Memory of Others' Disclosures Is Consolidated during Rest and Associated with Providing Support: Neural and Linguistic Evidence

Eleanor Collier and Meghan L. Meyer

Abstract

■ Social scientists have documented the power of being heard: Disclosing emotional experiences to others promotes mental and physical health. Yet, far less is known about how listeners digest the sensitive information people share with them. We combined brain imaging and text analysis methods with a naturalistic emotional disclosure paradigm to assess how listeners form memories of others' disclosures. Neural and linguistic evidence support the hypothesis that listeners consolidate memories for others' disclosures during rest after listening and that their ability to do so facilitates subsequently providing the speakers with support. In Study 1, brain imaging methods showed that functional connectivity between the dorsomedial subsystem of the default network and frontoparietal control network increased during rest after listening to others' disclosures and predicted subsequent memory for their experiences. Moreover, graph analytic methods demonstrated that the left anterior temporal lobe may function as a connector hub between these two networks when consolidating memory for disclosures. In Study 2, linguistic analyses revealed other-focused thought increased during rest after listening to others' disclosures and predicted not only memory for the information disclosed but also whether listeners supported the speakers the next day. Collectively, these findings point to the important role of memory consolidation during rest in helping listeners respond supportively to others' disclosures. In our increasingly busy lives, pausing to briefly rest may not only help us care for ourselves but also help us care for others. ■

INTRODUCTION

Think about the first person you talk to in trying times. What makes this person good at responding to your difficult emotions? There are likely a number of reasons, but chances are that when you disclose your struggles, they form a clear memory of your experiences. They may even refer back to your experiences when they check in with you later. In contrast, if you disclosed your experiences to someone today and they forgot about them by tomorrow, you probably would not seek support from them again.

Remembering other people's disclosures is one of the most crucial—yet underresearched—social skills. Without it, we would have a difficult time maintaining close relationships or responding intelligently to others' struggles. Yet, virtually all studies on memory for other people have focused on how we recognize faces (Mitchell, Macrae, & Banaji, 2004; Clark, Maisog, & Haxby, 1998; Bruce & Young, 1986); learn to associate faces with names, personality traits, and social roles (Meyer, Davachi, Ochsner, & Lieberman, 2019; Wang et al., 2017; Tsukiura, Suzuki, Shigemune, & Mochizuki-Kawai, 2008); or recall our own autobiographical

memories of social experiences (Speer & Delgado, 2019; Meyer, Williams, & Eisenberger, 2015; Spreng & Mar, 2012). Although remembering this type of basic social information certainly matters, it only scratches the surface of interpersonal learning and memory. How we consolidate the nuanced information we glean from others' disclosures to us remains largely overlooked. Here, we ask (i) How do 'listeners' form memories of 'disclosers' (i.e., the individuals sharing their experiences)? and (ii) Does skill in this domain help listeners interact supportively with disclosers?

Two bodies of research, when taken in conjunction, suggest that engaging the brain's default network during rest may help listeners create memories of disclosers' experiences. First, memory research finds that functional connectivity between brain regions during rest periods after encoding ("postencoding rest") is associated with memory consolidation, or the process by which new information becomes solidified in memory (Murty, Tompary, Adcock, & Davachi, 2017; Tambini, Ketz, & Davachi, 2010; Peigneux et al., 2006). Of particular relevance here, consolidating basic facts about people (i.e., others' faces, traits, and jobs) is associated with postencoding resting state connectivity between default network regions (Meyer, Davachi, et al., 2019). Second, the default network is implicated in listening during

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communication. For example, listening to others share their personal experiences (Zaki, Weber, Bolger, & Ochsner, 2009) or tell an entertaining story (Baldassano et al., 2017; Zadbood, Chen, Leong, Norman, & Hasson, 2017; Simony et al., 2016) preferentially engages the default network. Given these past findings, we predict that the default network may be associated with consolidating information about disclosers' experiences during rest after listening.

If the default network is associated with consolidating information about disclosers' experiences during postencoding rest, there are multiple ways in which the network may accomplish this feat. The default network can be further divided into three subsystems (Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010): a midline core subsystem associated with self-referential processing (Lieberman, Straccia, Meyer, Du, & Tan, 2019; Denny, Kober, Wager, & Ochsner, 2012; Gusnard, Akbudak, Shulman, & Raichle, 2001), a medial temporal lobe (MTL) subsystem associated with remembering and imagining mental scenes (Schacter & Addis, 2009; Squire & Zola-Morgan, 1991), and a dorsomedial (dorsomedial pFC [dMPFC]) subsystem associated with thinking about other people and social interactions (Wagner, Kelley, Haxby, & Heatherton, 2016; Van Overwalle & Baetens, 2009; Mitchell et al., 2004; Saxe & Kanwisher, 2003). Although each of these subsystems may be important to consolidating different facets of social information, the dorsomedial subsystem—given its sensitivity to thinking about others and social interactions—may be particularly key. Moreover, the dMPFC subsystem might facilitate consolidation on its own (i.e., greater connectivity within regions of the dMPFC subsystem) or by communicating with other brain networks (i.e., greater connectivity between the dMPFC subsystem and other networks). There is a growing appreciation that brain networks do not operate in silos but rather work together with other networks to process information (Ryali et al., 2016; Uddin, Supekar, Ryali, & Menon, 2011; Bressler & Menon, 2010). Interestingly, the default network and frontoparietal control network (FPCN) increase in tandem to sustain social information processing in the absence of social stimuli (e.g., during a working memory delay period; Meyer, Taylor, & Lieberman, 2015; Meyer, Spunt, Berkman, Taylor, & Lieberman, 2012), pointing to the possibility that they may work together to consolidate social information during rest as well. Collectively, a network neuroscience framework suggests that listeners' default network, particularly the dorsomedial subsystem, may partner with other brain systems, particularly the FPCN, to learn about disclosers during rest. Our first goal was to test these possibilities, to determine whether and how listeners may use their default network to consolidate information about disclosers' experiences.

Moving beyond how listeners consolidate information about disclosers' experiences, we next sought to answer why doing so matters for real-world social behavior. A large body of research has shown that disclosures benefit the discloser's own health and well-being (Kelley, Lumley, & Leisen, 1997; Pennebaker, Kiecolt-Glaser, & Glaser, 1988) and that disclosers benefit the most when listeners respond supportively (Gramling et al., 2016; Goldstein, Vezich, & Shapiro, 2014; Lun, Kesebir, & Oishi, 2008). In fact, even listeners' health may be improved by connecting with disclosers (Inagaki & Orehek, 2017; Inagaki & Eisenberger, 2016). Thus, identifying factors that promote supportive responding on the part of listeners is critical. So far, work on this topic largely focuses on how empathy for another person's experiences leads to immediate helping behavior or helping intentions toward that person (Masten, Morelli, & Eisenberger, 2011; Mathur, Harada, Lipke, & Chiao, 2010; Oswald, 1996; Dovidio, Allen, & Schroeder, 1990; Schroeder, Dovidio, Sibicky, Matthews, & Allen, 1988; Coke, Batson, & McDavis, 1978). Yet in real life, supportive behavior often operates on longer time-scales, and as noted above, if a friend forgot about your struggles from yesterday, they would not be very helpful today. However, only a single study has considered the potential role of memory in support-giving, finding that remembering one's own past helping behavior increases the intention to help others in the future (Gaesser & Schacter, 2014). It remains unknown whether our memory for other people's experiences (rather than our own) predicts actual subsequent helping (rather than an intention to help). To fill this gap, we tested whether listeners' memory for disclosers' experiences corresponds with subsequently providing disclosers support.

