Real-time fMRI links subjective experience with brain activity during focused attention

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ABSTRACT

Recent advances in brain imaging have improved the measure of neural processes related to perceptual, cognitive and affective functions, yet the relation between brain activity and subjective experience remains poorly characterized. In part, it is a challenge to obtain reliable accounts of participant's experience in such studies. Here we addressed this limitation by utilizing experienced meditators who are expert in introspection. We tested a novel method to link objective and subjective data, using real-time fMRI (rt-fMRI) to provide participants with feedback of their own brain activity during an ongoing task. We provided real-time feedback during a focused attention task from the posterior cingulate cortex, a hub of the default mode network shown to be activated during mind-wandering and deactivated during meditation. In a first experiment, both meditators and non-meditators reported significant correspondence between the feedback graph and their subjective experience of focused attention and mind-wandering. When instructed to volitionally decrease the feedback graph, meditators, but not non-meditators, showed significant deactivation of the posterior cingulate cortex. We were able to replicate these results in a separate group of meditators using a novel step-wise rt-fMRI discovery protocol in which participants were not provided with prior knowledge of the expected relationship between their experience and the feedback graph (i.e., focused attention versus mind-wandering). These findings support the feasibility of using rt-fMRI to link objective measures of brain activity with reports of ongoing subjective experience in cognitive neuroscience research, and demonstrate the generalization of expertise in introspective awareness to novel contexts.

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Introduction

Recent advances in brain imaging have improved the measure of neural processes underlying human experience, yet the relation between objective measures of brain activity and subjective experience remains poorly characterized (Lutz and Thompson, 2003). Efforts to link objective and subjective data are challenged by inaccuracy or bias in self reports (Hurlburt and Heavey, 2001) and the potential to disrupt or modify an experience by generating a contemporaneous self report, among others (Schooler, 2002).

Recent strategies have improved the correspondence of objective and subjective data by probing subjects to report on their ongoing experience during standard neuroimaging. A recent study probed subjects during a sustained attention task during fMRI to ask whether their attention was focused and if they were on-task (Christoff et al., 2009). When they reported being off-task, subjects showed activity in the default mode network (DMN), a network implicated in mind-wandering and self-referential processing (Whitfield-Gabrieli et al., 2011). DMN activity was greatest when subjects were unaware of their own mind-wandering, but made mistakes on the task. In another study (Hasenkamp et al., 2011), meditators were asked to practice focused attention on the breath meditation and press a button any time their mind wandered. Again, DMN activity was related to mind-wandering. These methods improve objectivity, yet still disrupt

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experience, and garner limited subjective information, that may be confounded by reverse inference of cognitive processes from brain activity (Christoff et al., 2009; Poldrack, 2006).

A novel way to overcome these limitations is to use real-time fMRI (rt-fMRI) to provide feedback of brain activity continuously during an ongoing task. Rt-fMRI combines the high spatial resolution of fMRI with improved temporal resolution lacking in blocked design fMRI, where subjects report averaged experience over the course of a block interval, rather than momentary experience. In so doing, rt-fMRI may allow for tighter coupling between real-time reports of experience and concomitant measures of brain activity. In theory, this method may be used to confirm group and time-averaged results at the individual subject level, in real time.

In this study, we link subjective experience with brain activity on a moment-to-moment basis during a focused attention task, by using rt-fMRI to provide feedback from the posterior cingulate cortex (PCC), a hub of the DMN shown to be activated during mind-wandering and self-referential processing, among other activities such as remembering the past and predicting the future (Whitfield-Gabrieli et al., 2011) and deactivated during three types of meditation—focused attention on the breath, lovingkindness, and choiceless awareness (Brewer et al., 2011). We used the PCC for neurofeedback rather than another hub of the DMN (i.e., the mPFC) because PCC deactivation was the most robust finding associated with experienced meditators in our prior study (Brewer et al., 2011), and based on the purported role of the mPFC in relaying information to the PCC, rather than being directly involved in self-related processing (Ongur and Price, 2000). This study was designed to test the feasibility of using rt-fMRI to link ongoing subjective experience with an objective measure of brain activity in real time. We use an advantageous group, experienced meditators, who are practiced at both focused attention and monitoring moment-to-moment experience, and non-meditators as a control group.

Materials and methods

To assess whether real-time fMRI feedback can be used to more tightly couple an objective measure of brain activity with subjective experience, we conducted two studies. In Experiment 1A, experienced meditators and non-meditators were provided real-time feedback from the PCC or a control region during a focused attention task, and asked to rate how well the feedback graph corresponded with their subjective experience of focused attention or mind-wandering. In Experiment 1B, meditators and non-meditators were then instructed to volitionally decrease the feedback graph, in order to provide objective validation of their subjective experience. In Experiment 2, to replicate Experiment 1 without the potential confounds of experiential anchors for the graph—focused attention and mind-wandering—provided in the earlier experiment, a separate group of meditators took part in a novel step-wise rt-fMRI blinded discovery protocol in which they were instructed to use their subjective experience during the task to discover the relationship between their experience and the feedback graph. All participants gave informed consent in accordance with the Yale University Human Investigation Committee.

