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Neural differences between internal and external episodic counterfactual thoughts

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Episodic counterfactual thoughts (eCFT) consist of imagining alternative outcomes to past experiences. A common sub-class of eCFT—*upward* eCFT—involves imagining how past negative experiences could have been *better*, either because one could have done something differently (internal) or because something about the circumstances could have been different (external). Although previous neuroimaging research has shown that the brain's default mode network (DMN) supports upward eCFT, it is unclear how it is differentially recruited during internal versus external upward eCFT. We collected functional magnetic resonance imaging data while participants remembered negative autobiographical memories, generated either internal or external upward eCFT for the memory, and then rated the plausibility, perceived control and difficulty of eCFT generation. Both internal and external eCFT engaged midline regions of cingulate cortex, a central node of the DMN. Most activity differentiating eCFT, however, occurred outside the DMN. External eCFT engaged cuneus, angular gyrus and precuneus, whereas internal eCFT engaged posterior cingulate and precentral gyrus. Angular gyrus and precuneus were additionally sensitive to perceived plausibility of external eCFT, while postcentral gyrus and insula activity scaled with perceived plausibility of internal eCFT. These results highlight the key brain regions that might be involved in cases of maladaptive mental simulations.

This article is part of the theme issue 'Thinking about possibilities: mechanisms, ontogeny, functions and phylogeny'.

1. Introduction

When we recall autobiographical memories, we do not always replay past experiences the way they happened. Sometimes, we modify the remembered contents by, for instance, imagining alternative ways in which the past event could have unfolded. We may imagine having answered an important phone call we actually missed, or maybe having said something we actually never did. In the last decade, cognitive neuroscientists have explored the neural basis of these *episodic counterfactual thoughts* (eCFT; [1]) and have found that they share a common neural basis with both *episodic memory* and *episodic future thoughts* [2]. In a pioneer study revealing overlap in neural activity during episodic memory retrieval, episodic future thoughts, and eCFT, participants were shown different components from their own autobiographical memories [3]. When the components belonged to the same memory, participants were asked to remember the event as it had happened. However, if the components belonged to different memories, they were asked instead to either imagine them in a novel possible future event (i.e. episodic future thought) or in a novel possible past situation (i.e. eCFT). All three kinds of mental simulations recruited core regions of the brain's default mode network

(DMN), a well-documented set of functionally connected brain regions typically associated with off-line mental activity [4]. In particular, these three kinds of episodic simulation were shown to recruit the medial prefrontal cortex, anterior cingulate cortex, lateral and medial temporal lobes (including hippocampus), inferior parietal lobule, and caudate. Indeed, this initial observation was further corroborated by a series of subsequent neuroimaging studies directly asking participants to engage in eCFT [5,6].

Neuropsychological evidence also indicates that eCFT is supported by core regions of the DMN. For instance, individuals with schizophrenia present impairments in episodic memory and future thinking that are associated with volumetric reductions in the hippocampus, and also exhibit difficulties with eCFT [7]. Relatedly, patients with amnesia owing to hippocampal damage experience difficulties in generating and maintaining spatially based eCFT [8]. Recent work indicates that patients in relapsing–remitting stages of multiple sclerosis also have difficulties with eCFT associated with lack of white matter integrity in neural tracks underlying the DMN, particularly in the hippocampal portion of the cingulum and the inferior longitudinal fasciculus [9]. Finally, patients with damage to the ventromedial prefrontal cortex—also a core region of the DMN critical for episodic memory and episodic future thinking—have difficulties generating spontaneous eCFT [10] and exhibit poor performance in certain tasks requiring the voluntary generation of eCFT [11]. Taken together, then, extant neural evidence from neuroimaging and neuropsychological work indicates that core regions of the DMN support the generation of eCFT.

However, not all eCFT are created equal. When imagining alternative ways in which past personal events could have occurred, we may modify their outcomes in different ways. We may engage, for instance, in *upward* eCFT, and imagine how an event could have turned out *better*, which has been shown to elicit feelings of regret and disappointment [12]. By contrast, we may engage in *downward* eCFT, and imagine instead how the past event could have been *worse*, which in turn elicits feelings of relief and contentment [13]. Furthermore, the modification of retrieved autobiographical memories during eCFT can involve the addition or subtraction of details [14] as well as the manipulation of the perceived plausibility of the imagined scenario [15,16]. Moreover, counterfactual thoughts can vary depending on the degree to which they involve semantic—as opposed to episodic—information, as when we mentally modify factual knowledge rather than past personal episodes (e.g. 'What if New York was the capital of the US') [1,17].

In recent years, these and similar variations on counterfactual simulations have been explored using diverse neuroimaging techniques to clarify how different DMN regions contribute to each type of hypothetical thought. Generally, simulating eCFT preferentially recruits dorsomedial prefrontal, lateral prefrontal and cerebellar regions to a greater extent than episodic future thinking and visual perspective shift [5,18]. However, the engagement of the DMN during eCFT varies based on whether the eCFT is upward [5] or downward [6], and whether its possible occurrence is perceived as more or less plausible [16,19]. Thus, inferior and middle portions of the frontal gyrus are recruited more as *upward* eCFT are perceived to be more plausible, while temporal regions—including hippocampus and parahippocampal gyrus—are recruited more as *downward*

eCFTs are perceived to be more plausible. A subsequent study showed that the DMN was preferentially involved in the construction of person-based (as opposed to object-based) eCFT, which tended to recruit more lateral regions of the temporal lobes, probably owing to their increased reliance on semantic memory [2]. A further study directly manipulating episodic versus semantic counterfactuals corroborated the preferential recruitment of the DMN during eCFT, as well as the parametric modulation of hippocampal activity as a function of perceived plausibility [19]. Interestingly, the degree of hippocampal activation during eCFT seems also to depend on whether the eCFT has been previously thought of. More precisely, the hippocampus tends to be recruited for the initial construction of an episodic counterfactual simulation, whereas eCFT that are frequently ruminated upon tend to recruit more frontal regions, including the middle frontal gyrus and the anterior cingulate cortex as well as the insula [20]. In summary, extant neuroimaging evidence suggests that distinct regions within the DMN are differentially recruited as a function of the kind of counterfactual simulation individuals engage in.