To answer these open questions, we developed a new experimental paradigm that involved listening to others share information, resting, and subsequent memory assessments. Specifically, participants alternated between (i) listening to someone share information about a personal experience (i.e., watching YouTube videos in which patients with cystic fibrosis [CF] share their experience of dealing with their disease), (ii) listening to someone share information that pertained to the same subject matter but devoid of personal experiences with it (i.e., watching videos from the online educational organization Khan Academy, in which teachers describe the science behind the patients' disease), and (iii) resting for several minutes at a time. Next, participants completed a surprise memory test for the information they encoded.

To test whether and how default network connectivity during postencoding rest consolidates emotional disclosures, in Study 1, participants completed the rest and encoding portions of the paradigm while undergoing fMRI and completed the surprise memory test outside the scanner. To test whether memory for the emotional disclosures predicts subsequent support-giving, in Study 2, participants completed our paradigm over the Internet and then, the next day, were recontacted with the option to provide support to disclosers. Participants in Study 2 also provided written descriptions of their thoughts across the rest periods. This allowed us to additionally

unpack, through linguistic analyses, the postencoding cognitive processes in listeners during rest that facilitates their memory for disclosers' experiences. Collectively, our multimethod approach provides novel insight into how listeners form memories of disclosers' experiences and how such memory relates to subsequent support-giving.

STUDY 1

Methods

Participants

Forty right-handed participants (26 women; mean age = 29 years, $SD = 11$) were recruited from Dartmouth College, NH, and surrounding towns. Participants were paid $20 per hour or awarded course credit for completing the experiment. Of these participants, 65% were white; 23% were Asian; 8% were Hispanic; and 4% were mixed/other. Participants provided informed consent in accordance with the Dartmouth College institutional review board.

Procedures

Participants first completed an fMRI session. Upon beginning the experiment, participants were scanned during a 6-min "baseline rest" scan (Figure 1) to determine baseline levels of functional connectivity between our ROIs. Participants were told that they would see a blank screen and, during this time, they could rest or mind-wander but should remain awake. After this baseline rest scan, participants were scanned while watching eight approximately 4-min videos, four of which constituted a block of "patient videos" and four of which constituted a block of "science videos." Disclosure has been defined as the process of sharing our experiences of events with others (Tamir & Mitchell, 2012; Collins & Miller, 1994). Thus, to assess how people consolidate others' disclosures, in the patient videos, YouTube vloggers with the terminal illness CF

described their experience with the disease. In the science videos, a Khan Academy teacher delivered lessons on the science behind CF (e.g., its symptoms). In this way, the science videos covered the same broad subject matter as the patient videos (i.e., CF) but did not involve disclosures about the subjective experience of CF. Video order within blocks was randomized, and the order of patient and science blocks was counterbalanced across participants. Each block of four videos was followed by another 6-min rest scan ("postpatient rest" and "postscience rest," respectively).

After the scan session, we tested participants' memory of the videos with a surprise free recall test in a quiet testing room. Participants were given a laptop on which they viewed a picture of each video along with its title and were asked to type everything they could remember from that video. After data collection, their responses were scored for the number of distinct, correct facts recalled.

fMRI Acquisition

Scanning was performed on a Siemens 3-T Trio. Functional images were acquired using an EPI gradient-echo sequence (2.5 × 2.5 × 2.5 mm voxels, repetition time = 1000 msec, echo time = 30 msec, 2.5-mm slice thickness, field of view = 24 cm, matrix = 96 × 96, flip angle = 59°, multiband acceleration factor = 4). A T2-weighted structural image was acquired coplanar with the functional images (0.9 × 0.9 x 0.9 mm voxels, repetition time = 2300 msec, echo time = 2.32 msec, 0.9-mm slice thickness, field of view = 24 cm, matrix = 256 × 256, flip angle = 8°).

fMRI Data Preprocessing

All functional and anatomical images were reoriented in SPM12 (Wellcome Department of Imaging Neuroscience) to set the origin to the anterior commissure and the
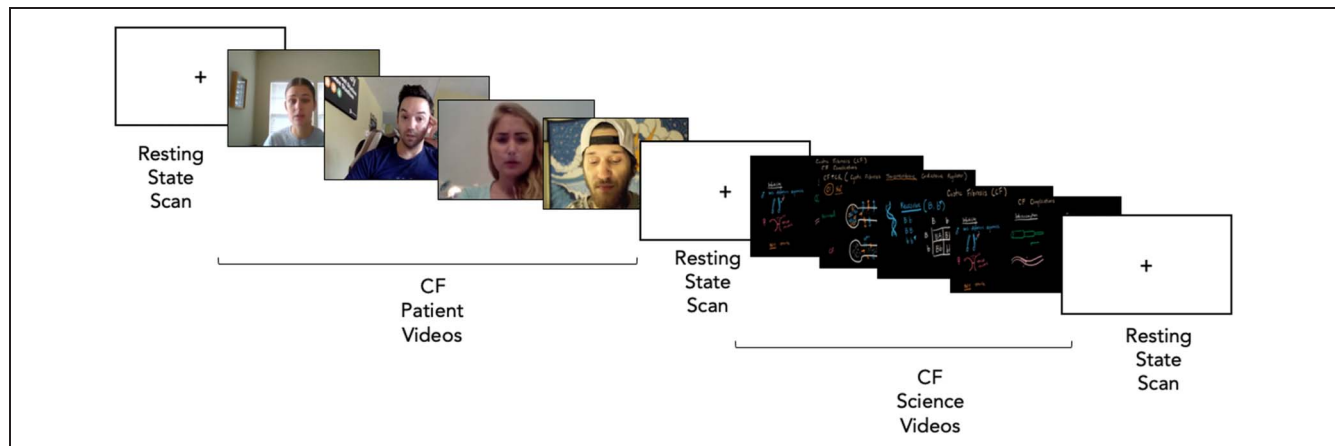
Figure 1. Brain imaging paradigm. Participants first completed a baseline resting state scan. Next, participants listened to patients with CF share their experience of dealing with their disease, and separately, teachers explain the science behind CF (order counterbalanced across participants). Each condition was followed by a postencoding resting state scan.

horizontal (y) axis parallel to the AC–PC line. Anatomical images were skull-stripped using the Brain Extraction Tool in FMRIB Software Library (FSL; Oxford University). For the creation of nuisance regressors, white matter and cerebrospinal fluid masks were generated from each anatomical image using FSL's FMRIB's Automated Segmentation Tool.