Experiment 1

Experiment 1A

Participants. 22 meditators and 22 non-meditators took part in Experiment 1A. All participants were right-handed and case-control matched for gender, race, education, and employment status (Table 1). Meditators were drawn from the Theravada tradition. One meditator additionally practiced Buddhist non-dual meditation. Meditators reported a total of 9249 ± 1449 (mean ± standard error of the mean) practice hours over 12.0 ± 1.6 years, consisting

of both daily practice and retreats. Non-meditators reported no prior meditation experience.

fMRI task. Experiment 1A included six 3.5-minute runs. Each run consisted of a 30-second active baseline task designed to elicit self-referential processing, followed by a 3-minute focused attention task. For the active baseline task, individuals viewed adjectives and mentally decided whether or not the words described them (Kelley et al., 2002). This task was used to provide a more standard baseline between groups than rest, given that we have previously found differences in DMN activity between meditators and non-meditators at rest (Brewer et al., 2011). For the focused attention task, traditional focused attention on the breath meditation instructions were operationalized for the fMRI setting (see Focused attention task instructions section). From onset of the focused attention task, a column graph was back-projected onto a screen visible to participants in the scanner, and a new column was plotted every time to repetition (TR = 2 s). Instructions were: "*A graph will be displayed on the screen that will track the activity of a certain brain area involved in self-related processing. While you are meditating, the graph will have an upward, red signal if you engage in self-related processes such as when your mind wanders, and a downward, blue signal if you are fully absorbed in concentrating on the breath.*" Participants were instructed to practice focused attention on the breath, letting the graph rest in the background of their awareness, and to check in with the graph periodically to assess how it corresponded with their experience. They were told that due to signal processing, there would be a 4 to 8-second delay between their brain activity and the graph [based on the time course of the hemodynamic response function], and thus they should check the graph after noticeable periods of focused attention or mind-wandering, and then immediately return their attention to their breath. Their aim was to determine how well the graph corresponded with their momentary subjective experience. Participants were also instructed that they may receive feedback from different brain regions during separate runs, and to consider each run individually. Participants practiced the study procedure to proficiency outside the scanner, prior to scanning.

Focused attention task instructions. Standard mindfulness concentration meditation instructions were operationalized for fMRI, as follows: "*During the meditation, please pay attention to the physical sensation of the breath wherever you feel it most strongly in the body. Follow the natural and spontaneous movement of the breath, not trying to change it in any way. Just pay attention to it. If you find that your attention has wandered to something else, gently but firmly bring it back to the physical sensation of the breath*" (Brewer et al., 2011; Gunaratana, 2002).

Self report. After each run, participants were asked to respond verbally over the scanner intercom and: (1) rate how well the graph corresponded with their moment-to-moment subjective experience of focused attention on the breath, in blue, and mind-wandering, in red, from 0 = not at all to 10 = perfectly; (2) briefly describe their rating i.e., to concisely describe what about the graph did or did not correspond with their subjective experience; and (3) rate how well they were able to follow the instructions from 0 = not at all to 10 = perfectly.

Real-time fMRI feedback. The feedback graph shown to participants during focused attention in each run showed percent change in the blood oxygenation level-dependent (BOLD) signal in a region of interest (see Region of interest definition section) relative to baseline. For runs 1–4, the graph displayed feedback from the PCC. Runs 5-6 were randomized to display feedback from the PCC or a control region, the posterior parietal cortex. The PCC was used for feedback during the focused attention task because PCC activity has been

Table 1
Demographics.

Experiment 1A	Meditators (n = 22)		Novices (n = 22)			
	n	%	n	%	χ2	p
Sex					0.00	1.00
Male	13	59	13	59		
Female	9	41	9	41		
Race					n/a	n/a
White (Non-Hispanic)	22	100	22	100		
	Mean	SD	Mean	SD	t	p
Age	44.7	12.6	42.9	13.8	0.43	.67
Years of Education	17.9	3.1	16.8	3.5	1.16	.25
Experiment 1B	Meditators (n = 9)		Novices (n = 11)			
	n	%	n	%	χ2	p
Sex					0.002	0.96
Male	5	56	6	55		
Female	4	44	5	45		
Race					n/a	n/a
White (Non-Hispanic)	10	100	11	100		
	Mean	SD	Mean	SD	t	p
Age	41.2	11.2	37.1	13.9	−0.72	.48
Years of Education	18	2.3	16.5	2.3	−1.5	.15
Experiment 2			Meditators (n = 10)			
			n			%
Sex						
Male			7			70
Female			3			30
Race						
White (Non-Hispanic)			9			90
Hispanic			1			10
			Mean			SD
Age			49.2			12.5
Years of Education			19.2			3.0

shown to robustly increase during self-referential processing (Kelley et al., 2002; Mason et al., 2007; Northoff et al., 2006; Weissman et al., 2006), and, conversely, to decrease during different types of meditation (Brewer et al., 2011). The posterior parietal cortex was used as a control region because it is considered a node of the DMN that shows tight temporal coupling with the PCC, but activity in the posterior parietal cortex is not associated with self-referential processing (Andrews-Hanna et al., 2010; Northoff and Bermpohl, 2004; Northoff et al., 2006; Whitfield-Gabrieli et al., 2011). Thus, the posterior parietal cortex should show a comparable pattern of activity to the PCC, but should not correspond to subjective experience of focused attention. After run 6, participants were informed which of runs 5-6 showed feedback from the control region.

