC and the vmPFC network should mediate prospective thinking when using stored memories (for example, 'me using reusable cups') to simulate the future occurrence of sustainable behaviours (for example, 'to increase my use of reusable cups').

To test these predictions, we used a cue-exposure paradigm featuring sustainable and unsustainable daily-life behaviours (Fig. 1). Participants were exposed to cues and were requested to reflect on the feasibility of 'doing more' of the sustainable behaviour or 'doing

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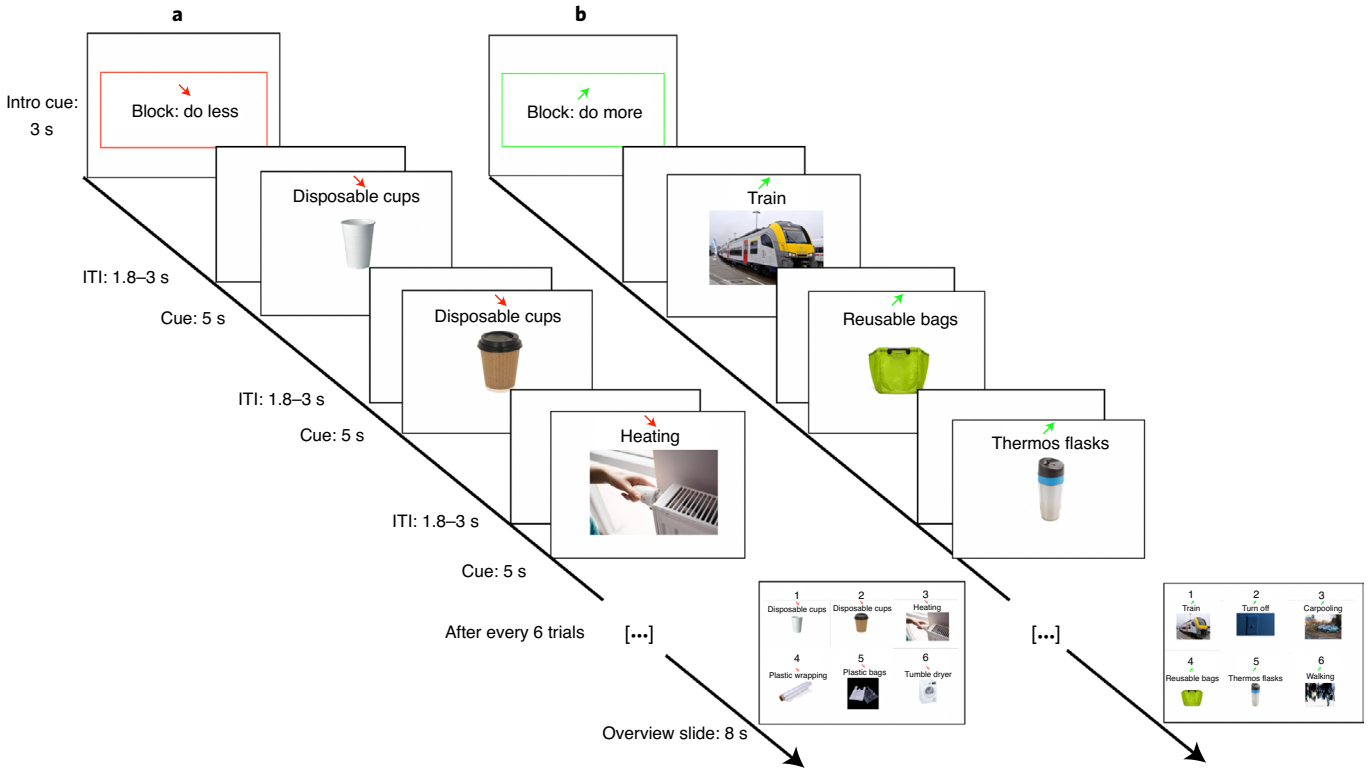

Fig. 1 | Examples of 'do more' and 'do less' cues used during the cue-exposure task. a,**b**, Participants viewed cues representing behaviours that could be reduced (**a**) (unsustainable behaviours, 'do less') or promoted (**b**) (sustainable behaviours, 'do more'). Participants were instructed to choose, after a run of six trials, the behaviour that was the most feasible for them to do less or to do more in the near future to protect the environment. ITI, inter-trial interval.

less' of the unsustainable behaviour in the future, during which fMRI monitoring was performed. At the end of each block (each of which featured six cues), participants were asked to indicate the behaviour that was the most feasible for them to implement (sustainable behaviour) or diminish (unsustainable behaviour) in the future. We also used post-task ratings to weigh each behaviour according to its (perceived) feasibility level. This enabled us to examine whether and how brain activation is modulated by feasibility. Using this procedure, we hypothesized that (1) rdlPFC is activated when viewing 'do less' cues and (2) the HC and vmPFC are activated when viewing 'do more' cues. Finally, given the presumed inhibitory function of the rdlPFC, we expected activity in this region to be negatively associated with activation in the vmPFC and HC when the viewing of 'do less' cues. This hypothesis was tested through functional connectivity analyses.

Feasibility of sustainable and unsustainable behaviours

The overall post-task rating scores of feasibility (averaged across the 36 ratings of each condition) were normally distributed (Shapiro–Wilk tests, 'do more': $W=0.97$, $P=0.12$; 'do less': $W=0.98$ $P=0.34$). Internal consistency across the feasibility ratings of the 'do less' ($\alpha=0.88$) and 'do more' behaviours ($\alpha=0.87$) was high (descriptive statistics associated with each of the 72 cues are provided in the Supplementary Information). Bayes factor for related-sample *t*-tests (Rouder's method with default SPSS priors and criteria) provided strong evidence in favour of a difference between the mean overall score of feasibility ratings of 'do more' behaviours (mean = 2.97, s.d. = 0.36, 95% confidence interval (CI) = 2.90–3.06) and 'do less' behaviours (mean = 2.85, s.d. = 0.43, 95% CI = 2.76–2.94; Bayes factor 10 = 10.41; Fig. 2). Bayes factor inference on pairwise correlations (using Pearson correlation coefficient *r*, JZS Bayes factor with default SPSS priors and criteria) revealed a positive linear relationship between mean scores of 'do less' and 'do more' behaviours ($r_{84}=0.58$, Bayes factor $10>100$).