Preprocessing of functional data was carried out in FSL and was consistent with past approaches to studying functional connectivity during rest and memory consolidation (Meyer, Davachi, et al., 2019; Tambini et al., 2010). First, each EPI volume underwent the following preprocessing steps: removal of low-frequency noise below 0.009 Hz with a high-pass filter, motion correction using FMRIB's Linear Image Registration Tool (MCFLIRT), skull-stripping using the Brain Extraction Tool, spatial smoothing with a 6-mm radius, and registration to the anatomical image using Boundary-Based Registration. Second, nuisance variables were prepared for use as regressors in a general linear model (GLM). These included the six standard motion parameters and their derivatives, as well as the signal extracted from white matter and cerebrospinal fluid regions. Finally, all nuisance variables were regressed out of the data in a GLM, using a high-pass filter to remove any frequencies in the regressors below 0.009 Hz. To correct for extreme motion, additional nuisance variables were included in the GLM for global signal regression (the average brain signal) and motion scrubbing (volumes with framewise displacement > 0.2 mm). Past work has demonstrated this to be the most effective way of removing motion artifacts (Power et al., 2014). That said, given that these additional steps are not universally accepted (Parkes, Fulcher, Yucel, & Fornito, 2018; Yan, Craddock, He, & Milham, 2013), we also examined our primary findings without these conservative motion-correction steps. This demonstrated that the functional connectivity results indicating greater dMPFC-FPCN$_A$ connectivity during postpatient rest and its link to social memory performance remain significant when global signal regression and motion scrubbing are not included in our preprocessing pipeline (dMPFC-FPCN$_A$ functional connectivity postpatient rest vs. all other rest, $t(78) = 1.86$, $p = .03$, $\beta = 0.09$, $SE = 0.05$; correlation between dMPFC-FPCN$_A$ postpatient rest and subsequent social memory, $r = .33, p = .04$).

Brain Networks

For our functional connectivity analyses, we used the canonical brain networks defined by Yeo et al. (2011). Consistent with prior work, extremely small clusters (fewer than five voxels) were excluded from the analysis (Meyer, Hershfield, Waytz, Mildner, & Tamir, 2019). The Yeo et al. (2011) parcellation generates three default network subsystems that map onto known functional dissociations (Andrews-Hanna et al., 2010): a midline core, associated with self-referential processing (medial pFC [MPFC],

posterior cingulate/precuneus, posterior inferior parietal lobule [IPL]; Lieberman et al., 2019; Denny et al., 2012; Gusnard et al., 2001); an MTL subsystem, associated with remembering and imagining mental scenes (hippocampal formation, retrosplenial cortex, posterior IPL; Schacter & Addis, 2009; Squire & Zola-Morgan, 1991); and a dorsomedial subsystem (dMPFC), associated with thinking about others and social interactions (dMPFC, TPJ, temporal poles, inferior frontal gyrus; Wagner et al., 2016; Van Overwalle & Baetens, 2009; Mitchell et al., 2004; Saxe & Kanwisher, 2003).

The parcellation also generates regions for the FPCN, dorsal attention network, and ventral attention network, systems key to cognitive control, attention, and emotion processing (Nummenmaa et al., 2012, 2014; Dosenbach et al., 2007; Cabeza & Nyberg, 2000). We therefore also included these networks in our analyses to assess whether and how default network subsystems may increase functional connectivity with other, large-scale brain networks throughout our experimental conditions. The FPCN was further divided into two subsystems based on a 2018 meta-analysis by Dixon et al. (2018), suggesting this network is composed of two dissociable subsystems: one associated with the regulation of internally directed attention, shown to preferentially connect to the default network (posterior middle frontal gyrus [MFG], right lateral pFC, anterior IPL [aIPL], anterior middle temporal gyrus [MTG], pre-SMA), and another associated with the regulation of externally directed attention (anterior and posterior inferior frontal sulcus, posterior intraparietal lobule, posterior MFG), shown to preferentially connect to the dorsal attention network. To stay consistent with the naming conventions of Dixon et al. (2018), we refer to these networks as FPCN$_A$ and FPCN$_B$, respectively. Brain networks are visualized in Figure 2.

In addition to these networks, we also examined the role of the hippocampus during our experimental conditions. This included left and right anatomical hippocampal ROIs (based on automated anatomical labeling definitions in WakeForest PickAtlas [Maldjian, Laurienti, Kraft, & Burdette, 2003]) as well as two functionally defined hippocampal ROIs. One functionally defined hippocampal ROI was based on the Neurosynth association test map for the term "consolidation." Inclusion of this ROI allowed us to assess whether our data align with past (nonsocial) memory research implicating hippocampal–cortical connectivity in memory consolidation (Tambini et al., 2010; Ji & Wilson, 2007; Qin, McNaughton, Skaggs, & Barnes, 1997). This ROI was constrained to only include regions within the anatomical bilateral hippocampus using SPM's tool MarsBaR (Brett, Anton, Valabregue, & Poline, 2002). The other functionally defined ROI was an 8-mm sphere centered at Montreal Neurological Institute coordinates ($-24, -20, -18$), based on two studies that examined autobiographical memory and mentalizing (Rabin, Gilboa, Stuss, Mar, & Rosenbaum, 2010; Spreng & Grady, 2010). This hippocampal region

Figure 2. Brain networks used in functional connectivity analyses.
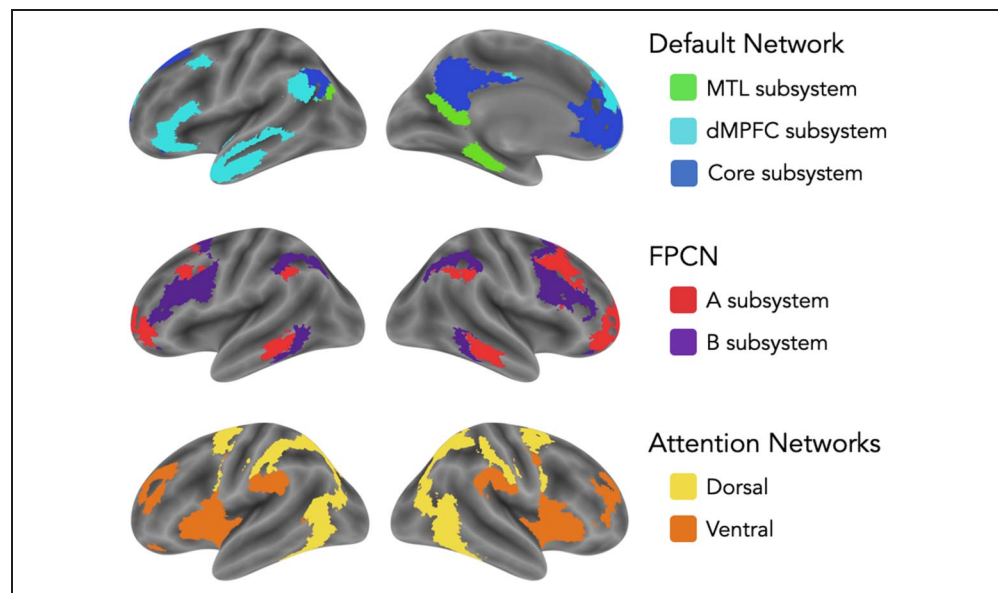
has been found to connect with regions associated with mentalizing during rest (Spreng & Mar, 2012).

Functional Connectivity and Graph-based Network Analyses

Computing connectivity. ROIs were registered to Montreal Neurological Institute space and then to each participant's anatomical image, using FSL's FLIRT tool. After preprocessing the BOLD data, average BOLD time courses were extracted from ROIs using fslmeants. The pairwise connectivity between ROIs was found by computing the Pearson correlation between BOLD time courses for each ROI pair. These Pearson correlations were then Fisher z transformed to allow for statistical comparisons of connectivity between conditions. Within-network connectivity was calculated by averaging across correlation coefficients for each ROI pair in a given network. Between-network connectivity was calculated by averaging across correlation coefficients for each between-network ROI pair.