Image data acquisition. Participants were scanned using a Siemens 1.5 Tesla Sonata MRI with standard eight-channel head coil. A high-resolution anatomical scan was acquired using an MPRAGE sequence (TR/TE = 2530/3.34 ms, 160 contiguous sagittal slices, slice thickness 1.2 mm, matrix size 192 × 192, flip angle = 8°). A lower resolution T1-weighted anatomical scan was then acquired: TR/TE = 500/11 ms, field of view = 220 mm, slice thickness = 4 mm, gap = 1 mm, 25 AC-PC aligned axial-oblique slices. Functional image acquisition began at the same slice location as the T1 scan. Functional images were acquired using a T2*-weighted gradient-recalled single shot echo-planar sequence: TR/TE = 2000/35 ms, flip angle = 90°, bandwidth = 1446 Hz/pixel, matrix size = 64 × 64, field of view = 220 mm, voxel size = 3.5 mm, interleaved, 210 volumes (after 2

volumes were acquired and automatically discarded). Ten additional functional volumes were acquired prior to real-time feedback, two were discarded, and the remaining eight volumes were used for registering single subject reference space for motion correction and region of interest definition.

Region of interest definition. Gray matter regions of interest (ROIs) for real-time feedback were defined using Bioimage Suite (www.bioimagesuite.org). For the PCC, we used reported activation coordinates in Brewer et al. (Brewer et al., 2011) for the local maximum for between-group differences (meditators versus non-meditators) during a focused attention on the breath meditation task (−6, −60, 18). For the posterior parietal cortex, we used anatomically defined coordinates (−55, −51, 19) in the intraparietal sulcus. 9 mm diameter spheres (volume = 461 mm³) were drawn from each of these coordinates. An additional gray matter mask was defined from all gray matter excluding the PCC and posterior parietal cortex (960455 mm³) on the MNI template brain.

Real-time image processing. Image processing for real-time feedback involved first transforming the ROIs from template space to single subject reference space using a series of linear and non-linear registrations, as described in prior studies (Hampson et al., 2011; Martuzzi et al., 2010). First, a non-linear transformation was used to warp the template brain to the individual 3D (MPRAGE) anatomical scan. Next, a linear registration of the individual 2D to 3D anatomical scan was performed. Finally, a linear registration of the short

functional series to the 2D anatomical scan was performed. All transformations were estimated using the intensity-only component of the method implemented by Bioimage Suite, as reported previously (Papademetris et al., 2004), and were manually inspected for accuracy prior to feedback runs.

Real-time feedback display. The real-time feedback graph displayed to the participant was generated using a series of preprocessing steps for each frame of the fMRI time series, using the real-time fMRI feedback system described previously (Hampson et al., 2011; Scheinost et al., in press). Briefly, each slice of a functional volume was reconstructed in real-time and each volume was motion corrected and analyzed immediately after acquisition. The mean activation of each ROI and the gray matter mask was calculated for each frame. To account for motion correction and partial volume effects near the edge of the brain, voxels with intensity less than 25% of the overall brain mean were excluded from mean activation. Any mean ROI activation with greater than 10% change from the previous frame was treated as an outlier and was replaced by the previous frame (0th order interpolation). Mean ROI activation was temporally smoothed based on the last five values with a zero mean unit variance Gaussian kernel in order to provide less abrupt transitions in the feedback display from moment-to-moment. Percent signal change in the ROI during meditation was calculated relative to the ROI average value from the baseline task, and corrected for scanner drift by subtracting the percent signal change from the gray matter mask at each time point (deCharms et al., 2005). The corrected percent signal change relative to baseline was then presented as a graph to each participant in real-time using E-Prime version 1.2 (pstnet.com). The entire processing stream from each functional volume acquisition to feedback display required less than 1-second delay. Corrected percent signal change was stored for offline analysis.

Statistical analysis. Statistical analyses used SPSS (ibm.com). In order to evaluate whether real-time feedback from the PCC corresponded to the subjective experience of focused attention and mind-wandering, in meditators and non-meditators, we calculated the mean correspondence rating for the self report question "*How well did your experience correlate with the graph?*" (0 = not at all, 10 = perfectly), for runs 1–4, and performed between-group comparisons using an independent t-test. In order to evaluate whether participants could discriminate between feedback from the PCC and control region, the posterior parietal cortex, we compared mean correspondence ratings between ROIs from runs 5–6 using a paired t-test. We report mean ± standard error of the mean.

Experiment 1B

Participants. 9 meditators and 11 non-meditators from Experiment 1A took part in Experiment 1B (Table 1). This subset of meditators reported a total of 8803 ± 3282 practice hours over 9.5 ± 2.4 years, consisting of both daily practice and retreats. Experiment 1B was conducted in an additional 7th run added to Experiment 1A part-way through data collection; all subsequent participants completed this 7th run.