Brain activation related to unsustainable behaviours

Figure 3a shows brain activation patterns for the 'do less minus do more' contrast (the complete list of activations is provided in Supplementary Table 2), indicating the rdlPFC (cluster size = 1,172, peak $x,y,z=46,32,30$, $z_{max}=3.72$). A significant and positive effect of the covariate average feasibility scores on 'do less' behaviours was also observed. This effect occurred in the right posterior insular cortex ($z_{max}=4.35$; voxel cluster size = 184, peak = 38, −2, 6; Fig. 3b).

Figure 3c shows brain activation increases for the parametric contrast on the level of feasibility of 'do less' cues. This analysis revealed a large cluster of activation (the complete list of activations is provided in Supplementary Table 2). This included a significant cluster of activation in the bilateral superior parietal lobe, extending into the dlPFC, the superior frontal gyrus, the dorsal anterior insular cortex, the frontal pole and the orbitofrontal cortex (cluster size = 27,805, peak = −24, −56, 54; $z_{max}=6.40$).

For the parametric contrast 'feasibility of do less minus feasibility of do more', Fig. 3d shows an increased activation in the rdlPFC (voxel cluster size = 150, peak = 50, 20, 38; $z_{max}=3.90$; the rdlPFC seed was created on the basis of these local maxima; see the 'Brain imaging analyses' section in the Methods). The complete list of activations is provided in Supplementary Table 2.

Brain activation related to sustainable behaviours

For the 'do more minus do less' contrast, Fig. 4a shows higher activation in the right temporal fusiform cortex extending into the right parahippocampal gyrus, the right HC and the right amygdala (voxel cluster size = 3,431, peak = 28, −30, −26); the left parahippocampal gyrus extending into the left temporal fusiform cortex, left HC and

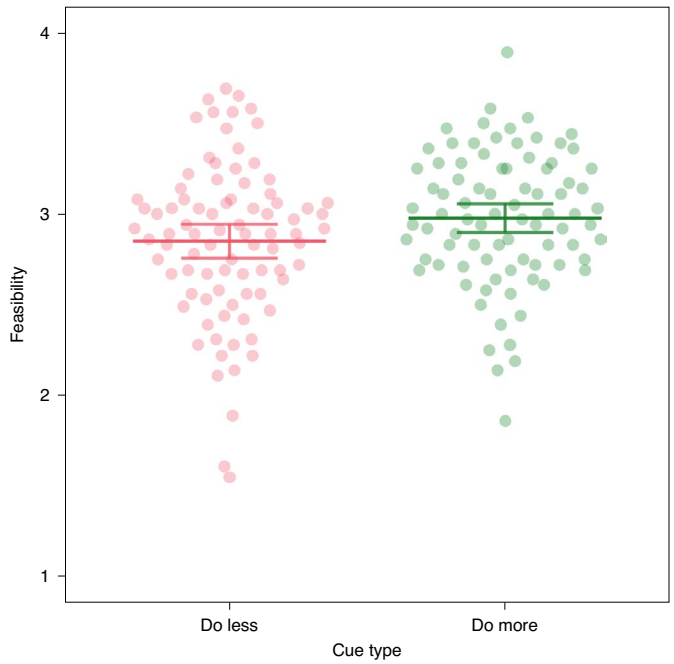

Fig. 2 | Feasibility ratings across the 'do less' and 'do more' cues. The data from each participant are shown as jittered dots. Data are mean ± 95% CI.

left amygdala (cluster size = 2,769, peak = −36, −10, −28); the left lingual gyrus (cluster size = 467, peak = −16, −52, 0); the right cingulate gyrus (voxel cluster size = 358, peak = 18, −48, 2); and the left lateral occipital cortex (voxel cluster size = 54, peak = −38, −80, 26). The complete list of activations is provided in Supplementary Table 2. No significant effect of the covariate (average feasibility scores of 'do more') behaviours was observed.

Figure 4b shows increases in brain activation for the parametric contrast on the level of the feasibility of 'do more' cues. This analysis revealed a large cluster of activation (voxel cluster size = 54,604, peak = 28, −48, −12; z_{max} = 7.48), featuring the vmPFC and the bilateral HC. The complete list of activations is provided in Supplementary Table 2.

For the parametric contrast 'feasibility of do more minus feasibility of do less', Fig. 4c shows an increase in activation in the bilateral temporal fusiform cortex extending into the bilateral lingual gyri, the bilateral parahippocampal gyri, the bilateral HC and the bilateral amygdala (voxel cluster size = 5,315, peak = −32, −40, −14; z_{max} = 7.11). We also observed significant activation within the vmPFC (cluster size = 354, peak = −6, 47, −14; z_{max} = 4.02). The complete list of activations is provided in Supplementary Table 2.

rdlPFC-centred functional connectivity

For the parametric contrast 'feasibility of do less behaviours', the analyses identified negative psychophysiological interaction (PPI) between the rdlPFC seed and the cingulate gyrus (voxel cluster size = 142, peak = −4, −28, 46; z_{max} = 4.29) and the left HC (voxel cluster size = 142, peak = −34, −22, −18; z_{max} = 3.86). Using a height threshold of $z > 2.3$ (for display purpose; Fig. 5), we observed a negative PPI between the rdlPFC seed and the cingulate gyrus (voxel cluster size = 1,092, peak = −4, −28, 46; z_{max} = 4.29); the right parahippocampal gyrus (voxel cluster size = 936, peak = 22, −18, −28, z_{max} = 4.24); the left parahippocampal gyrus extending into the left HC (voxel cluster size = 906, peak = −30, −34, −8, z_{max} = 4.44); the left middle temporal gyrus (voxel cluster size = 573, peak = −68, −38, −10, z_{max} = 3.96); and the postcentral gyrus (voxel cluster size = 430, peak = −50, −28, 50, z_{max} = 3.71). No significant positive PPI was found for this contrast (with either $z > 3.1$ or $z > 2.3$).