Despite the increase in research in the past decade, there remains an important distinction that has yet to be explored in the cognitive neuroscience of mental simulations of alternative possibilities, namely that between *internal* versus *external* eCFT. Consider a situation in which something undesirable happens to you, such as getting so badly sunburnt on your last day of vacation that you needed to cancel your plans for that evening. Thinking back, you may consider having done something different: 'If only I had applied sunscreen before going to the beach!'. Alternatively, you could imagine that something about the situation itself had been different to prevent the negative outcome from happening: 'If only it had been cloudier that morning!'. This difference in counterfactual thought reflects a well-known distinction in social psychology between internal and external loci of action initiation. Individuals, according to a pioneer proposal, feel the result of an action as depending 'on two sets of conditions, namely, factors within the person and factors within the environment' [21, p. 551]. Actions initiated by or within oneself are known as *internal*, while those that are brought about by changes in the environment are considered *external* [22–24].

Earlier work on counterfactual thinking suggested that people were more likely to mutate internal aspects of an event, insofar as they were perceived to be controllable [25]. However, subsequent work found that when it came to eCFT, this tendency varied. For instance, when people generate eCFT of past events that were self-initiated they tend to focus on internal and more controllable factors relative to when they generate eCFT of past events that were initiated by others, in which case they focus more on external and less controllable ones [26]. Additionally, depressed individuals are more likely to modify internal aspects of past decisions relative to non-depressed individuals, who tend to report more eCFT involving external changes [27,28]. More recently, Girotto *et al.* [29] showed that the tendency to mentally mutate internal aspects of past decisions may have been an artefact of past experimental designs, as most research on counterfactual thinking involved reading vignettes depicting fictional characters making choices. However, when individuals made choices for themselves, their post-decisional eCFT were much more likely to modify external rather than internal aspects of the choice. Given the importance of perceived control in eCFT,

and its impact of behaviour modification, it is important to understand the cognitive mechanisms underlying the difference between internal versus external loci of action initiation in the mental simulation of alternative possibilities.

The current study seeks to contribute to this goal by exploring neural differences between internal and external modifications in eCFT. In an initial session, participants reported negative autobiographical memories of past personal events. A week later, while undergoing functional magnetic resonance imaging (fMRI), participants recalled these memories, generated either external or internal upward eCFT and provided ratings of plausibility, difficulty, and perceived control over the counterfactual outcome. Behaviourally, we hypothesized that internal eCFT would be perceived as more controllable, more plausible, and easier to simulate relative to external eCFT. Neurally, we expected to observe recruitment of DMN regions during both kinds of eCFT as well as dissociations based on whether participants see themselves as having been able to bring about an alternative outcome as opposed to an external factor of the remembered external context. To thoroughly investigate potential differences in brain activity during each kind of eCFT, we used both univariate and multivariate analyses of the neuroimaging data.

2. Methods

(a) Participants

Thirty-two individuals (10 male, 22 female; $M_{age} = 21.47$; s.d. = 2.97 years) participated in both sessions of this study. Four additional participants were recruited but not included in the analyses because they only completed the first session. The sample size was chosen on the basis of previous studies investigating differences in eCFT [2,6,20]. Participants were recruited via digital and physical flyers posted on a Duke University website and around campus. All participants were right-handed, had no history of psychiatric or neurological illness, and were native English speakers. Written, informed consent was obtained prior to any data collection. Participants were compensated and debriefed about the purpose of the study upon completion. All experimental procedures were approved by the Duke University Health System Institutional Review Board.

(b) Pre-scan stimulus collection session

One week prior to the experimental session, participants generated 80 negative autobiographical memories to be used as stimuli in the scanner. To ensure that the memories were amenable to targeted and specific eCFT generation, participants were instructed to list negative life events that occurred in a particular place within a 24 h period. Examples were provided to assist recollection (electronic supplementary material, table S13). For each memory, participants provided a 1–3 word title, a description of the episode, a rating of the amount of detail in the memory (1-no detail to 7-highly detailed), a rating of the vividness of the memory (1-low vivid to 7-high vivid), a rating of how much they regret the event (1-no regret to 7-high regret) and a rating of how much control they felt they had over the outcome (1-no control to 7-full control). Two experimenters read each memory and independently issued a rating (on a scale of 1–7) of whether concrete counterfactual alternatives to the memory could be generated in the experimental session. Initial ratings were titrated via discussion between the raters until Cronbach's alpha between their ratings passed 0.75. The 64 memories presented in the scanner were those for which experimenter ratings were highest and participant-reported valence was lowest.