Real-time feedback task. Experiment 1B was comprised of the same 30-second active baseline task as in Experiment 1A, followed by an additional real-time feedback task (Fig. 1). For the real-time feedback task, participants were given the following instructions: "*Now you have gotten a chance to see how activation of this brain region correlates with meditation. Given what you have learned from the previous runs, in the next run, please see how much you can actively make the graph go blue.*" During the run, participants were again shown a graph of real-time feedback from the PCC as in Experiment 1A. Image acquisition, ROI definition, real-time image processing and feedback display were the same as in Experiment 1A.
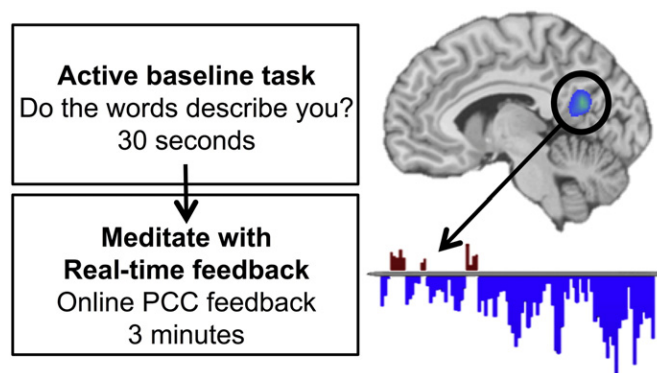

Fig. 1. Real-time fMRI neurofeedback protocol for Experiment 1A. Participants performed 3 runs of a 30-second active baseline task, during which they viewed words and decided if the words described them, and a 3-minute focused attention task, during which they focused attention on the breath while viewing a real-time feedback graph representing activity in the posterior cingulate cortex (PCC).

Statistical analysis. Mean percent signal change in the PCC during real-time feedback was calculated and compared between groups using independent t-tests. We also tested for Pearson's correlations between percent signal change in the PCC and meditation experience (total lifetime hours).

Offline motion analysis. In order to ensure that feedback from the PCC was not due to subject motion during the real-time feedback task, we ran a correlation analysis between offline motion parameter estimates and percent signal change in the PCC during real-time feedback. Functional images were realigned for motion correction using SPM 8 (www.fil.ion.ucl.ac.uk/spm). Each resultant motion parameter was averaged across all slices for the run. A two-tailed correlation was tested between mean percent signal change in the PCC and each average motion parameter for each group (meditators/non-meditators), given that there may be group differences in movement during scanning. No significant correlation was found (controls: x: $r = .04$, $p = .91$; y: $r = -.25$, $p = .45$; z: $r = .04$ $p = .9$; pitch: $r = .03$, $p = .93$; roll: $r = .37$, $p = .26$; yaw: $r = .21$, $p = .53$; meditators: x: $r = .25$, $p = .48$; y: $r = -.24$, $p = .51$; z: $r = -.29$, $p = .41$; pitch: $r = -.11$, $p = .76$; roll: $r = -.25$, $p = .49$; yaw: $r = -.2$, $p = .58$). Additionally, no correlation was found between motion parameters and mean percent signal change in the PCC if the absolute value of the motion parameters were averaged. For simplicity, we present only the purely averaged parameters.

Experiment 2

Participants

10 meditators (9 right-handed, 1 ambidextrous) took part in Experiment 2 (Table 1). Meditators were drawn from a number of contemplative traditions including Theravada (N = 4), Zen (N = 3), Catholic Contemplative (N = 1), Catholic Contemplative and Zen (N = 1), and Gelug-pa of Tibetan Buddhism (N = 1). Meditators reported a total of 10567 ± 4276 practice hours over 18.4 ± 4.9 years, consisting of both daily practice and retreats.

Blinded discovery fMRI protocol

A subsequent experiment was then designed to replicate Experiment 1A without providing participants with experiential anchors for the feedback graph—such as focused attention in blue and mind-wandering in red—thus eliminating potential bias in how participants link their subjective experience to the feedback graph. The protocol was designed to allow participants to discover how the feedback graph corresponded to their own subjective experience of focused attention in real-time. This blinded discovery protocol was

comprised of a 4-step series of fMRI runs progressing from (1) focused attention on the breath with offline feedback (feedback graph shown offline immediately after each run), (2) focused attention on a simulated graph with offline feedback, (3) focused attention with real-time feedback from the PCC, to (4) volitional decrease of the feedback graph. This stepwise protocol was designed to progress from the most naturalistic setting for focused attention (step 1), to focused attention using a dynamic graph as the object of focus (step 2), to focused attention with a graph of feedback from one's own brain activity in real-time (step 3), to volitional decrease of the feedback graph (step 4) (Fig. 2). Step 1 included 4 runs because it was the most naturalistic setting for focused attention on the breath, and was thus crucial for discovering how one's own experience corresponded with the feedback graph, shown to participants offline. Steps 2–4 each included 3 runs. Each run was comprised of the same 30-second active baseline task as in Experiment 1, followed by the same focused attention meditation task, with the exception that the focused attention task was shortened from 3 min to 1 min to aid recall of moment-to-moment experience. Pilot testing of the focused attention task using durations ranging from 30 s to 3 min, with meditators who were not included in the current analysis, yielded that 60 s was optimal for practicing focused attention and also recalling one's momentary subjective experience. Participants practiced the study procedure to proficiency outside of the scanner prior to scanning. Image acquisition, ROI definition, real-time image processing and feedback display were the same as in Experiment 1.