Condition comparisons. Our primary goal for Study 1 was to assess whether and how the default network may be associated with consolidating disclosures during rest after listening. To find connectivity that was preferentially elevated for this rest period, relative to all other conditions, we ran linear mixed-effect models using R's lme4 package (Bates, Mächler, Bolker, & Walker, 2015). For a given within- or between-network comparison, the model evaluated connectivity as a function of block and controlled for multiple within-participant measures by including a random intercept for each participant. Connectivity during postpatient rest was compared to the average connectivity during all other conditions (i.e., all other rest and video-watching conditions) using a sum contrast. For connectivity that was found to be preferentially enhanced during postpatient rest, we also ran

follow-up sum contrasts comparing postpatient rest versus each of the other rest conditions (baseline rest and postscience rest), to ensure that our functional connectivity results were not simply driven by idiosyncrasies during video encoding (as opposed to our primary interest in changes during rest). Because we had specific predictions of enhanced connectivity during postpatient rest, these follow-up analyses were one-tailed.

Graph-based network analyses. For network pairs with elevated between-network functional connectivity during postpatient rest, we used graph-based network analyses to investigate whether particular ROIs helped bridge the two networks during postpatient rest. Because follow-up, between-network functional connectivity analyses showed dMPFC-FPCN$_A$ connectivity was greater during postpatient rest versus baseline and postscience rest (see Results section), we only performed graph analyses on resting state scans with these regions. Network analyses were carried out in BRAPH (Mijalkov, Kakaei, Pereira, Westman, & Volpe, 2017) on the weighted undirected graph of a given network pair, with negative correlations between ROIs set to zero. A predefined community structure was established, with each network assigned to a separate community. Linear mixed effects models with sum contrasts were used to test for greater participation during postpatient rest relative to baseline rest and postscience rest. Because we had specific predictions of enhanced participation during postpatient rest, these follow-up analyses were one-tailed.

For every rest period, we computed each ROI's participation coefficient, which indicates the extent to which one ROI preferentially connects to ROIs outside its own community. The participation coefficient for each ROI was calculated as

$$P_i = 1 - \sum_S \left(\frac{K_{S_i}}{K_i}\right)^2$$

where the sum runs over all communities, K_{S_i} is the number of edges connecting the ROI i within its community S_i, and K_i is the total number of edges of ROI i. Unlike between-network functional connectivity, which represents how strongly on average ROIs in one network connect with ROIs in another network, the participation coefficient of a given ROI represents the proportion of its connections to ROIs outside its network versus ROIs within its own network. ROIs with high participation coefficients can be considered "connector hubs" and are likely to facilitate integration between networks (Guimerà, Sales-Pardo, & Amaral, 2007; Guimerà & Amaral, 2005). Thus, the participation coefficient provides a more nuanced measure of how two networks connect than functional connectivity does and can be used to identify individual ROIs critical to cross-network integration.

We tested ROI participation at (1) the network level of analysis and (2) the ROI level of analysis. At the network level of analysis, we averaged across all ROIs in a given network to compute the mean participation of ROIs in that network. This resulted in two distinct values: the mean participation of dMPFC ROIs (preferential connection with $FPCN_A$ ROIs) and the mean participation of $FPCN_A$ ROIs (preferential connection with dMPFC ROIs). Note that these two measures are not redundant, as the participation of dMPFC ROIs depends partly on within-dMPFC connections, whereas the participation of $FPCN_A$ ROIs depends partly on within-$FPCN_A$ connections (thus, it would be possible for one network to have high mean participation and the other to have low mean participation). At the ROI level of analysis, we used each ROI's individual participation coefficient (preferential connection with ROIs in the opposite network) as the unit of analysis.

Memory performance. Finally, to evaluate whether default network functional connectivity during rest after listening may facilitate consolidation of disclosures, we assessed the relationship between individual differences in connectivity during rest and subsequent memory of the videos. We computed the Pearson correlation between connectivity and graph-based participation results that was found to be preferentially enhanced during postpatient rest and the number of patient facts recalled. Because we had specific predictions of a positive correlation between connectivity and memory, these analyses were one-tailed. To assess the specificity of observed memory correlations, we also assessed whether similar patterns emerged during postscience rest and the number of science facts recalled.

To generate memory scores, the number of pieces of information recalled was summed across all videos, separately within each video block. A recalled piece of information was only counted if it was both distinct (nonredundant with other pieces of information recalled) and correct. For the patient videos, pieces of information were additionally limited to memory of patients' experiences (as opposed to perceptions of the

patient unrelated to what they disclosed, such as patients' physical features or participants' opinions about the patient). Although participants recalled more facts about the patients' experiences ($M = 25.4$, $SD = 12.5$) than the science of CF ($M = 18.2$, $SD = 11.0$), $t(39) = 3.66$, $p < .001$, these two indices of memory were significantly correlated ($r = .45$, $p = .004$), indicating that they tapped into similar, although not fully redundant, aspects of memory.

Results

Functional Connectivity Results

The primary goal of Study 1 was to identify brain networks that may help consolidate information about others' disclosures during subsequent rest. Networks that specifically aid in this process should connect most strongly during the rest period after patients' disclosures or "postpatient rest." Using a linear mixed model with sum contrasts, we tested for within- and between-network connectivity that was preferentially increased during postpatient rest, relative to our other conditions. Only connectivity between the dMPFC subsystem of the default network and the $FPCN_A$ subsystem was preferentially elevated during postpatient rest, $t(156) = 3.24$, $p = .001$, $\beta = 0.17$, $SE = 0.05$ (Figure 3A). This comparison survives Bonferroni correction for the number of network comparisons made ($p < .002$). The follow-up contrast assessing whether functional connectivity between these regions during postpatient rest was significantly greater than baseline and postscience rest was significant, $t(78) = 1.77$, $p = .041$, $\beta = 0.12$, $SE = 0.07$.