(c) Experimental session

The experimental session consisted of an fMRI scan and a post-scan questionnaire. In the scanner, participants were presented with an event title and spent 6 s remembering the episode referenced by the title. Immediately after, the word 'SELF' (for internal eCFT) or 'CONTEXT' (for external eCFT) appeared on the screen for 8 s, which cued participants to imagine an alternative outcome to the memory brought about either by their own actions (in the internal condition) or by circumstantial changes (in the external condition; figure 1). For example, if the cue was 'Sunburn' + 'SELF', a participant might imagine reapplying sunscreen and returning from the beach with a nice tan instead of a nasty sunburn. If the cue was 'Sunburn' + 'CONTEXT', however, they might imagine clouds obscuring the sun while at the beach, effectively preventing the sunburn from ever happening. Participants were instructed to maintain and/or elaborate upon the chosen eCFT for the entirety of the time the title and cue remained on screen. Each eCFT generation period was immediately followed by a set of three ratings about the eCFT. Participants used a magnetic resonance (MR)-compatible 4-button box to rate: (i) the plausibility of the counterfactual (1-totally implausible to 4-totally plausible), (ii) perceived control over the counterfactual outcome (1-no control to 4-full control), and (iii) the difficulty of generating the counterfactual (1-very difficult to 4-very easy). Each rating lasted 4 s, and the order of ratings was randomized on each trial. Trials were separated by a left–right arrow discrimination task jittered around 4 s. Each run contained 16 trials, eight in each condition, with a total of four runs in the experiment. The order of conditions was pseudorandomized within a run such that no more than two trials in the same condition appeared consecutively.

To ensure that participants understood the parameters constraining their eCFT and were comfortable with performing the task, three of the remaining negative memories from session 1 were used for pre-scan practice. Participants completed a full trial of the task, using a computer keyboard to respond instead of the button box. At the end of the trial, participants described the memory they recalled and the eCFT they generated. The experimenter corroborated the memory from their stimulus list, provided feedback on the eCFT they described, and asked them to generate an eCFT for the same memory in the alternative condition (to drive home the distinction between the types of eCFT to be generated in each condition). This process was repeated until participants successfully and consecutively generated three eCFT in each condition.

After scanning, participants completed a post-scan questionnaire. The questionnaire consisted of the event titles and their counterfactual cues presented in the same order as in the scanner. For each combination of cues, participants were asked to detail the content of their counterfactual and provide a rating of how frequently they had imagined that specific eCFT before (1-never imagined to 7-imagined very frequently). Upon completing the post-scan questionnaire, participants were debriefed about the experiment and compensated for their time.

(d) Functional magnetic resonance imaging data acquisition and preprocessing

Scans were acquired on a 3.0 T GE MR750 scanner in the Duke Brain Imaging and Analysis Center. The session started with a localizer and a T1-weighted structural scan (162 1 mm slices, repetition time (TR) = 8.16 ms, echo time (TE) = 3.18 ms). We then collected four runs of functional scans comprising the task. We used a whole-brain, T_2^* echo-planar imaging sequence (TR = 2 s, TE = 27 ms, field of view = 240 mm, matrix size = 64 × 64, flip angle = 77°). Slices were acquired in an interleaved fashion (41 × 3.75 mm slices; 0.5 mm skip) parallel to the anterior commissure/posterior commissure plane as identified by the structural scan. Inside the coil, participants' heads were held in place with

session 1 (on zoom): recall 80 negative autobiographical memories
- generate memory titles to serve as cues in session 2
- provide ratings of detail, vividness, regret and perceived control

session 2 (approx. one week later, in scanner): recall negative memories and imagine a *better* outcome based either on self- or context-based factors
- provide ratings about the eCFT (difficulty of generation, plausibility, control)
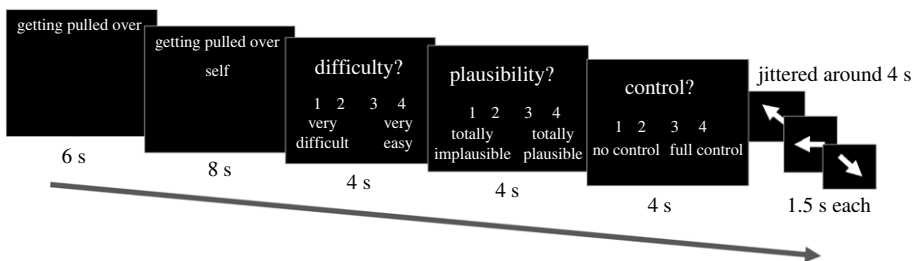- after scanning, provide description of each eCFT and a frequency rating

Figure 1. Task design. In the experimental session, participants had 6 s to recollect a negative autobiographical memory. Then they were cued to generate an internal or external upward eCFT by the words 'SELF' and 'CONTEXT', respectively. Participants had 8 s to generate and imagine an eCFT, and then made three different subjective ratings (presented in random order) about the eCFT. They had 4 s to make each subjective rating (difficulty, perceived plausibility, perceived control). Trials were separated by an active fixation period of judging arrows to be pointing leftwards (index finger) or rightwards (middle finger).

cushions to restrict motion. The task was projected into the scanner and viewed via a mirror above the head coil. Stimuli were presented as white text on a black background using PSYCHTOOLBOX3 [30], which was also used to collect responses. Participants made behavioural responses using an MR-compatible 4-button box placed on the right side of their body inside the scanner bore.

Functional data preprocessing was performed using fMRIPREP [31,32]. In brief, preprocessing consisted of slice-time correction, spatial smoothing with a 6 mm full-width half-maximum Gaussian kernel, and automatic removal of motion artefacts with independent components analysis. Each subject's functional volumes were co-registered to their high-resolution T1 anatomical scan and normalized to FMRIB Software Library's (FSL's) MNI152Lin6Asym. Prior to analysis, the non-aggressively AROMA denoised outputs from fMRIPREP were skull-stripped using FSL's brain extraction tool and high-pass filtered at 100 s (see the electronic supplementary material for further details of preprocessing conducted via fMRIPREP).