Discussion

Humans have the ability to project themselves into future events to promote the implementation and maintenance of goal-directed behaviours. This study aimed to make an initial step towards identifying the core network of brain regions that are involved in prospective thinking of daily-life pro-environmental behaviours. Beyond providing new data regarding the brain regions implicated in this process, our findings have important implications for understanding how feasibility judgements modulate the prospective thinking of (un)sustainable behaviours.

We observed that prospective thinking towards sustainable behaviours activates a brain network that encompasses the vmPFC, HC and parahippocampal gyrus. These results are consistent with

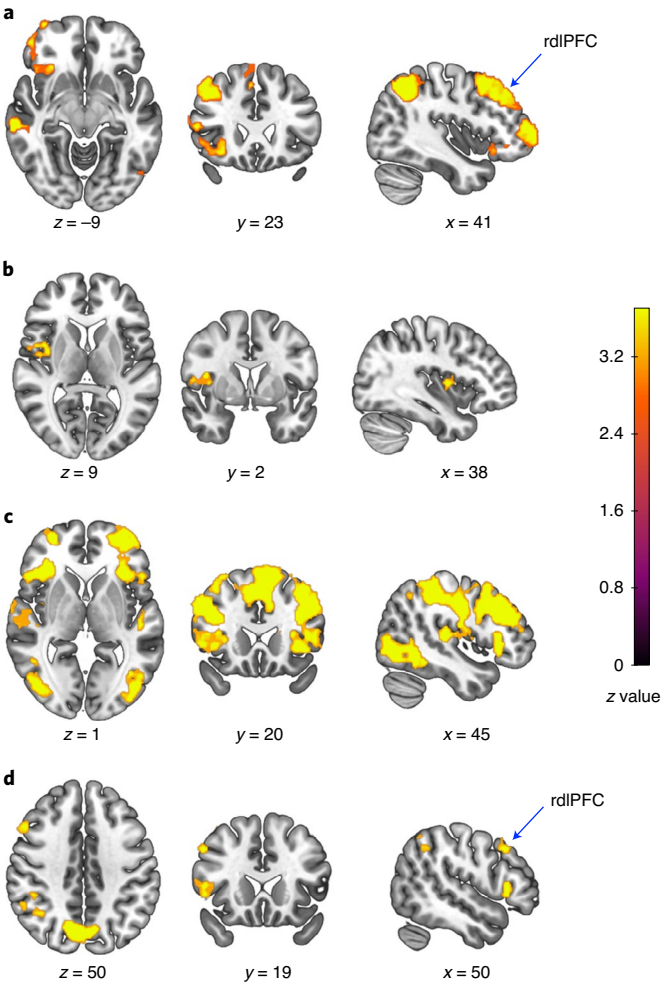

Fig. 3 | Brain imaging results for 'do less' trials. a, Regions that exhibited greater activation for the 'do less' cue in the 'do less minus do more' contrast included the rdlPFC. **b**, A higher feasibility of 'do less' behaviours was associated with posterior insular activation for the 'do less minus do more' contrast. **c**, Whole-brain activation for parametric increases in feasibility for 'do less' trials. **d**, Regions that exhibited greater activation for the parametric increase in the 'do less minus do more' contrast included the rdlPFC. All of the images were thresholded using FSL FLAME 1, with a height threshold of $z > 3.1$ and a cluster probability of $P < 0.05$, family-wise error (FWE)-corrected for multiple comparisons across the whole brain. The colour scale applies to **a**–**d**.

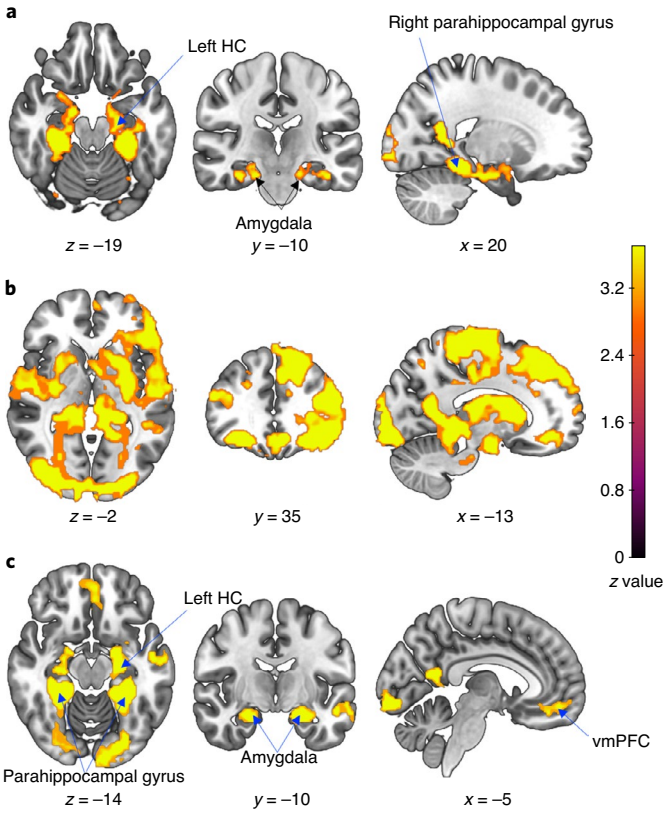

Fig. 4 | Brain imaging results for 'do more' trials. a, Regions that exhibited greater activation for the 'do more' cues in the 'do more minus do less' contrast included the bilateral hippocampi, parahippocampal gyri and amygdala. **b**, Whole-brain activation for parametric increases in feasibility for the 'do more' trials. **c**, Regions that exhibited greater activation for the parametric increase in the 'do more minus do less' contrast included the bilateral hippocampi, parahippocampal gyri, amygdala and vmPFC. All of the images were thresholded using FSL FLAME 1, with a height threshold of $z > 3.1$ and a cluster probability of $P < 0.05$, FWE-corrected for multiple comparisons across the whole brain.

our hypothesis and confirm that the core networks of brain areas associated with the future imagination of sustainable behaviours overlap with the brain systems that are involved in the episodic simulation of events that are likely to occur in the future[7].