Given that dMPFC-$FPCN_A$ connectivity increased during postpatient rest, we next tested whether the gain in connectivity between these networks was associated with better memory for the patients' experiences. If so, this would be consistent with the idea that communication between these networks after listening to disclosers facilitates memory for them. Indeed, dMPFC-$FPCN_A$ connectivity during postpatient rest (vs. baseline rest) correlated with the number of distinct, correct facts recalled from the patient videos ($r = .36$, $p = .02$; Figure 3B). In contrast, dMPFC-$FPCN_A$ connectivity during rest after the Kahn academy videos, or "postscience rest" (vs. baseline rest), did not significantly correlate with the number of facts recalled from the science videos ($r = .22$, $p = .17$), although it should be noted that these two correlations with memory are not significantly different from one another ($z = 1.04$, $p = .15$). Previous work has shown that the dMPFC subsystem plays a role in interpreting other people (Wagner et al., 2016; Van Overwalle & Baetens, 2009; Mitchell et al., 2004; Saxe & Kanwisher, 2003), whereas the $FPCN_A$ subsystem helps regulate and sustain internal reflection (Dixon et al., 2018). It is possible that the integration of these two processes in the brain, that is, sustaining reflection about
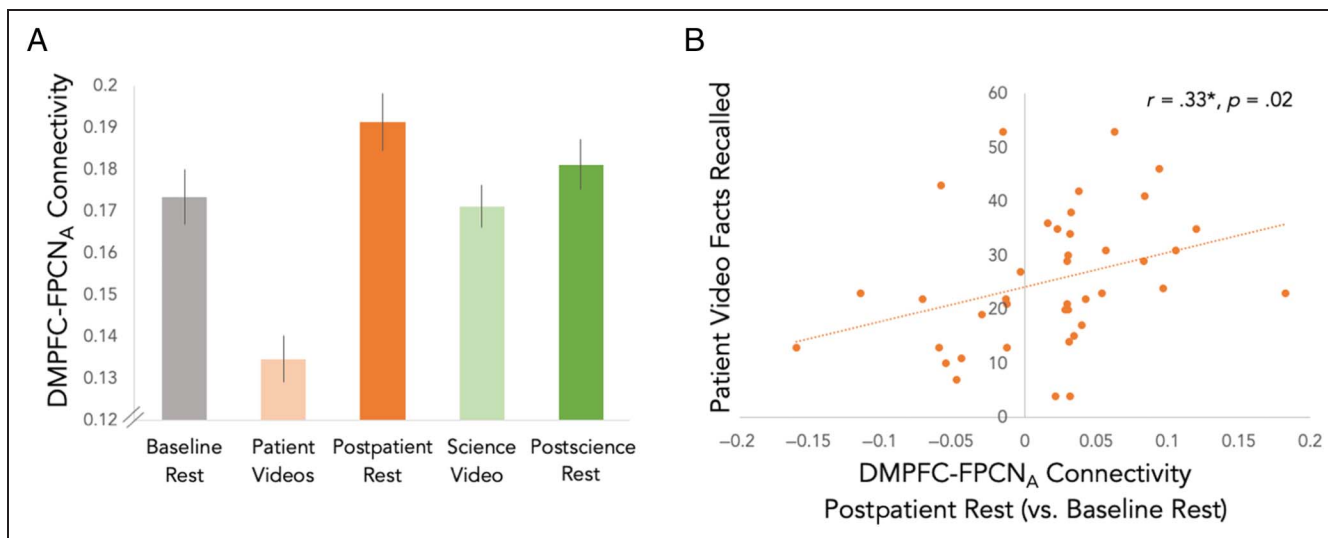
Figure 3. Functional connectivity results from Study 1. (A) dMPFC-FPCN$_A$ connectivity was greater during postpatient rest, relative to each of the other conditions. (B) Greater dMPFC-FPCN$_A$ connectivity during postpatient rest (vs. baseline rest) correlates with greater subsequent memory for the patients' experiences.

others during postencoding rest aids in subsequent recollection of others' experiences.

It is also noteworthy that, whereas dMPFC-FPCN$_A$ connectivity was highest during postpatient rest, as noted above, it was significantly lower during the patient videos, $t(156) = -6.53$, $p < .001$. Thus, the dMPFC subsystem's partnership with the FPCN$_A$ may be more important for sustaining social information processing during postencoding rest, rather than during encoding itself. In contrast, within-network dMPFC subsystem connectivity was greater during patient video encoding ($M = 0.26$, $SD = 0.03$) versus science video encoding ($M = 0.23$, $SD = 0.03$), $t(39) = 6.40$, $p < .001$. This result is consistent with past research showing that the dMPFC subsystem is preferentially associated with social versus nonsocial inferences during encoding (Wagner et al., 2016; Van Overwalle & Baetens, 2009; Mitchell et al., 2004; Saxe & Kanwisher, 2003) and survives Bonferroni correction for the number of possible within- and between-network comparisons ($p < .002$). However, neither dMPFC within-system connectivity nor any of the other network comparisons that significantly varied for encoding conditions correlated with subsequent memory (rs < .14, ps > .39). This further implicates the potential importance of postencoding rest periods, above and beyond encoding, for consolidating information about disclosers' experiences.

Although it was not our main goal, we also looked for connectivity that may help consolidate memory for the science videos. A large body of research has already explored the neural correlates of nonsocial memory consolidation during rest, finding that hippocampal–cortical connectivity plays a critical role (e.g., Murty et al., 2017; Tambini et al., 2010; Peigneux et al., 2006). However, to our knowledge, no studies have done so using stimuli

that mimic how students learn in classrooms. Our results showed that none of our hippocampal ROIS, or any of the Yeo et al. (2011) networks we examined, were uniquely elevated during postscience rest (ps > .2). However, during postscience rest (vs. baseline rest), connectivity between the core subsystem of the default network and the hippocampus ROI defined by the search term "consolidation" in NeuroSynth correlated with memory for the science videos ($r = .37$, $p = .02$).

Graph-based Network Results

Thus far, our results suggest that dMPFC-FPCN$_A$ between network functional connectivity during postpatient rest is associated with consolidating others' disclosures in memory. To further understand this phenomenon, we next sought to determine which of these regions are particularly strong connector hubs that may help integrate the two networks during postpatient rest. To this end, we used graph-based network analyses on our resting state scans to assess (1) network-level participation (i.e., how much, on average, each ROI in a network preferentially connects with the opposite network) and (2) ROI-specific participation (i.e., how much an ROI preferentially connects with all other ROIs outside its own network).