(e) Statistical analyses
(i) Behavioural analysis
Behavioural data were analysed in R (v.4.1.1; [33]). All linear mixed-effects models had random slopes for condition and random intercepts for participant. Models were fit with the *lme4* package (v.1.1–27.1; [34]) and estimates were extracted using the *emmeans* package (v.1.7.0; [35]). *p*-values and 95% confidence intervals were estimated using the Satterthwaite method. Plots for behavioural and partial least squares (PLS) results were made with the *ggplot2* package (v.3.3.5; [36]).

(ii) Mean-centred partial least squares analysis
All neuroimaging analyses used the final preprocessed data that was AROMA denoised through fMRIPREP, skull-stripped and temporally filtered. The mean-centred PLS analysis was conducted using the PLS Toolbox (http://www.rotman-baycrest.on.ca/) in MATLAB (2021b). The brain region threshold was set to 0.15 and the data were normalized to the first scan of the eCFT period. The mean-centred analysis was conducted on a 5TR (10 s) temporal window beginning at the onset of the eCFT cue. Confidence intervals were computed via 250 rounds of bootstrap resampling, and *p*-values were computed using 1000 permutations

of the data. Salience maps were constructed using a bootstrap ratio (BSR) value greater than ±3.2 (approximate $p = 0.0014$), and clusters are reported if they contain at least 15 voxels.

(iii) Univariate analyses
Univariate general linear model (GLM) analyses were performed using FSL's FEAT [37]. First-level GLMs were created for each subject and for each run, based on task regressors and temporal derivatives that modelled both experimental conditions (internal and external eCFT), as well as the onset and durations for initial memory recall, plausibility ratings, difficulty ratings and control ratings. Button presses that occurred during memory recall (when participants had remembered the event) were also modelled to account for motor-related activity. First-level GLMs included confound regressor timeseries for cerebrospinal fluid, white matter, motion parameters (DVARS) and framewise displacement (FD). Timepoints with FD above 0.5 mm or standardized DVARS above 1.5 were censored in the model. The regressors were convolved with a double-gamma hemodynamic response function. For the parametric modulation analysis, additional regressors were added for the external and internal conditions where the intensity value was modulated by mean-centred plausibility ratings (centred within each condition and run). Functional runs were combined within-subject at second-level analyses using fixed effects. The resulting maps were then used as input to third-level group analyses, which used FMRIB's local analysis of mixed effects (FLAME 1 + 2). A single-group average (one-sample *t*-test) design was used to evaluate the average response for each contrast originally defined at the lower level, while a single-group paired difference (paired *t*-test) was used for double subtractions. Group results were assessed at a cluster-forming threshold of $z = 2.3$ and a cluster significance threshold of $p = 0.05$. When combined with FLAME 1 + 2, these thresholds provide an effective control against inflated false positive findings in fMRI studies [38].

3. Results
(a) Behavioural results: autobiographical memory and episodic counterfactual thoughts characteristics
Three separate linear mixed-effects models were fitted to quantify the effect of condition (internal versus external) on
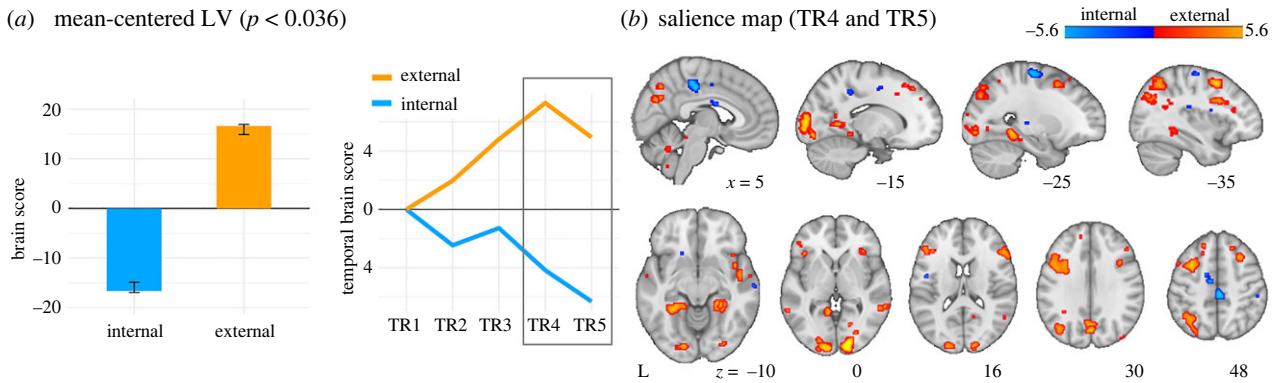
(a) mean-centered LV (p < 0.036)

(b) salience map (TR4 and TR5)

Figure 2. Mean-centred PLS results. (a) Brain scores for the mean-centred latent variable (LV) differentiating activity related to internal and external eCFT. (b) Salience maps for the LV, extracted at the TRs of maximal differentiation between conditions (TR4 and TR5; see (a)). Clusters associated with external eCFT (plotted in orange) were found bilaterally in the parahippocampal gyrus, cuneus, middle frontal gyrus and middle temporal gyrus. Clusters associated with internal eCFT (plotted in blue) were found in the left cingulate, right paracentral lobule and left precentral gyrus.

the subjective assessments of an eCFT. Internal eCFT were judged as easier to generate ($M_{ease} = 2.96$, s.d. $= 1.01$, $\beta = 0.16$, $p = 0.04$), more plausible ($M_{plausibility} = 2.99$, s.d. $= 0.97$, $\beta = 0.52$, $p < 0.001$) and more controllable ($M_{control} = 3.11$, s.d. $= 1.01$, $\beta = 1.36$, $p < 0.001$) relative to external eCFTs ($M_{ease} = 2.79$, s.d. $= 1.00$; $M_{plausibility} = 2.47$, s.d. $= 1.04$; $M_{control} = 1.75$, s.d. $= 0.91$). Also, as reported in the post-scan interview, internal eCFT were also more frequently generated prior to scanning ($M_{frequency} = 3.06$, s.d. $= 1.93$) relative to external eCFT ($M_{frequency} = 2.63$, s.d. $= 1.83$, $\beta = 0.42$, $p = 0.001$). Model summaries, visualizations and summary statistics are provided in the electronic supplementary material, which also contain summary statistics about the phenomenological characteristics of autobiographical memories generated during the pre-scan stimulus collection session.