Blinded discovery fMRI protocol instructions

Participants were instructed that any time they viewed a graph of their brain activity, the graph would show activity from the same brain region, and their aim was to see whether or not activity in this brain region corresponded with their subjective experience. They were not provided experiential anchors for the feedback graph (e.g., focused attention/mind-wandering). Instead, they were instructed that increases in the graph, in red, indicated increased activity in the brain region, and decreases in the graph, in blue,

indicated decreased activity in the same brain region. Specific instructions for each step were as follows:

Focused attention with offline feedback. For the first meditation task, after the word task, the screen will go blank. This will be your cue to meditate for about 60 s. During the meditation, please pay attention to the physical sensation of the breath wherever you feel it most strongly in the body. Follow the natural and spontaneous movement of the breath, not trying to change it in any way. Just pay attention to it. If you find that your attention has wandered to something else, gently but firmly bring it back to the physical sensation of the breath. Please keep your eyes open.

Focused attention on a graph with offline feedback. For the second meditation task, after the word task, you will see a graph start to form, that will fill in a new line every 2 s. This is an arbitrary graph, and does not show your brain activity. We ask that when you see the graph start to form, you again meditate for 60 s, here using the graph as your object of meditation—just paying attention to the graph as you would any other object of focus or concentration such as your breath. Pay attention to the graph, not trying to change it in any way. If you find that your attention has wandered to something else, gently but firmly bring it back to the graph. Please keep your eyes open.

Focused attention with real-time feedback. For the third meditation task, after the word task, you will see a similar graph start to form, and again we ask that you meditate for 60 seconds, using the graph as your object of meditation. Now the graph you see during the run will show relative activity in a particular region of your brain. Thus for these runs, the graph you see during the run may correspond with your experience. There is a 2–4 second delay between your brain activity and the graph, thus if the graph does correspond with your experience, it will do so with a delay of 2–4 seconds [Authors note: from Experiment 1B and pilot testing, meditators reported a shorter lag between their experience and the feedback graph than 4–8 s. This may be due to a differential hemodynamic response function across the brain (Miezin et al., 2000), with the PCC possibly having a shorter lag. We updated the
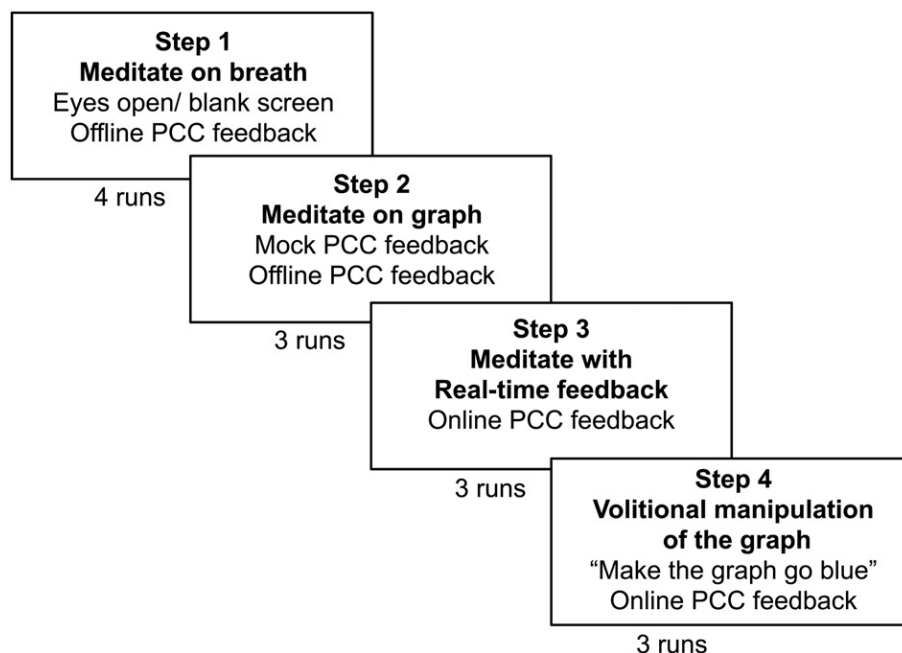

Fig. 2. Real-time fMRI neurofeedback protocol for Experiment 2. Participants performed 13 runs of the same 30-second active baseline task, during which they viewed words and decided if the words described them, and a 60-second focused attention task, for which the instructions changed every 3–4 runs. For specific instructions, see Blinded discovery fMRI protocol section.

instructions accordingly for Experiment 2]. *It may be helpful to look back at short stretches of time to notice your experience in relation to how the graph changes. We ask that you meditate, using the graph as your object of meditation, and now also notice your moment-to-moment experience in relation to how the graph changes.*

Volitional decrease of the feedback graph. For the final task, after the word task, you will see a similar graph start to form that will show relative activity in a particular region of your brain, and may correspond with your experience. For these runs, we will ask you to use your mind to make the graph go blue. You may draw from your experience over the previous runs. You will have 60 s.