At the network level of analysis, we found that, on average, regions in the dMPFC subsystem and FPCN$_A$ subsystem demonstrated higher participation during postpatient rest compared to the other rest periods, $t(78)_{FPCNA} = 2.47$, $p = .016$, $\beta = 0.18$, $SE = 0.07$; $t(78)_{dMPFC} = 1.95$, $p = .054$, $\beta = 0.15$, $SE = 0.08$ (Figure 4A and 4C). In addition, their participation during postpatient rest (vs. baseline rest) significantly correlated with memory for the patient videos ($r_{dMPFC} = .30$, $p = .029$; $r_{FPCNA} = .41$, $p = .004$;
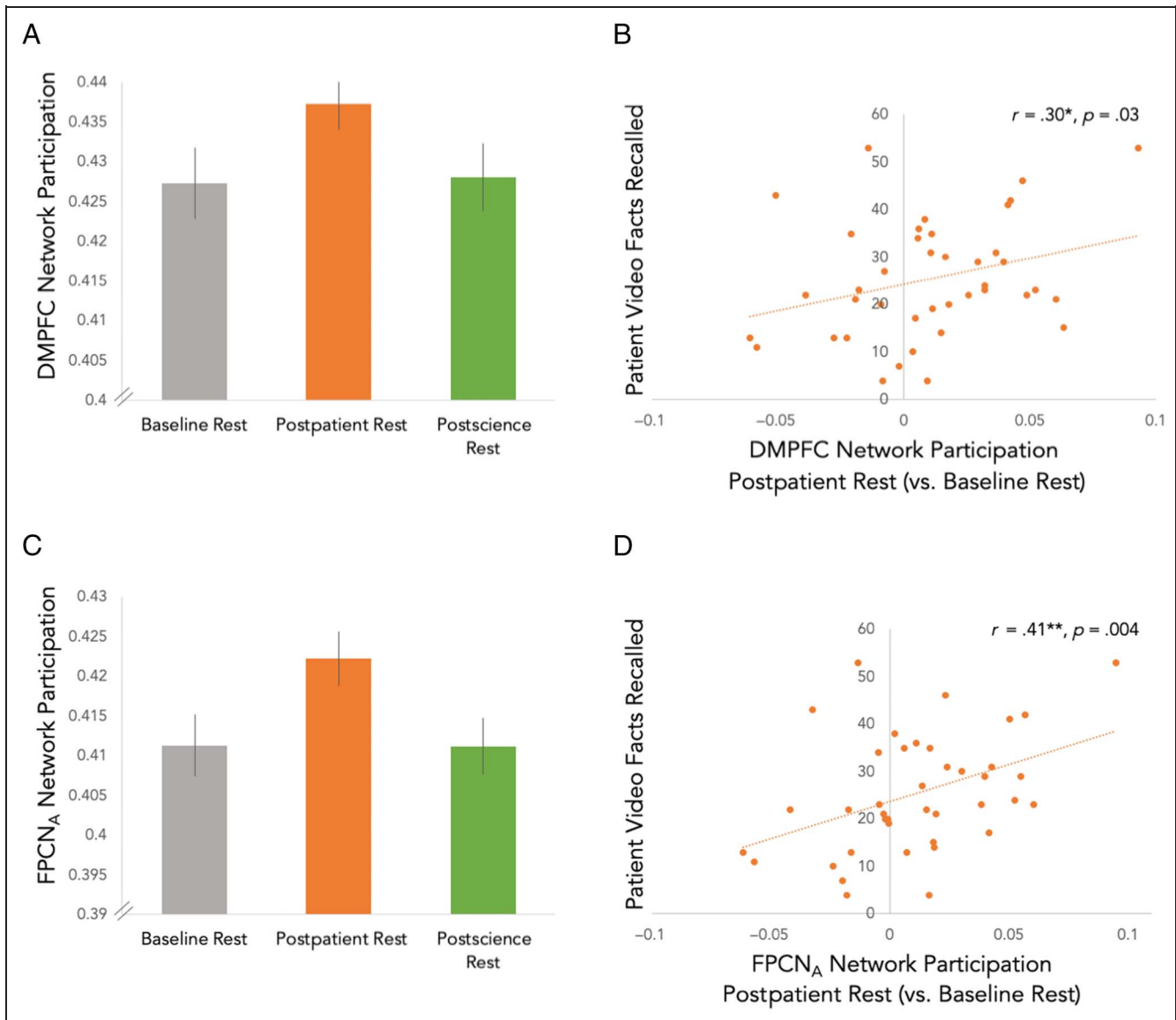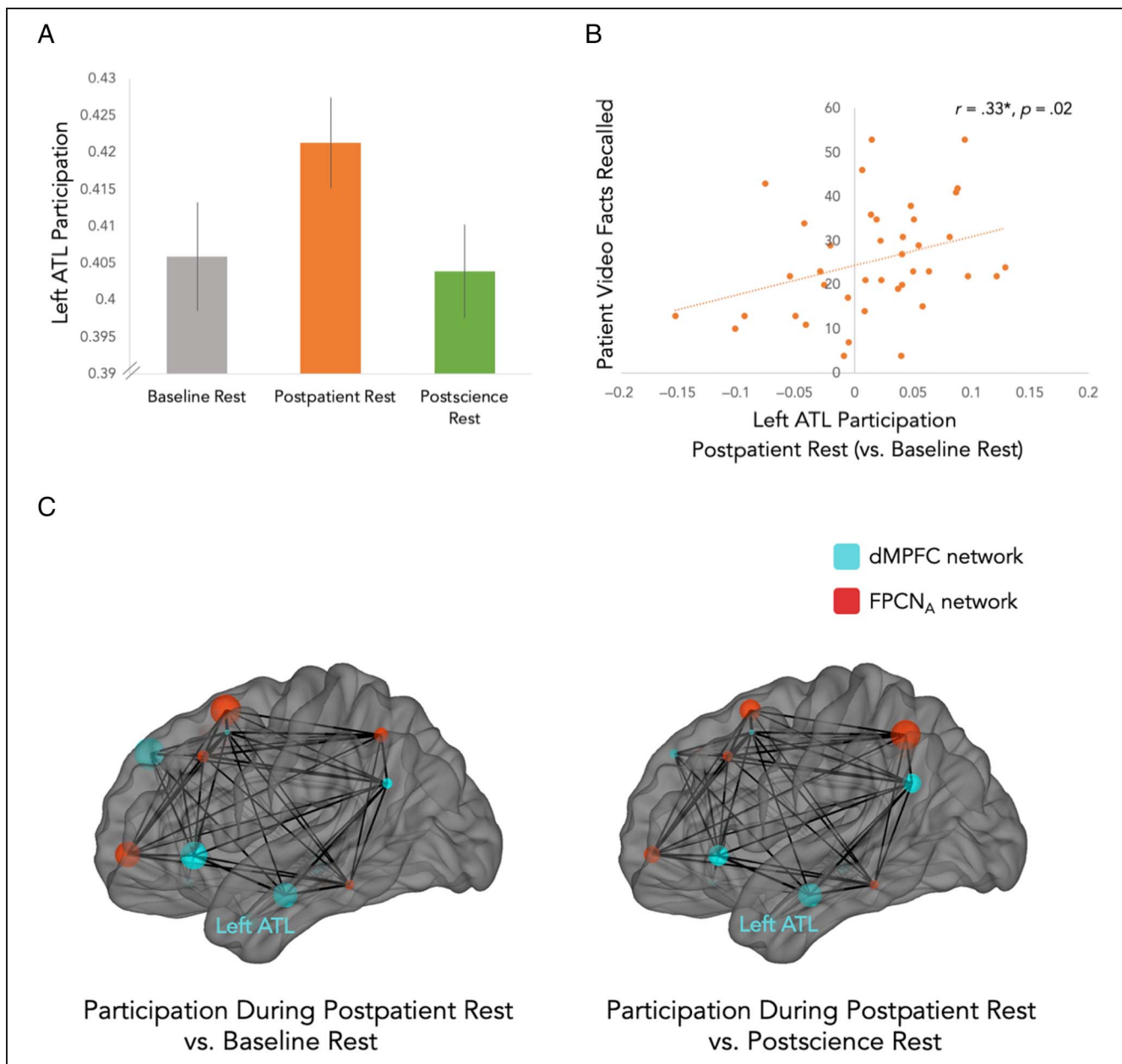
Figure 4. Network-level participation coefficient results from Study 1. (A) Average participation of dMPFC ROIs was greater during postpatient rest, relative to each of the other conditions. (B) Average participation of dMPFC ROIs during postpatient rest (vs. baseline rest) correlates with greater subsequent memory for the patients' experiences. (C and D) show the same pattern of results for average participation of FPCN_A ROIs.

Figure 4B and 4D). In contrast, average subsystem participation during postscience rest (vs. baseline rest) did not significantly correlate with memory for the science videos ($r_{\text{FPCNA}} = .19$, $p = .12$; $r_{\text{dMPFC}} = .23$, $p = .08$). Moreover, the correlations between (1) participation during postpatient rest and patient memory and (2) participation during postscience rest and science memory were significantly different from one another for FPCN_a participation ($z = 1.84$, $p = .03$), although not dMPFC subsystem participation ($z = 0.62$, $p = .27$). Thus, FPCN_a participation with dMPFC subsystem ROIs during postpatient rest is preferentially associated with better memory for patients' disclosures.