(b) Functional magnetic resonance imaging results: mean-centred partial least squares

The mean-centred PLS analysis identified a significant ($p < 0.036$) latent variable that differentiated neural activity related to internal versus external eCFT (figure 2a). During the TRs of maximal differentiation between conditions (TR4 and TR5), external eCFT engaged more regions in the DMN than internal eCFT. Within the DMN, external eCFT recruited bilateral clusters in the parahippocampal gyrus, middle frontal gyrus, inferior parietal lobule, middle temporal gyrus, precuneus and cingulate. Additionally, external eCFT recruited a large swath of posterior visual cortex (cuneus), a critical area involved in the construction of episodic simulations [39]. Within the DMN, internal eCFT also recruited the cingulate and middle frontal gyrus. Internal eCFT additionally were associated with activity in right paracentral lobule and left precentral gyrus (figure 2b; table 1).

(c) Functional magnetic resonance imaging results: univariate analysis

A univariate analysis of whole-brain activity during counterfactual thinking corroborated results from the PLS analysis (figure 3a). A simple contrast between conditions revealed large clusters of activation that were greater in magnitude for external than internal eCFT; most notably the cuneus, frontal pole, superior frontal gyrus, frontal orbital cortex

and anterior cerebellum, all regions that have been identified as part of the DMN [4]. Internal eCFT preferentially engaged smaller clusters of activity in right posterior cingulate and left precentral gyri, replicating findings from the PLS analysis that implicated these non-DMN regions in the generation of internal eCFT. To delineate more specific differences between conditions, we then conducted a double subtraction analysis which first contrasted activity during each eCFT period to standard memory retrieval (averaged across the 6 s retrieval windows before counterfactual manipulation). This analysis allowed us to specifically compare neural activity related to counterfactual thinking above and beyond the effects of naturally recalling a memory. Consistent with the PLS results indicating greater DMN recruitment by external eCFT, clusters associated with external eCFT in the bilateral cuneus, left angular gyrus and left precuneus were returned by this analysis, but no clusters associated with internal eCFT survived the double subtraction (table 2). Finally, although our driving question pertained to differences in neural activation between internal and external eCFT, we also sought to identify regions that were commonly engaged by these two kinds of eCFT relative to a baseline of episodic recollection. For both conditions, greater activation was observed in large clusters encompassing the left superior frontal gyrus (extending into left middle/inferior frontal gyri and left caudate), left angular gyrus (extending into left middle temporal gyrus) and left cerebellum (crus I/II). Only the external eCFT condition also elicited greater activation in right superior/middle frontal gyri and left occipital pole, when compared to natural recall. See the electronic supplementary material, figure S12 and table S13 for visualizations and a cluster report.

(d) Functional magnetic resonance imaging results: parametric modulation by perceived plausibility

To evaluate the role of perceived plausibility in shaping the neural activity underlying external and internal eCFT, we next investigated whether activation associated with each condition was parametrically modulated by online ratings of perceived plausibility. This analysis revealed that the perceived plausibility of external eCFT parametrically modulated activation in the angular gyrus (bilateral) and precuneus (right), both key nodes in the DMN. Voxels in right superior frontal gyrus

Table 1. Cluster report for TR4. Clusters are reported if they pass the BSR threshold of ∓ 3.2, have a minimum cluster size of 15 voxels, and are separated by at least 10 mm. (BA, Brodmann area; hemi, hemisphere; BSR, boostrap ratio; asterisk indicates that this cluster does not have a corresponding Brodmann area; superscript C indicates a cluster in the cerebellum.)