Importantly, we further performed parametric contrasts to identify the brain regions that are most strongly activated when feasibility ratings are high. Our data show that the vmPFC was activated in the parametric contrast in which the feasibility of 'do more' minus 'do less' behaviours was compared. In other words, vmPFC activation was triggered during prospective thinking about highly feasible sustainable behaviours. These findings echo previous fMRI results showing that the vmPFC is strongly activated in situations in which new representations of past behavioural routines are being established[24].

Also consistent with our hypothesis, the parametric and the nonparametric 'do less minus do more' contrasts revealed that simulating the reduction of unsustainable behaviours triggered higher activation in the rdlPFC. Complementing this finding, PPI analyses results show that rdlPFC activity was negatively associated with activity within the left HC, which is a key brain structure for retrieval and episode-construction processes[11]. This pattern was observed using a whole-brain approach, which further confirms the specificity of these brain regions during tasks that tap into prospective thinking. This finding is consistent with previous fMRI studies on EFT that showed comparable patterns of (effective) connectivity between the rdlPFC and hippocampal and parahippocampal regions[9,21].

One interpretation of the present PPI results is that simulating the reduction of unsustainable behaviours decreased rdlPFC coupling (that is, a context specific modulation of effective connectivity[25]). Specifically, the rdlPFC is thought to downregulate brain regions that support memory storage and retrieval to inhibit access to episodic details, which would enable the creation of alternative prospective thinking[14–16,19–21]. Another interpretation is that the rdlPFC modulated responses of the left HC while simulating the reduction of unsustainable behaviours (that is, a modulation of stimulus-specific responses[25]). The use of effective connectivity analyses should help to further shed light on whether the negative coupling between dlPFC and HC involves the suppression of interfering memories of past behaviours. It would also be important to include a control condition that does not require participants to engage in future-oriented thinking (for example, perceptual discrimination of the object featured in the cue/picture). This would enable researchers to better identify the pattern of hippocampal activation that is associated with both the 'do more' and the 'do less' conditions, and whether these conditions engage the HC to different degrees.

A large spectrum of brain activation was observed across all of the contrasts computed. These patterns might reflect the complex nature of processes that are involved during the cue-exposure task. Moreover, each cue featured a picture and the name of a specific (un) sustainable behaviour. Participants might have therefore adhered to the instructions by engaging in different forms of prospection, including EFT (for example, by imagining themselves in a particular place at a specific time, bringing specific details to mind), but also semantic future thinking (SFT; that is, thinking about the future in a general, abstract manner[26]). For example, the 'do more minus do less' (parametric and nonparametric) contrasts encompass large clusters of activation within the middle temporal gyrus. This brain region is commonly activated during autobiographical and semantic memory tasks, and may support the processing of personal semantic and conceptual information[27].

The distinction between EFT and SFT is especially relevant as recent research has shown that engaging in EFT (about previously experienced climate change–related risk events) is associated with a higher level of risk perception and a greater tendency towards pro-environmental behaviour compared with engaging in SFT[28,29]. Furthermore, although each cue referred to common daily-life behaviours, the degree of familiarity with each behaviour (for example, no past experience versus extensive experience with a behaviour) probably affected the observed pattern of brain activations. Reflecting on behaviour feasibility should also differ when people consider themselves and others, with a bias towards picking behaviours that are convenient for themselves[30]. Future brain imaging studies should therefore compare the conditions of EFT and SFT to better understand individuals' construals of future sustainable behaviours (for example, by manipulating the level of vividness and concreteness of mental representations, and by controlling the degree of familiarity with each behaviour[28]).

Another central result of this study is that increasing sustainable behaviours was rated as more feasible than reducing unsustainable ones. This finding has practical and societal implications as it suggests that forming sustainable or 'good' habits might be more efficient[31,32] or less effortful[33,34] compared with reducing unsustainable or 'bad' ones. This pattern should be especially relevant for decreasing the time inconsistencies pertaining to pro-environmental conducts (that is, low short-term impact and high temporal discounting associated with negative consequences of climate change[35,36]). Previous research has shown that leveraging time perspectives foster pro-environmental conducts (for example, environmental

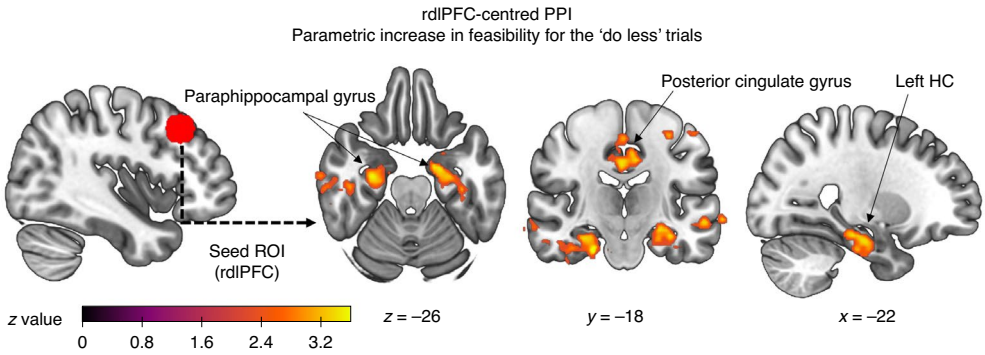

Fig. 5 | Significant PPI with the rdlPFC seed for the parametric contrast for feasibility ratings linked to 'do less' trials. The rdlPFC seed is a 10 mm sphere around peak = 39, 24, 39. These images were thresholded using FSL FLAME 1, with a height threshold of $z > 2.3$ (for display purpose) and a cluster probability of $P < 0.05$, FWE-corrected for multiple comparisons across the whole brain.

donations[37]). Our findings suggest that the way humans project themselves into future events should also be useful for increasing pro-environmental behaviours in the near future.