At the ROI level of analysis, only the left anterior temporal lobe (ATL) from the dMPFC subsystem showed higher participation across the two networks during postpatient rest relative to the other two rest periods, $t(78) =$

2.02, $p = .047$, $\beta = 0.16$, $SE = 0.08$ (Figure 5A). The left ATL's participation during postpatient rest (vs. baseline rest) also correlated with memory for the patient videos ($r = .33$, $p = .02$; Figure 5B). In contrast, left ATL participation during postscience rest (vs. baseline rest) did not correlate with memory for the science videos ($r = .19$, $p = .13$), although it should be noted that these two correlations with memory are not significantly different from each other ($z = 1.16$, $p = .12$). To explore which particular regions of the FPCN_A subsystem the left ATL works together with to facilitate learning about disclosures, we tested whether functional connectivity between FPCN_A regions and the left ATL during postpatient rest (relative to baseline rest) was associated with memory for patients' disclosures. Connectivity between the left ATL and the left MFG, left MTG, and left aIPL correlated

Figure 5. ROI-level participation coefficient results from Study 1. (A) The left ATL's participation was greater during postpatient rest, relative to each of the other conditions. (B) The left ATL's participation during postpatient rest (vs. baseline rest) correlates with greater subsequent memory for the patients' experiences. (C) The relative participation of all ROIs for postpatient rest versus baseline rest and for postpatient rest versus postscience rest. A larger sphere indicates that an ROI had greater participation during postpatient rest relative to the other rest period. Edges between ROIs are based on the weighted undirected graph for postpatient rest.

with memory for patients' disclosures (r_{MFG} = .40, p = .005; r_{MTG} = .28, p = .04; r_{aIPL} = .28, p = .04). These ATL findings complement and extend previous work showing this region is associated with representing and retrieving information about others in memory (Wang et al., 2017; Olson, McCoy, Klobusicky, & Ross, 2013).

In summary, Study 1 provides the first insight into the large-scale brain networks that are associated with consolidating memory for others' disclosures during rest. We found that dMPFC-FPCN$_A$ between-network functional connectivity preferentially increased during rest after the patient videos and correlated positively with participants'

subsequent memory for the patients' experiences. Graph-based network analyses further demonstrated that this preferential gain in functional connectivity corresponds with greater participation of regions in these networks. The left ATL in particular may help bridge these two networks to consolidate memory for others' disclosures. Critically, although some within- and between-network comparisons statistically varied in response to each encoding condition, no connectivity during video watching related to subsequent memory. These patterns point to the possibility that idle rest after listening, above and beyond listening in the moment, is important for interpersonal learning and memory.

STUDY 2

Results from Study 1 suggest that dMPFC-FPCN$_A$ between-network connectivity during rest after listening to disclosures is associated with consolidating information about disclosers' experiences. Given that the dMPFC and FPCN$_A$ are associated with interpreting other people and regulating internal reflection, respectively (Dixon et al., 2018; Wagner et al., 2016; Van Overwalle & Baetens, 2009; Mitchell et al., 2004; Saxe & Kanwisher, 2003), it is possible that listeners reflect on the newly encoded information about disclosers' experiences during subsequent rest to learn about them. To test this psychological interpretation more explicitly, in Study 2, a new sample of participants completed the same experimental paradigm used in Study 1 (however, without undergoing fMRI). At the end of each rest period, participants were asked to write a journal entry describing what they thought about during the idle period. These journal entries were submitted to a text analysis to assess whether participants preferentially engaged in other-focused thought during postpatient rest as well as whether this objectively assessed form of other-focus predicted subsequent memory for the patients.

In Study 2, we also tested whether listeners' memory for disclosers' experiences predicts whether and how well listeners subsequently provide them with support. To this end, participants in Study 2 were provided the option to write the patients a supportive message. Critically, participants did not receive additional payment if they chose to write a letter, to help ensure that only prosocial motivation drove the decision. These messages were then assessed by a new set of participants, who rated them for their supportiveness. We were therefore able to test whether memory for disclosers' experiences is associated with deciding to provide support and, if so, whether it additionally related to the effectiveness of support-giving.

Methods

Participants

Participants ($n = 197$; 106 women; mean age = 36.96 years, $SD = 10.53$) recruited online from Amazon's Mechanical Turk completed Study 2 for monetary payment ($6/hr). Of these participants, 85% were white; 4% were African American; 4% were Asian; 2% were Hispanic; and 5% were mixed/other. Participants provided informed consent in accordance with the Dartmouth College institutional review board.

Online Task

Day 1. Upon beginning the experiment, participants completed the same paradigm used in Study 1, with a few differences. To facilitate engagement online, but without changing the overall length of the experiment, rest blocks were slightly shorter (4 min rather than 6 min), and the video blocks were slightly longer (six videos rather

than four). Participants completed the experiment in the Inquisit 5 Player application, which ensured that participants could not do other tasks on their computers during the videos or rest periods as it locks users into the Inquisit screen. Compliance during rest periods was further ensured by asking attention check questions every minute plus or minus a random interval; data were discarded for participants who failed more than one attention check (36 participants who are not reflected in our final sample of $n = 197$). After each rest period, participants were additionally asked to free write about all of the thoughts they had during the previous rest period. At the end of the task, participants completed the same surprise memory test used in Study 1, and their responses were later scored for the number of distinct, correct facts recalled.

Day 2. On the second day of the experiment, participants had the option to write a message of support to any of the patients they had listened to the day prior. To ensure that choosing to write a message was not driven by interest in monetary reward, participants were not paid extra for choosing to write, nor their time spent doing so. To increase participants' perception that their support could be impactful, they were told that their messages would be delivered to the patients they addressed.

Supporters' messages were scored by an independent sample of Mechanical Turk raters ($n = 28$). Raters answered the following four questions for each message, on a scale of 0–100: (1) "Overall, how supportive does the writer seem?"; (2) "To what extent does the writer express concern for the difficulties the recipient is facing?"; (3) "To what extent does the writer express encouragement (e.g., You can do it)?"; and (4) "To what extent do you think this message would make the recipient feel better?" Similar questions have been used in past work studying support-giving to evaluate the supportiveness of messages (Inagaki & Eisenberger, 2016). As ratings for these four questions were highly related (Cronbach's alpha = .98), we averaged across them to generate a single supportiveness score.

Data Analysis

Linguistic analysis of rest thought content. We used the 2015 Linguistic Inquiry and Word Count (Pennebaker, Boyd, Jordan, & Blackburn, 2015) software to assess the amount of other-focused reflection in participants' free writes. For each participant, we summed the percentages from the Linguistic Inquiry and Word Count categories that referenced other people and social interaction more generally. This included all non-first-person singular personal pronouns (e.g., "she," "him," "they"), nouns that pertain to people (e.g., "girl," "neighbor"), and verbs that suggest human interaction (e.g., "talking," "sharing"). We refer to this score in all subsequent analyses as "other-focus."