| TR	region	BA	hemi	X	Y	Z	BSR	cluster size
positive saliences associated with external eCFT								
4	parahippocampal gyrus	36	R	24	−38	−10	6.4335	152
4		37	L	−30	−44	−8	5.317	192
4	cuneus	17	R	18	−92	0	6.3181	410
4		18	L	−14	−96	10	6.2541	515
4		7	L	0	−68	30	4.2704	194
4	middle frontal gyrus	6	L	−34	8	50	6.031	224
4		46	R	52	34	22	5.4518	227
4		9	L	−48	10	34	5.3802	591
4		6	R	32	18	52	4.8831	149
4		9	R	38	14	32	4.0575	37
4		8	R	24	14	42	3.4802	17
4		47	L	−44	34	−2	3.9368	18
4	inferior parietal lobule	7	L	−32	−58	46	4.4138	515
4	middle temporal gyrus	21	L	−60	−50	−4	4.2897	56
4		39	L	−48	−58	24	4.2112	74
4		37	R	58	−46	0	4.1294	42
4		21	R	58	−4	−18	3.8524	17
4	anterior insula	47	R	34	24	−4	4.2242	70
4	superior temporal gyrus	38	R	46	8	−16	4.2194	37
4		38	R	50	−4	−10	4.031	52
4	precentral gyrus	6	R	34	4	24	4.1424	18
4	inferior frontal gyrus	47	R	40	16	−12	3.9851	24
4	nodule^C	*	R	4	−58	−30	3.9666	15
4	lingual gyrus	18	L	−18	−52	4	3.884	48
4	cingulate gyrus	31	R	16	−54	24	3.8262	40
4	superior parietal lobule	7	R	42	−54	56	3.4974	19
4	superior frontal gyrus	6	L	−18	26	50	3.4644	19
5	lingual gyrus	17	R	16	−88	−4	6.4925	347
5		18	L	−12	−98	−4	5.8754	272
5		19	L	−12	−54	2	4.0759	68
5		18	L	−16	−86	−10	4.0418	33
5	inferior semilunar lobule^C	*	R	12	−80	−38	4.8179	34
5	precuneus	19	L	−32	−76	36	4.5428	46
5	cuneus	7	R	2	−72	30	4.4522	63
5	parahippocampal gyrus	30	R	16	−46	6	4.3618	106
5	middle frontal gyrus	46	L	−40	28	18	4.0329	55
5	middle temporal gyrus	39	L	−40	−66	28	3.8906	58
5		37	L	−58	−50	−6	3.5497	17
5	inferior temporal gyrus	21	R	60	−6	−14	3.81	21
5	fusiform gyrus	37	R	26	−40	−12	3.7107	42
negative saliences associated with internal eCFT								
5	cingulate gyrus	31	L	−10	−10	46	−4.6048	32
5	paracentral lobule	5	R	4	−28	48	−4.4552	118
5	precentral gyrus	6	L	−26	−18	62	−4.196	91
5	middle frontal gyrus	6	R	28	−12	62	−3.491	17
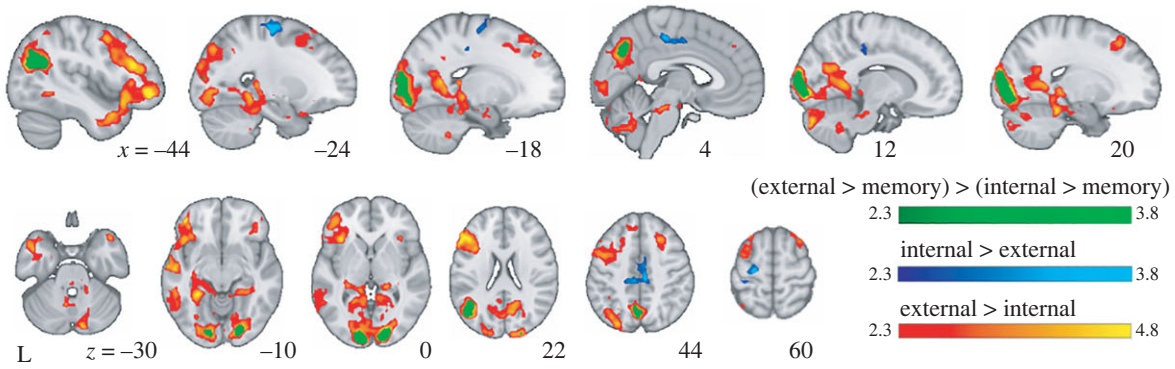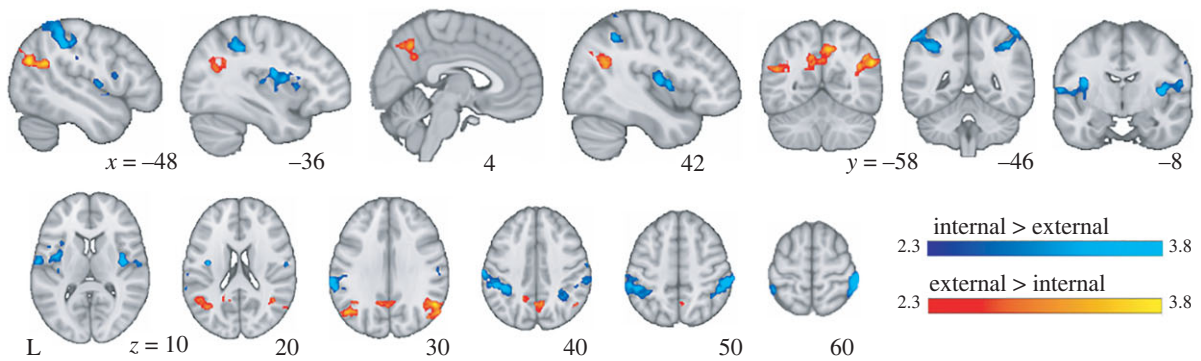
Figure 3. Whole-brain univariate analyses. Statistical maps representing the group result after mixed effects analysis ($z > 2.3$, cluster-corrected $p < 0.05$). (a) Results from whole-brain univariate contrasts assessing activation differences between the eCFT conditions. Contrasted against internal eCFT, external eCFT (represented by warm colours) engaged the cuneus, frontal pole, superior frontal gyrus, frontal orbital cortex and anterior cerebellum. When contrasted against external eCFTs, internal eCFTs (represented by cool colours) engaged the posterior cingulate and precentral gyrus. Green clusters represent results from the double subtraction, where each eCFT condition was first contrasted with memory retrieval before being contrasted with respect to task conditions. No clusters associated with internal eCFTs were returned by this analysis. Clusters associated with external eCFT were found in the cuneus, precuneus and angular gyrus. (b) Results from whole-brain univariate contrasts including the perceived plausibility of the eCFT as a parametric modulator. Perceived plausibility modulated internal eCFT engagement (represented by cool colours) of the insula and supramarginal gyrus, as well as external eCFT engagement (represented by warm colours) of the precuneus and angular gyrus.