Moreover, when using average post-task rating scores for examining individual differences in the overall feasibility of 'do less' behaviours, we observed increased posterior insula activity for the 'do less minus do more' contrast. In other words, the higher the self-reported feasibility of 'do less' unsustainable behaviours, the higher the posterior insula activity when simulating the prospective reduction of unsustainable behaviours.

Related to this, previous research by Sawe and Knutson[38] showed that the insular cortex is specifically activated when individuals are considering to donate money to protect the environment from destructive use (for example, avoid mining around Yosemite and the Grand Canyon), as compared with considering to donate money to protect the environment from non-destructive use (for example, avoid the closure of California's state parks due to budget crises). Furthermore, insula activity predicted increased donations to preserve environments threatened by destructive use, and was positively associated with pro-environmental attitudes[38]. Together, these results further emphasize the important role of the insular cortex when reflecting on sustainable or pro-environmental behaviours in an inhibitory avoidance state of mind.

However, from this pattern alone, it is not possible to infer a specific role for the insular cortex regarding the actual change of sustainable or unsustainable behaviours (for example, insular activation at time 1 predicts behavioural engagement at time 2). Accordingly, an important limitation of this study is that we used feasibility judgements (during the cue-exposure task, and as the main outcome of post-task ratings). Future studies should therefore extend the present findings by asking participants to indicate which behaviours they think they will engage in during the days following the experiment, or by using ecological momentary assessment. Such an approach should offer a more fine-grained understanding of the association between brain cue reactivity, prospective judgement of feasibility and the future enactment of pro-environmental behaviours.

Here participants were recruited through advertisements for taking part in a study on pro-ecological behaviours. This may have led to a selection bias, which limits the generalizability of our findings. Indeed, prospective thinking is strongly influenced by an individual's personal goals and motives[27]. Personal goals facilitate access to related episodic details while structuring and organizing future thoughts[26,39,40], and shape the content of prospective simulations to increase the saliency of goal-relevant information[41]. In future studies, it will therefore be important to examine how brain activity is modulated by individual differences in pro-environmental values and goals[1,42] (see also refs. [43,44] for recommendations and debates on validated measures of pro-environmental behaviour).

Nevertheless, it has also been shown that the enactment of pro-environmental behaviours has a low follow-through rate, despite high environmental attitudes and climate change awareness (that is, a value-action gap[45]). This suggests that prospective thinking should not be seen as the sole product of the individual (that is, as an independent agent), but as an enactive cognitive process that emphasizes the role of the individual and his/her environment in co-constructing pro-environmental representations and related behaviour[46,47]. This enactive perspective is rooted in the concept of affordance, which refers to a potential action made available to an agent by his/her surrounding environment[48] (for a discussion on the brain mechanisms see ref. [49]). A more integrated approach is therefore needed to better grasp how the individual and the environment interact into forming prospective judgement towards pro-environmental behaviours.

In conclusion, here we identified brain activity patterns in response to different ways of framing prospective thinking of pro-environmental conducts, that is, either by reflecting on doing more sustainable behaviours or by reflecting on doing less unsustainable behaviours. These findings open new paths for a better understanding on how the human mind switches from mere feasibility judgements to actual and persistent (dis)engagement into (un) sustainable conducts.

Methods

Participants. Eighty-six adults participated in this study (51 males; mean age, 27.31 years, s.d. = 6.76, range = 19–48). All of the participants provided written informed consent to the experimental procedure, which was approved by the institutional review boards of Ghent University and the University of Luxembourg. All of the participants were right-handed and had normal or corrected-to-normal vision. Participants were advised to avoid drinking alcohol during the 24 h before participating in the scanning session. Participants received a fixed amount of €20 as compensation for participation.

The participants were recruited on the Internet through advertisements that were displayed on social media. The advertisements asked for adult individuals to participate in a neuroimaging study on pro-ecological behaviours. Interested individuals were then asked to complete an online survey. All of the participants were assessed as physically healthy on the basis of their answers on an MRI screening form, which was included in the online survey. The prescreening tool was also used to exclude any participant who reported having used mood stabilizers, antidepressants, antipsychotics, sleep medications, morphine, cocaine, heroin or cannabis during the past 12 months. The prescreening tool is available online (http://www.panlablimesurvey.ugent.be/PAN200/index.php/771876/lang-nl).

Experimental task and MRI procedure. We used a cue-exposure task (Fig. 1) in which pictures appeared on a screen (task length, ~11 min 50 s). There were two types of blocks: the 'do less' blocks (Fig. 1a) and the 'do more' blocks (Fig. 1b). Each trial of the 'do less' blocks showed the name and picture (with a red arrow

pointing down) of a behaviour that compromises sustainability. Each trial of the 'do more' blocks showed the name and picture (with a green arrow pointing up) of a behaviour that promotes sustainability. Each block consisted of six trials and started with a cue (3 s) that signalled the block type. Each cue appeared for 5 s and was separated by a jittered delay (blank screen; range = 1.8–3 s). Participants were asked to look attentively at each cue. When viewing each cue separately, participants were asked to look attentively at each picture and to reflect on the feasibility of the depicted behaviour in a future-oriented manner. Specifically, they were told to reflect on whether it would be feasible to further increase (for the 'do more' trials; for example, 'could I further increase my use of reusable cups in the near future') or further decrease (for the 'do less' trials; for example, 'could I further decrease my use of plastic bags in the near future') the adoption of the behaviour in the future. In cases in which participants had no past experience with the behaviour, they were asked to reflect on whether it would have been feasible to increase ('could I eat more vegetarian meals in the near future') or decrease ('could I decrease my consumption of meat in the near future') its adoption in the future.