Online feedback and self report

For steps 1–2, after each run, participants were first asked to briefly describe their experience during the focused attention meditation. They were then shown a graph of their brain activity from the focused attention meditation period (offline feedback), and asked "*How well did the graph correspond with your experience during the meditation, from 0 = not at all to 10 = perfectly*". They were instructed to consider how the graph did or did not correspond with their experience during the focused attention task, for example, with their general experience of meditation, including mental effort, concentration, or mental state, and at the beginning, middle, or end of the focused attention task. For step 3, participants were again asked to briefly describe their experience during the focused attention meditation, and then to rate how well the graph they saw *during the run* (real-time feedback) corresponded with their experience. For step 4, participants were asked to briefly describe their experience during the focused attention meditation, to rate how well the graph they saw during the run corresponded with their experience, and additionally, to report what strategy they used to try to decrease the feedback graph.

Statistical analysis

Mean correspondence rating for the self-report question "*How well did the graph correspond with your experience during the meditation from 0 = not at all, 10 = perfectly?*" was calculated from step 3, *focused attention with real-time feedback* (3 runs). Mean percent signal change during real-time feedback was calculated for the PCC from step 4, *volitional manipulation of the feedback graph* (3 runs). One participant was unable to take part in step 4 due to arriving late, thus mean percent signal change during real-time feedback is calculated from N = 9. We used two-sided one-sample t-tests relative to zero to test for significance.

Results

Experiment 1A

In Experiment 1A, all participants reported success in following the instructions. Mean rating for runs 1–6 when participants were asked *How well were you able to follow the instructions from 0 = not at all to 10 = perfectly* was 8.8 ± 0.1 and did not differ between groups ($t_{(42)} = .31, p = .78$).

Meditators and non-meditators reported a significant correspondence between their subjective experience and the feedback graph for runs 1–4, such that focused attention corresponded with decreases in the graph, in blue, and mind-wandering and/or self-referential processing corresponded with increases in the graph, in red. Mean correspondence rating for all participants between subjective experience and the feedback graph was 7.6 ± 0.2 and did not differ between groups ($t_{(42)} = 1.1, p = .29$). Feedback graphs representing mean percent signal change from the PCC in run 1 and run 4 for an example meditator and non-meditator are displayed in Fig. 3.

Participants were able to discriminate between real-time feedback from the PCC and from the posterior parietal cortex control region.
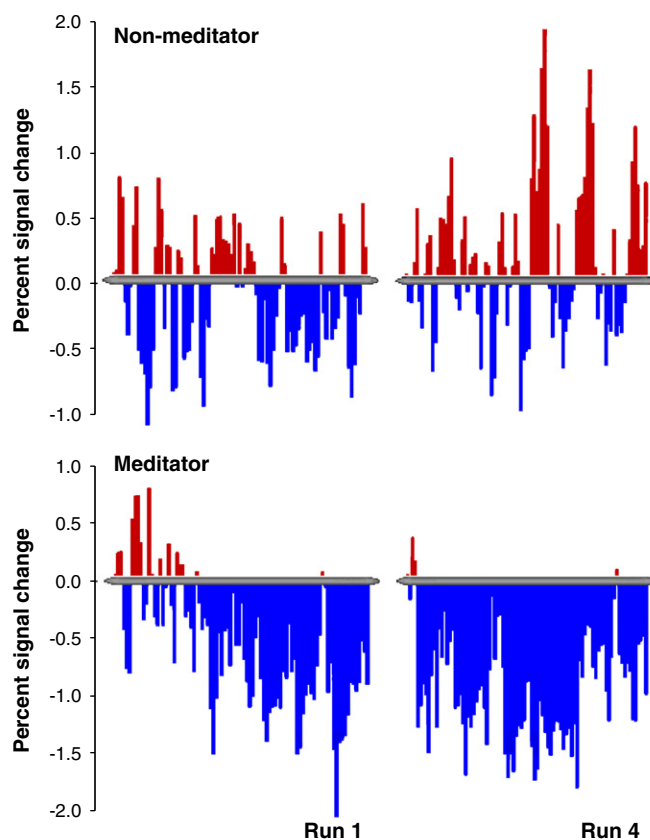

Fig. 3. Real-time feedback from the PCC during focused attention. Mean percent signal change from the PCC during focused attention with real-time feedback is shown from an example non-meditator (top) and meditator (bottom) for run 1 and run 4, from Experiment 1A.

For runs 5–6 when participants received feedback from the PCC and control region in a randomized order, mean correspondence rating for all participants was significantly higher for runs with feedback from the PCC (8.1 ± 0.3) as compared to runs with feedback from the posterior parietal cortex (6.9 ± 0.4; $t_{(42)} = 3.1, p = .004$). We note that the moderate mean correspondence rating found between subjective experience and feedback from the posterior parietal cortex was likely due to tight temporal coupling of the posterior parietal cortex with the PCC during focused attention, shown in prior studies in both meditators and non-meditators (Andrews-Hanna et al., 2010; Brewer et al., 2011).

Experiment 1B

For run 7 in which participants were asked to volitionally decrease the feedback graph, meditators showed significant PCC deactivation (-0.26 ± 0.1), as compared to non-meditators (0.07 ± 0.09; $t_{(18)} = -2.40, p = .028$, Fig. 4). For meditators, no correlation was found between meditation hours and percent signal change in the PCC ($r = -.08, p = .83$).