Table 2. Cluster report of max z-statistics for the primary univariate contrasts of interest. (BA, Brodmann's area (retrieved from https://bioimagesuiteweb.github.io/webapp/mni2tal.html); hemi, hemisphere.)

region	BA	hemi	X	Y	Z	z-score	cluster size
external > internal							
cuneus/occipital pole	18	R	16	−88	−4	6.84	18 039
frontal pole	10	L	−44	44	−8	5.22	7891
superior frontal gyrus	8	R	22	30	50	4.16	838
frontal orbital cortex	47	R	30	26	−22	4.07	632
anterior cerebellum		L	−8	−58	−30	3.59	601
internal > external							
posterior cingulate	31	R	2	−26	48	3.69	484
precentral gyrus		L	−24	−18	62	4.01	435
(external > memory) > (internal > memory)							
cuneus/occipital pole	18	R	18	−88	−4	4.86	848
cuneus/occipital pole	18	L	−10	−96	2	5.12	762
angular gyrus	39	L	−40	−60	26	3.21	496
precuneus	7	L	−2	−64	40	3.7	442

Table 3. Cluster report of max *z*-statistics for the parametric modulation by perceived plausibility. (BA, Brodmann's area (retrieved from https://bioimagesuiteweb.github.io/webapp/mni2tal.html); hemi, hemisphere.)

region	BA	hemi	X	Y	Z	z-score	cluster size
external > internal							
angular gyrus	39	R	54	−58	30	4.06	1108
precuneus	7	R	8	−58	44	4.03	1008
superior frontal gyrus		R	28	42	46	3.06	776
angular gyrus	39	L	−40	−64	20	3.43	571
internal > external							
postcentral gyrus		R	54	−30	60	4.12	607
insula		L	−36	−10	22	3.41	456
insula	13	R	38	−10	8	3.91	432

were also sensitive to perceived plausibility of external eCFT. By contrast, the perceived plausibility of internal eCFT parametrically modulated bilateral insula and right postcentral gyrus, neither of which is considered part of the DMN (figure 3*b* and table 3).

4. Discussion

Previous research has shown that the brain's DMN is engaged during the mental simulation of eCFT [1,6,40], yet a large amount of evidence in the social psychology of eCFT also indicates important differences in the kinds of mental contents people tend to mutate when engaging in eCFT [17]. One such difference, until now unexplored in the cognitive neuroscience of eCFT, is that between internal and external counterfactual simulations [26,41]. When simulating alternative ways past personal events could have occurred but did not, we may imagine how we could have acted differently to bring about an alternative result (internal eCFT), or we may imagine how circumstances of the past situation could have been different so as to have altered what actually occurred (external eCFT). The current study sought to shed light on the mechanisms underlying these kinds of mental simulations by investigating behavioural and neural differences between upward internal and external eCFT derived from negative autobiographical memories.

Consistent with our hypothesis, and in agreement with previous research [42], we found that participants reported less difficulty simulating internal relative to external eCFT. Additionally, participants tended to perceive alternative possibilities in internal eCFT as being more plausible than in external eCFT, and tended to think of imagined alternative outcomes during internal eCFT as being more controllable than alternative outcomes during external eCFT. These results are consistent with our predictions, given that in the internal condition participants were specifically instructed to think about how their own actions could have created an alternative outcome to the negative event.

We then examined whether external and internal eCFT engaged distinct neural regions within the DMN. First, we employed a data-driven multivariate analysis using a mean-centred spatio-temporal PLS approach. The PLS analysis revealed a single latent variable significantly distinguishing patterns of brain activity supporting external from internal

eCFT. Next, we conducted a separate set of hypothesis-driven univariate analyses that compared the magnitude of activity between conditions. Corroborating the findings from the PLS analysis, the univariate approach revealed that external eCFT were more likely to engage large clusters of voxels encompassing the cuneus/occipital pole, precuneus, angular gyrus and portions of the superior and middle frontal gyri. By contrast, internal eCFT were more likely to engage the posterior cingulate and precentral gyrus. According to the *constructive episodic simulation hypothesis*, simulating counterfactual thoughts elicits greater activation in the same episodic system that supports memory retrieval, owing to the constructive demands of generating a novel episodic scene [43]. Both the behavioural and neural data seem to indicate that reconstructing an episodic memory by changing external factors placed the greatest demands on this system, as evidenced by ratings of higher difficulty and less plausibility for external compared to internal eCFT, as well as generally more robust levels of activity for external eCFTs among core DMN regions. In particular, generating external eCFTs engaged the precuneus, angular gyrus and occipital regions to a greater extent than internal eCFTs, even after accounting for activity related to naturally retrieving a memory.

To understand these effects, one must consider that the mental simulation of external eCFT probably involves a kind of mental 'decentring' [44], whereby one changes the focus of attention from oneself onto the surrounding context. From that perspective, the preferential engagement of the angular gyrus in external eCFT is consistent with numerous findings showing the importance of the angular gyrus for the multimodal integration of contextual information in the generation of episodic simulations [45]. In fact, recent studies employing transcranial magnetic stimulation have shown that temporarily disrupting activity in the angular gyrus affects the capacity to generate coherent episodic simulations, including autobiographical memories [46,47]. Likewise, mentally simulating changes in the circumstances surrounding a particular past situation probably requires processing, updating and manipulating spatial information from the episodic memory upon which the eCFT is based. As such, the engagement of these cognitive operations probably explains the recruitment of the cuneus and precuneus, which have been shown to be critical for spatial and perspective-taking shifts during the mental simulation of imagined episodes [48–51]. Behaviourally, perspective shifting has been shown to be a critical factor in

changing attribution patterns, with shifts from third- to first-person perspective decreasing the amount of intentionality ascribed to a harmful actor [52,53] and shifts from first- to third-person perspectives making belief attribution more effortful [54]. Neurally, recent work indicates that posterior regions of the DMN—namely the precuneus and angular gyrus—are more closely affiliated with visually shifting one's perspective of an event than necessarily changing the outcome of what occurred via counterfactual thought [18].