Each block terminated with an overview slide (8 s), displaying the six behaviours presented during the block (Fig. 1). During this phase, participants orally reported the number of the behaviour (for example, 'one') that was the most feasible for them to implement (for the 'do more' block) or to decrease (for the 'do less' block) to protect the environment, that is, only one behaviour had to be selected in each block. Participants were informed that the overview slide was not to reflect on their choice, but to help them to remember their preference (that is, to decrease working memory updating during cue-exposure). The orally reported data were recorded manually by the experimenter and were not used for analyses (that is, there was no hypothesis regarding the specific type of behaviour that was chosen by the participants at the end of each block). Participants were informed that the task consisted of six 'do more' and six 'do less' blocks (36 trials in each condition, 72 trials in total), presented in an alternating order (5 s white screen between blocks). The cues that were used in the cue-exposure task are reported in Supplementary Table 1.

Directly after the scanning session, participants were asked to complete rating scales. For each behaviour of the 'do less' blocks, participants were asked to indicate how much it would be possible for them to reduce it to protect the environment (1 = not at all, 2 = very little, 3 = somewhat, 4 = to a great extent). For each behaviour of the 'do more' trials, participants were requested to indicate how feasible it would be for them to implement it.

Data acquisition. Cue presentation was implemented using Python v.2.7.16 and Pygame v.1.9.3 on an IBM-compatible PC. fMRI imaging was conducted using a 3T Siemens MAGNETOM Prisma scanner at the GIfMI Center, UZ Ghent, Ghent University. Functional scanning used a *z*-shim gradient echo EPI sequence with prospective acquisition correction (PACE). This sequence was designed to reduce signal loss in the prefrontal and orbitofrontal areas. The PACE option helps to reduce the impact of head motion during data acquisition. The parameters were as follows: TR = 1720 ms; TE = 27 ms; flip angle = 66°. Fifty-two 2.5 mm axial slices were used to cover the whole cerebral cortex and most of the cerebellum without gap. The slices were tilted approximately 30° clockwise along the AC–PC plane to improve the signal-to-noise ratio. A 176-slice MPRAGE structural sequence was also acquired (1 mm slice thickness; TI = 900 ms; TR = 2250 ms; TE = 4.18 ms; flip angle 9°). Before the EPI sequence, standard Siemens magnetic field maps were collected with the same slice prescription as the functional scans using a multi-echo gradient echo acquisition (effective EPI echo spacing = 0.52 ms, EPI TE = 27 ms, percentage signal loss threshold = 10). These field maps were used for correction of geometric distortions in the EPI data caused by magnetic field inhomogeneity.

Image preprocessing. Image preprocessing was performed using the fMRI Expert Analysis Tool (v.6.00, part of the FSL package, FMRIB software library, v.5.0.9; www.fmrib.ox.ac.uk/fsl). The first three sets of each participant's functional data were discarded to enable the MR signal to reach a steady state. Functional data for each participant were motion-corrected using rigid-body registration, implemented in the FMRIB Software Library's (FSL) linear registration tool, MCFLIRT[50]. All of the participants demonstrated less than 1.0 mm of either absolute or relative motion, so no participant was excluded from the analyses. After motion correction and temporal high-pass filtering, each time series for geometric distortions caused by magnetic field inhomogeneity was corrected using field maps[51,52]. Data were spatially smoothed using a 5 mm full-width-half-maximum Gaussian kernel. The data were filtered in the temporal domain using a nonlinear high pass filter with a 90 s cut-off (estimated using FSL's FMRI Export Analysis Tool, FEAT). A two-step registration procedure was used whereby EPI images were first coregistered to the MPRAGE structural image, and warped to standard (MNI) space using FLIRT[50,51]. Registration of the MPRAGE structural image to MNI standard space was then further refined using FNIRT nonlinear registration[52,53]. Statistical analyses were performed in the native image space, with the statistical maps normalized to the standard space before higher-level analysis.

Analyses of post-task ratings of feasibility. All analyses on post-task ratings were undertaken using SPSS Statistics v.26.0.0.1.

Brain imaging analyses. We compared blood-oxygen-level-dependent activity during the onset of 'do less' and 'do more' trials (5 s). To this aim, the brain imaging data were modelled using event-related general linear model (GLM) within FSL's Improved Linear Model module. First-level statistical analysis included the trial conditions ('do less' versus 'do more') as explanatory variables. The event onsets were convolved with a canonical haemodynamic response function (double-gamma) to generate regressors used in the GLM. For each participant, we computed the following contrasts: (1) 'do less minus do more' trials and (2) 'do more minus do less' trials. These were then included into a random-effects model for group analysis across participants. To examine the impact of individual differences on the average feasibility scores of 'do less' and 'do more' behaviours, mean-centred scores of post-task ratings (averaged across the 36 ratings in the 'do less' and the 'do more' condition) were entered as covariates at the second-level statistical analysis.

Another event-related whole-brain GLM was used to perform parametric contrasts on the basis of scores obtained from the post-task rating questionnaires (the feasibility level associated with each 'do less' and 'do more' behaviour). This GLM included the parametric regressors on the 'do more' and 'do less' trials. Specifically, 'do less' and 'do more' events were weighted according to the feasibility level (−3 = not at all, −1 = very little, 1 = somewhat, 3 = to a great extent). For each participant, we computed the following parametric contrast images: (1) feasibility ratings linked to 'do less' trials, (2) feasibility linked to 'do more' trials, (3) feasibility linked to 'do less' trials minus feasibility linked to 'do more' trials and (4) feasibility linked to 'do more' trials minus feasibility linked to 'do less' trials. These contrasts were then included into a random-effects model for group analysis across all of the participants ($n = 84$; two participants were excluded from these analyses due to non-completion of the post-task ratings). Notably, we did not observe any significant activation (with either $z > 3.1$ or $z > 2.3$) while running these parametric contrasts with reversed coded scores of feasibility (−3 = to a great extent, −1 = somewhat, 1 = very little, 3 = not at all).