Experiment 2

The aim of Experiment 2 was to replicate Experiment 1 without potential bias from experiential anchors for the real-time feedback graph, using a 4-step blinded discovery fMRI protocol, whereby participants discovered how their subjective experience corresponded with the feedback graph. We again assessed mean correspondence rating and percent signal change in the PCC. All participants reported coupling between their subjective experience of focused attention and decreases in
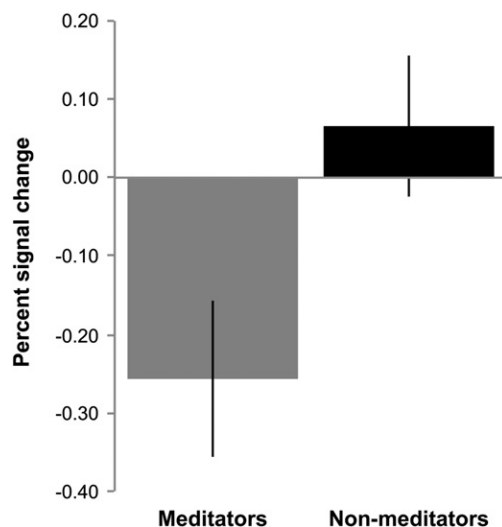
Fig. 4. Experienced meditators show significantly greater deactivation of the PCC during volitional decrease of the feedback graph than non-meditators. Mean percent signal change ± SEM in the PCC during volitional decrease of the feedback graph for meditators (gray) and non-meditators (black), from Experiment 1B, $p = .028$.

the feedback graph representing PCC activity by the end of discovery step 1. Meditators again reported a significant correspondence between the feedback graph and their subjective experience during focused attention, as in Experiment 1A. From step 3, *focused attention with real-time feedback*, mean correspondence rating was 7.6 ± 0.3 ($t_{(9)} = 25.4$, $p < .0001$). Meditators again showed significant volitional decrease of the feedback graph, as in Experiment 1B. From step 4, *volitional manipulation of the graph*, mean percent signal change in the PCC was $-0.26 \pm 0.1\%$ ($t_{(8)} = -2.71$, $p = .026$; Fig. 5). All participants reported using focused attention on the breath as their strategy for volitional decrease of the feedback graph.

Discussion

In this study, we used real-time fMRI neurofeedback to assess the coupling between a real time objective measure of brain activity in the PCC, and momentary subjective experience during a focused attention task, in meditators and non-meditators. In so doing, we demonstrated the feasibility of using rt-fMRI to link subjective mind states and objective measures of brain activity.

In Experiment 1A, we showed that a feedback graph representing PCC activity provided information closely related to ongoing subjective experience during a focused attention task in meditators and non-meditators. Both groups reported significant correspondence
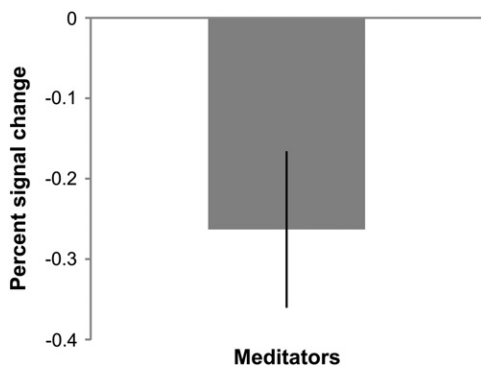

Fig. 5. Experienced meditators show significant deactivation of the PCC during volitional decrease of the feedback graph in blinded discovery protocol. Mean percent signal change ± SEM from the PCC during volitional decrease of the feedback graph for meditators (gray), from step 4 of Experiment 2, $p = .026$.

between their mental experience and the feedback graph during the task. Participants were further able to distinguish feedback from the PCC from feedback from a control brain region, reducing the likelihood of confirmation bias. A limitation of Experiment 1A was the provision of experiential anchors for the feedback graph: participants were informed that decreases in the graph, in blue, represented focused attention, and increases in the graph, in red, represented mind-wandering. Such anchors for feedback are helpful for testing specific hypotheses by limiting the range of subjective experience to which participants pay attention, but also may bias participants' self-report. To mitigate this potential confound, we replicated the study in Experiment 2, in which a separate group of meditators were able to learn how their own subjective momentary experience related to the feedback graph, without the use of experiential anchors for feedback. Participants had to, first, discover (in step 1, *focused attention on the breath with offline feedback*), and then evaluate (in step 3, *focused attention with real-time feedback*), how the feedback graph corresponded to their own subjective experience. Again meditators reported a significant correspondence between their experience and the feedback graph.

In both Experiments 1B and 2, we found that meditators were able to volitionally decrease the feedback graph, as assessed by PCC deactivation. Volitional decrease of the feedback graph may be considered, in part, a confirmation of correspondence ratings between subjective experience and the feedback graph. Because participants reported high correspondence between their subjective experience and the feedback graph, they should be able to use what they have discovered about *how* their experience relates to the feedback graph, to manipulate the graph. Meditators indeed showed significant PCC deactivation when asked to volitionally decrease the feedback graph. In contrast, non-meditators did not show PCC deactivation when asked to volitionally decrease the feedback graph. Meditators performance may have been due to their expertise at focused attention and monitoring of experience. However, interpretation of our results is limited beyond focused attention meditation in the research setting. Traditional meditation practices usually involve contextual components such as background beliefs, intentions for practice, and community support, among others; in the current study, focused attention was decontextualized (performed in an fMRI scanner), and these other factors were not measured. However, since meditators were long-term practitioners with significant life commitments to meditation practice, we cannot rule out that larger meaning components of the practice or memory of other practice contexts were active even during the decontextualized focused attention task. Due to these empirical differences, further studies are necessary to interpret our findings within the broader field of contemplative research, including in relation to cognitive and behavioral outcomes of contemplative practice.