Considering these previous findings, it is interesting to note that in our own data the neural signal in both the precuneus and the angular gyrus was parametrically modulated by the perceived plausibility of the external eCFT. One possibility is that the plausibility of the imagined simulations covaried with their spatial coherence, so that eCFT perceived as more plausible were in turn also experienced as more spatially coherent. Imagining a novel external alternative to a past event requires shifting the overall context in which the event occurred (e.g. a sunny day turning into a cloudy day), and this contextual shift seems to rely on a similar network of regions supporting general shifts in visual perspective. Future studies exploring the connection between perceived plausibility and the experience of spatial perspective and coherence in eCFT should help to shed light on this issue.

On the other hand, internal eCFT preferentially engaged the precentral gyrus and posterior cingulate cortex, with parametric modulation by perceived plausibility also observed in the postcentral gyrus and insula. Presumably, the engagement of these regions may reflect greater self-referential processing and mental emulation within the internal condition, provided that the posterior cingulate is a core region in the cortical midline system that mediates self-referential processing [55], while motoric regions are engaged when imagining hypothetical actions one could have taken [56]. Parametric modulation in the insula may further reflect a fluctuating affective signal, as more plausible actions may be correlated with a greater experience of regret among upward eCFT [57]. Indeed, as part of the cingulo-opercular network, the insula is thought to assign evaluative value when considering action-outcome information in counterfactual scenarios [58,59]. Thus, the neural regions preferentially engaged by internal eCFTs seem to constitute a cortical system that reflects on past behaviour, simulates alternative actions and considers the affective outcome of those actions.

For completeness, we also looked at neural activity common between internal and external eCFT as compared to episodic retrieval. Converging evidence from both analyses implicated some core regions of the brain's DMN [4,60,61] for both types of eCFT. Specifically, large left-lateralized clusters in the dorsomedial prefrontal cortex and angular gyrus (extending into lateral temporal regions) were implicated in the generation of both internal and external eCFTs, as well as left cerebellar crus I and crus II which are functionally connected to the DMN [62]. These activation profiles align closely with previous studies that have evaluated similar contrasts [18,63] and represent enhanced recruitment of the same episodic system supporting autobiographical memory recall when constructing novel hypothetical scenarios [43]. Importantly, despite this common neural profile, our comprehensive analyses that compare neural activation between internal and external eCFT conditions nonetheless suggest that this system is preferentially recruited depending on the focus of the counterfactual simulation.

Our results indicate an important connection between eCFT and degree of perceived control. Generating external eCFT led to a lower level of perceived control relative to generating internal eCFT. This might have implications for maladaptive biases in eCFT in both clinical and educational contexts. Clinically, a particularly interesting next step would be to investigate neural and behavioural differences in perceived control between internal and external eCFT in populations that present maladaptive biases of eCFT. Extant evidence shows that depression and anxiety are associated with increased counterfactual rumination and greater feelings of regret [64,65]. One possible explanation for the increase in dysfunctional eCFT in this population could be a bias towards imagining internal eCFT—which we showed were accompanied with a greater sense of controllability—when thinking about situations for which neurotypical populations may tend to generate external eCFT instead [28,41]. This hypothesis is consistent with the present findings as well as previous work demonstrating that individuals with high trait anxiety used more negative language to describe their eCFT and perceived them as less plausible than healthy adults [66]. It is important to note that there are a great many factors that contribute to the functionality versus dysfunctionality of eCFT [17]. For example, whether or not an internal eCFT focuses on a behaviour versus a trait [28,67], or if there is a future opportunity to change or repeat the situation [68]. Thus, future work investigating this question should be cognizant of the relationship between the content of the memory that gives rise to an eCFT and its possible functional and dysfunctional consequences.

In addition to clinical applications, our findings could also have consequences for pedagogy. Previous research has shown that self-blame for academic failures affect motivation in educational contexts for school-aged children at different stages of development [69,70]. Because blame scales with perceived control, greater self-blame for academic failures might be associated with increased internal rather than external eCFT. We believe that these questions are fruitful avenues for future research.

That said, it is important to acknowledge some limitations of the current study. First, while the sample size of the current study is consistent with previous neuroimaging studies employing similar designs (e.g. [2,5,6,18]), further studies would benefit from using much larger samples to corroborate the findings reported here. Second, while not completely colinear, judgements of perceived controllability were relatively correlated with our manipulation. In our study, this was by design, as we employed the controllability rating as a manipulation check. However, as mentioned in the introduction, locus of action initiation is just one of three dimensions of causal attribution, with controllability being another one of them [24,71]. As such, further research would be needed to fully disentangle differences in neural activity preferentially associated with these two dimensions during eCFT.

In summary, the present work aimed to investigate neural and behavioural differences between internal and external eCFT. We found that internal eCFT felt more controllable, more plausible, and were easier to generate on average than external eCFT. Additionally, participants reported having more frequently imagined internal relative to external eCFT. Neurally, both classes of eCFT engaged the cingulate cortex—a core region of the brain's DMN—and, when contrasted, we found that external eCFT were more likely to engage the cuneus/occipital pole, precuneus, angular gyrus and portions

of the superior and middle frontal gyri, whereas internal eCFT were more likely to engage the posterior cingulate and precentral gyrus. Further, activity in precuneus, angular gyrus and superior frontal gyrus was parametrically modulated by perceived plausibility of external eCFT, while perceived plausibility of internal eCFT was reflected in the activity of the insula and postcentral gyrus. These results contribute to the nascent literature on the neural basis of eCFT, and help to elucidate content-specific differences in the engagement of the brain's DMN in the simulation of possibilities.

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