PPI analyses were performed on the parametric contrasts with feasibility ratings linked to 'do less' trials. We created a rdlPFC seed regressor by computing individual average time series within a 10 mm sphere surrounding the rdlPFC ($x = 39$, $y = 24$, $z = 39$; Fig. 5). The location of the peak voxels was based on rdlPFC local maxima from the parametric contrast 'do less minus do more' trials. The rdlPFC seed mask was first transformed into individual space using FLIRT. Next, the time-course of each seed was extracted. For each participant, a first-level PPI model was set up using FSL including the following user-specified regressors: (1) the time course of the seed region; (2) the parametric regressor coding for the task contrasts and (3) the regressor coding interaction term, that is, the positive and negative multiplications of the time course and the task contrast. Single-participant contrast images for each of these regressors were created. Each participant's PPI contrast image for the interaction regressor was then entered into a second-level random-effects analysis to test for group effects.

All group analyses were performed using FSL FLAME 1, with a height threshold of $z > 3.1$ and a cluster probability of $P < 0.05$, FWE corrected for multiple comparisons across the whole brain.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The raw data are available at OpenNeuro (https://openneuro.org/datasets/ds002770). The unthresholded statistical maps are available at Neurovault (https://neurovault.org/collections/7266/).

Code availability

The experimental task code and stimuli are available at GitHub (https://github.com/dbrevers/sustainable_task).

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Author contributions

D.B., C.B., C.V. and J.B. designed the study and wrote the protocol. D.B. recruited the participants, collected the data and conducted the statistical analysis. C.B., P.M., G.S., C.V. and J.B. provided experimental support and revision suggestions. D.B. wrote the original draft of the manuscript. All of the authors made a substantial contribution to and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Data collection	The experimental task code and stimuli are available on github: https://github.com/dbrevers/sustainable_task
Data analysis	The analyses were carried out using the fMRI Expert Analysis Tool (version 6.00, part of the FSL package, FMRIB software library, version 5.0.9, www.fmrib.ox.ac.uk/fsl).

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Research sample	Eighty-six adults participated in this study (51 males, mean age 27.31 years, SD = 6.76, range: 19-48). All participants were right-handed and had normal or corrected-to-normal vision.
Sampling strategy	Participants were recruited via the Internet through advertisements displayed on social media. The ads asked for adult individuals to participate in a neuroimaging study on pro-ecological behaviors. Interested individuals were then asked to complete an online survey. All participants were assessed as physically healthy on the basis of their answers on an MRI screening form, included in the online survey. The pre-screening tool was also used to exclude any participant who reported having used mood stabilizers, antidepressants, antipsychotics, sleep medications, morphine, cocaine, heroin or cannabis in the past 12 months.
Data collection	We used a neuroimaging cue-exposure paradigm requesting participants to reflect on the feasibility of promoting sustainable behavior or reducing unsustainable behavior in their future. Cue presentation was implemented using Python 2.7.16 and Pygame 1.9.3 on an IBM compatible PC. fMRI imaging was conducted with a 3T Siemens MAGNETOM Prisma scanner at the GIfMI Center, UZ Ghent, Ghent University.
Timing and spatial scale	The data collection took place between August 2019 and February 2020.
Data exclusions	Two participants were excluded from the parametric analyses due to non-completion of the post-task ratings (n = 84).
Reproducibility	The Methods section contains all the relevant details for the study to be replicated by an external group.
Randomization	N.A. Within-group design.
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To examine the impact of individual differences in the average feasibility scores of "do less" and "do more" behaviors, mean-centered scores of post-task ratings (averaged across the 36 ratings in the "do less" and the "do more" condition) were entered as covariates at the second-level statistical analysis.

Recruitment: Participants were recruited via the Internet through advertisements displayed on social media. The ads asked for adult individuals to participate in a neuroimaging study on pro-ecological behaviors.

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Methodology

Sample preparation	*Describe the sample preparation, detailing the biological source of the cells and any tissue processing steps used.*
Instrument	*Identify the instrument used for data collection, specifying make and model number.*
Software	*Describe the software used to collect and analyze the flow cytometry data. For custom code that has been deposited into a community repository, provide accession details.*
Cell population abundance	*Describe the abundance of the relevant cell populations within post-sort fractions, providing details on the purity of the samples and how it was determined.*
Gating strategy	*Describe the gating strategy used for all relevant experiments, specifying the preliminary FSC/SSC gates of the starting cell population, indicating where boundaries between "positive" and "negative" staining cell populations are defined.*

☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type	event-related design
Design specifications	We used a cue-exposure task where pictures appeared on a screen (task length ≈ 11min 50sec). There were two types of blocks: the “do less” blocks and the “do more” blocks. Each trial of the “do less” blocks depicted the name and picture (with a red arrow pointing down) of a behavior compromising sustainability. Each trial of the “do more” blocks depicted the name and picture (with a green arrow pointing up) of a behavior promoting sustainability. Each block consisted of 6 trials and started with a cue (3sec) signaling the block type. Each cue appeared for 5sec and was separated by a jittered delay (blank screen, range: 1.8-3sec). Each block terminated with an overview slide (8sec), displaying the 6 behaviors presented during the block. The task consisted of 6 “do more” and 6 “do less” blocks (36 trials in each condition, 72 trials in total), presented in an alternating order (5sec white screen between blocks).
Behavioral performance measures	No motor response was recorded. Directly after the scanning session, participants were asked to complete rating scales. For each behavior of the “do less” blocks, participants were asked to indicate how much it would be possible for them to reduce it to protect the environment (1 = not at all, 2 = very little, 3 = somewhat, 4 = to a great extent).