Utility of rt-fMRI feedback for cognitive neuroscience

This set of novel findings supports the use of real-time fMRI neurofeedback in cognitive neuroscience research to assess the coupling between real-time feedback from brain activity and concurrent self-reports of mental states. To our knowledge, our study demonstrates the first use of rt-fMRI to link first-person experience with neuroimaging data in real time.

Prior studies have used blocked design fMRI with self-report to assess brain activity during various aspects of a cognitive process. For example, Mason et al. measured DMN activity during blocks of a novel or learned working memory task, in order to test whether training participants 'to boredom' on a task would lead to greater DMN activity associated with mind-wandering (Mason et al., 2007). As predicted, they found greater DMN activity and greater self-reported mind-wandering during learned than novel blocks, despite the identical task. Here we report that activity in a hub of the DMN, the PCC, is related to focused

attention and mind-wandering in real time, and not just when averaged over an fMRI block. Our findings add convergent validity and improved temporal resolution to prior studies (Pagnoni, 2012). More broadly, our findings provide proof of concept that rt-fMRI may be used to more closely link activity in a particular brain region with varied aspects of a cognitive process. In addition, by having participants report their *direct* experience as it corresponds with feedback, the potential problem of reverse inference (Poldrack, 2006) is obviated. This does not imply that single brain regions such as the PCC can wholly account for complex cognitive processes such as focused attention or meditation, but instead, that targeted feedback may help to elucidate a set of processes related to networks of brain regions, such as those related to the DMN. To overcome this limitation, future studies may use real-time feedback from multiple hubs, or functional connectivity between hubs, to further refine our understanding of neural networks underlying such cognitive processes.

Prior work to link subjective experience with objective neuroimaging data has been limited in part by individual differences in subjective experience of mind states. For example, for meditation, the depth and quality of the meditative state may vary between individuals, or for an individual between meditation blocks, or even from moment-to-moment within a given meditation block. These inter- and intra-individual differences in experience contribute to the challenge of accurately characterizing underlying brain processes. Our experimental design takes advantage of this variability by asking participants to pay attention to how their own moment-to-moment experience changes, and to report how changes in their own experience relate to changes in the feedback graph. In this way, variability within individuals, and even variability within task blocks, does not confound results, but instead is utilized to more tightly couple subjective experience with brain activity. Directed methodologies such as this may also improve accuracy in more directly linking subjective experience to brain activity during a task and therefore increasing statistical power.

Our study has several additional limitations related to variability. First, a number of cognitive processes involved in the focused attention task may vary across individuals, including motivation, relaxation, interest, and so forth. Although correspondence between subjective experience and the feedback graph was significant, our findings are reduced to a single experiential dimension and we are unable to differentiate between focused attention and these other cognitive processes. For example, sub-regions of the PCC have demonstrated dissociable functional connectivity patterns above and beyond generalized PCC deactivation during a working memory task (Leech et al., 2011). To improve specificity, we provided feedback from a sub-region of the PCC robustly associated with self-referential processing, though again our paradigm was not designed to differentiate between specific elements therein (e.g. mind-wandering vs. future thinking) (Whitfield-Gabrieli et al., 2011). Further, we show that meditators are able to volitionally decrease the feedback graph with and without experiential anchors for the graph, and no meditator reported using a cognitive strategy other than related to focused attention to manipulate the graph. A further refinement would be to use multiple or extended runs, especially given the complexity of our task, which required both ongoing focused attention and evaluation of how one's experience corresponded to the graph. Successive runs might allow a more refined detection of which specific features of subjective experience relate to different aspects of the graph, such as highly associative thought, distraction and so on. In this way, task repetition would reduce variability. A previous study used a related approach to reduce noise resulting from varied cognitive strategy during a perceptual illusion task with electroencephalogram (Lutz et al., 2002). Self-reports were analyzed for recurrent patterns of cognitive strategy during the task, and runs were clustered and analyzed for brain activity related to each strategy. A similar design could be used with rt-fMRI by asking participants to notice which strategies they are using during an ongoing task in real time, and over successive or extended runs, to look for stable phenomenal invariants in how their task strategy relates to the feedback graph. This approach would further refine our understanding of how activity in a particular brain region relates to specific cognitive processes.

Conclusions

In sum, as demonstrated by this study, rt-fMRI provides a novel methodology for more tightly coupling the dynamics of subjective experience and changes in ongoing brain activity. Additional future uses include neurophenomenological investigations (Varela, 1996) in which specific subjective cognitive components of experience are linked to brain activity, and testing the robustness of cognitive strategies and tasks in real time (e.g. how reliably and to what degree does a new task actually activate or deactivate a hypothesized brain region in single subjects), among others. We also propose that experienced meditators provide a population of choice for future studies given their higher degree of introspective awareness and capacity to detect subtle changes in their subjective experience in real time.

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Conflict of interest

The funding sources had no role in conduct of the research or preparation of the article. The authors declare no competing financial interests.

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