Acquisition

Imaging type(s): functional

Field strength: 3T

Sequence & imaging parameters: The parameters were: TR = 1720ms; TE = 27ms; flip angle = 66°. Fifty-two 2.5mm axial slices were used to cover the whole cerebral cortex and most of the cerebellum without gap. The slices were tilted approximately 30 degrees clockwise along the AC-PC plane to improve the signal-to-noise ratio. A 176-slice MPRAGE structural sequence was also acquired (1mm slice thickness; TI = 900ms; TR = 2250ms; TE = 4.18ms; flip angle 9°). Prior to the EPI sequence, standard Siemens magnetic field maps were collected with the same slice prescription as the functional scans using a multi-echo gradient echo acquisition (Effective EPI echo spacing = 0.52ms, EPI TE = 27ms, % signal loss threshold = 10). These field maps were used for correction of geometric distortions in the EPI data caused by magnetic field inhomogeneity.

Area of acquisition: Whole brain

Diffusion MRI ☐ Used ☒ Not used

Preprocessing

Preprocessing software: Image pre-processing was carried out using the fMRI Expert Analysis Tool (version 6.00, part of the FSL package, FMRIB software library, version 5.0.9, www.fmrib.ox.ac.uk/fsl).

Normalization: A two-step registration procedure was used where EPI images were first co-registered to the MPRAGE structural image, and warped to standard (MNI) space, using FLIRT. Registration of MPRAGE structural image to MNI standard space was then further refined using FNIRT nonlinear registration.

Normalization template: MNI standard space

Noise and artifact removal: Functional data for each participant were motion-corrected using rigid-body registration, implemented in the FMRIB Software Library (FSL)'s linear registration tool, MCFLIRT. After motion correction and temporal high-pass filtering, each time series for geometric distortions caused by magnetic field inhomogeneity was corrected using field maps. Data were spatially smoothed using a 5-mm full-width-half-maximum (FWHM) Gaussian kernel. The data were filtered in the temporal domain using a non-linear high pass filter with a 90sec cut-off (estimated using FSL's FMRI Export Analysis Tool, FEAT).

Volume censoring: The first three sets of each participant's functional data were discarded to allow the MR signal to reach a steady state.All participants demonstrated less than 1.0mm of either absolute or relative motion, so no participant was excluded from the analyses.

Statistical modeling & inference

Model type and settings: Do less versus do more trials. We compared blood-oxygen-level-dependent (BOLD) activity during the onset of "do less" and "do more" trials (5ec). To this aim, the brain imaging data were modelled using event-related general linear model (GLM) within FSL's Improved Linear Model (FILM) module. First-level statistical analysis included the trial conditions (do less vs. do more) as explanatory variables (EV). The event onsets were convolved with canonical hemodynamic response function (HRF; double-gamma) to generate regressors used in the GLM. For each participant, we computed the following contrasts: (i) do less trials minus do more trials, and (ii) do more trials minus do less trials. These were then included into a random-effect model for group analysis across participants. To examine the impact of individual differences in the average feasibility scores of "do less" and "do more" behaviors, mean-centered scores of post-task ratings (averaged across the 36 ratings in the "do less" and the "do more" condition) were entered as covariates at the second-level statistical analysis.

Brain activation related to parametric increases of behavior's feasibility. Separate event-related whole-brain GLM analyses were used to perform parametric contrasts based on scores obtained from the post-task rating questionnaires (the feasibility level associated with each do less and do more behaviors). Specifically, "do less" and "do more" events were weighted according to the feasibility level (-3 = not at all, -1 = very little, 1 = somewhat, 3 = to a great extent). For each participant, we computed the following parametric contrast images: (i) feasibility ratings linked to "do less" trials, (ii) feasibility linked to "do more" trials, (iii) feasibility linked to "do less" trials minus feasibility linked to "do more" trials, and (iv) feasibility linked to "do more" trials minus feasibility linked to "do less" trials. These contrasts were then included into a random-effect model for group analysis across all participants (N = 84; two participants were excluded from these analyses due to non-completion of the post-task ratings).

Effect(s) tested:
"Do less" vs. "do more" events
Parametric increase of feasibility: "do more" events
Parametric increase of feasibility: "do less" events
Parametric increase of feasibility: "do more" vs. "do less"events

Specify type of analysis: ☒ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference (See Eklund et al. 2016): All group analyses were performed using FSL FLAME 1, with a height threshold of $z > 3.1$ and a cluster probability of $p < .05$, family-wise error (FWE) corrected for multiple comparisons across the whole brain.

Correction: FWE

Models & analysis

n/a	Involved in the study
☐	☒ Functional and/or effective connectivity
☐	☐ Graph analysis
☐	☐ Multivariate modeling or predictive analysis

Functional and/or effective connectivity

rDLPFC-centered functional connectivity analyses. Psychophysiological interaction (PPI) analyses were performed on the parametric contrasts with feasibility ratings linked to “do less” trials. We created a rdlPFC seed regressor by computing individual average time series within a 10-mm sphere surrounding the rdlPFC (x = 39, y = 24, z = 39). The location of the peak voxels was based on rdlPFC local maxima from the parametric contrast “do less” minus “do more” trials. The rdlPFC seed mask was first transformed into individual space using FLIRT. Next, the time-course of each seed was extracted. For each subject, a first-level PPI model was set up using FSL including the following user-specified regressors: (1) the time course of the seed region; (2) the parametric regressor coding for the task contrasts and (3) the regressor coding interaction term, i.e. the positive and negative multiplications of time course and the task contrast. Single-subject contrast images for each of these regressors were created. Each subject’s PPI contrast image for the interaction regressor was then entered into a second-level random-effect analysis to test for group effects using FSL FLAME 1, with a height threshold of $z > 3.1$ and a cluster probability of $p < .05$, family-wise error (FWE) corrected for multiple comparisons across the whole brain.

Graph analysis

Report the dependent variable and connectivity measure, specifying weighted graph or binarized graph, subject- or group-level, and the global and/or node summaries used (e.g. clustering coefficient, efficiency, etc.).

Multivariate modeling and predictive analysis

Specify independent variables, features extraction and dimension reduction, model, training and evaluation metrics.