Condition comparisons. To test whether other-focus was uniquely elevated during postpatient rest, we ran a linear

Figure 6. Results from Study 2. (A) Other-focused thought content was greatest during postpatient rest, relative to each of the other rest periods. (B) Results from the mediation model demonstrating that memory of patient videos partially explains the relationship between other-focused thoughts during postpatient rest and subsequently choosing to write a supportive message.
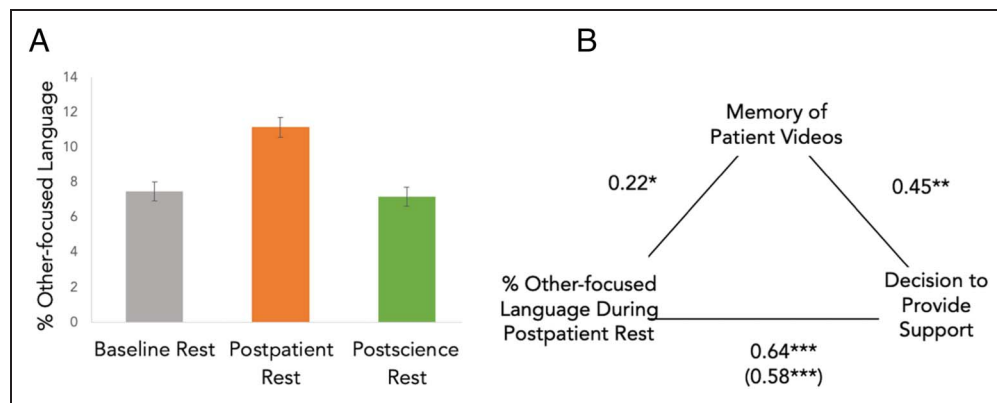
mixed-effect model using R's lme4 package (Bates et al., 2015). The model evaluated other-focus as a function of rest block and controlled for multiple within-participant measures by including a random intercept for each participant. Other-focus during postpatient rest was compared to other-focus during all other rest blocks using a sum contrast.

Memory performance and providing support. To evaluate the relationship between individual differences in other-focus during rest and subsequent memory for the videos, we computed the Pearson correlation between other-focus and number of facts recalled. t Tests were used to compare other-focus and memory across participants who wrote at least one supportive message and participants who wrote none. To examine the interactions between all three variables (other-focus, memory, and message writing), we tested for mediation with R's mediation package (Tingley, Yamamoto, Hirose, Keele, & Imai, 2014) using the bias-corrected bootstrap based on 5000 bootstrapped samples. In addition, for the participants who wrote at least one supportive message, we computed the Pearson correlation between the supportiveness of their messages and facts recalled from the patient videos.

Participants' memory performance for the patient ($M = 15.1$, $SD = 9.0$) and science ($M = 14.8$, $SD = 11.5$) videos were not significantly different from one another, $t(196) = 0.57$, $p = .57$, suggesting that the significant difference between memory scores observed in Study 1 is unlikely a robust finding and mitigates concerns that observed differences may be driven by differences in memory difficulty for the two types of encoding. Nonetheless, as in Study 1, these two indices of memory were significantly correlated ($r = .71$, $p < .001$), again indicating that they tap into similar, although not fully redundant, aspects of memory.

Results

Thought Content Preferentially Associated with Rest after Listening to Emotional Disclosures

Our first goal in Study 2 was to test whether other-focused thought during rest after listening to disclosures is associated with better subsequent memory for them. If

so, our linguistic measure of other-focus should parallel the neural findings from Study 1 (i.e., increase the most during postpatient rest and correlate with the number of patient facts recalled). Indeed, a linear mixed model showed that other-focus was uniquely elevated during postpatient rest, $t(392) = 6.28$, $p < .001$, $\beta = 0.26$, $SE = 0.04$ (Figure 6A). Moreover, other-focus during postpatient rest also correlated with the number of facts recalled from the patient videos ($r = .20$, $p = .005$).

The Relationship between Thought Content, Memory, and Supportive Behavior

Our next goal was to assess the relationship between memory for others' emotional disclosures and subsequent supportive behavior. When we compared memory between participants who wrote at least one supportive message ("supporters") and those who did not ("nonsupporters"), we found that supporters remembered, on average, 3.6 more facts from the patient videos, $t(195) = 2.95$, $p = .004$. Intriguingly, supporters also engaged in 1.5 times as much other-focused thought during postpatient rest compared to nonsupporters, $t(186) = 4.18$, $p < .001$. This observation led us to test for mediation, and we indeed found that the relationship between other-focus during postpatient rest and supportive behavior was partially mediated by memory of the patient videos (proportion mediated = 11%, 95% CI [2%, 38%], $p = .03$; Figure 6B, Table 1).

Table 1. Test of Mediation with Bootstrapped Results for Other-Focus → Memory of Patient Videos → Decision to Provide Support

	β Coefficient	Bias-corrected 95% CI		p Value
		Lower	Upper	
Indirect effect	0.02	0.002	0.04	.03
Direct effect	0.13	0.06	0.21	<.001
Total effect	0.15	0.08	0.22	<.001
Proportion of total effect mediated	0.11	0.02	0.38	.03
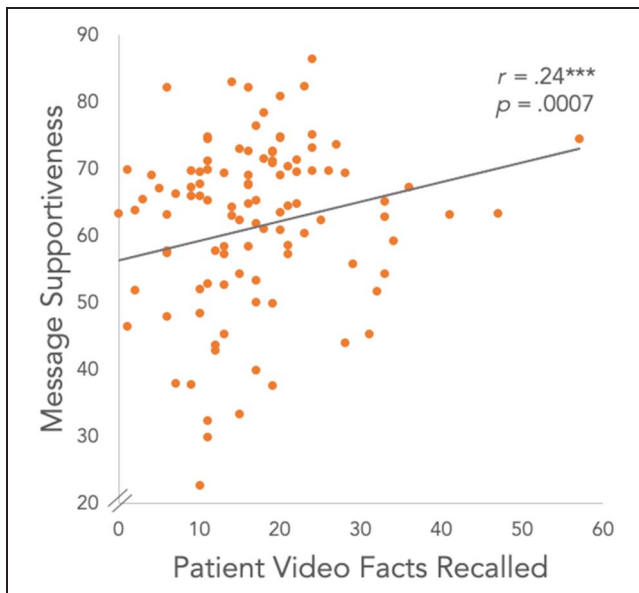
Figure 7. Among participants who wrote messages to the patients, memory of patients' experiences correlated with supportiveness of participants' messages. It is noteworthy that this correlation remains significant if the most extreme data point is removed ($r = .22, p = .002$).

Finally, among supporters, greater memory for disclosers' experiences also tracked with the supportiveness of their messages. That is, independent raters' assessments of letter supportiveness significantly correlated with supporters' memory for disclosers' experiences ($r = .24, p < .001$; Figure 7). Collectively, these results suggest that memory for others' disclosures has a real-world impact on supportive behavior and helps explain the link between the content of our thoughts after listening to disclosers and our decision to subsequently support them.

DISCUSSION

Disclosing difficult experiences is a hallmark of interpersonal relationships. Yet, virtually no research to date has examined how listeners digest this information to effectively learn about disclosers' experiences, nor whether the ability to do so helps listeners provide disclosers with support. Across two studies, we identified mechanisms during postencoding rest that help listeners consolidate information about disclosers' experiences and found that such memory facilitates subsequent supportive behavior. In Study 1, dMPFC-FPCN$_A$ between-network connectivity was uniquely elevated during rest after watching videos of patients' disclosures and correlated with memory for patients' experiences. In addition, graph-based network analyses revealed that regions in these two networks, most notably the left ATL, may help bridge these networks to consolidate memory for others' disclosures. In Study 2, memory for patients' disclosures predicted whether and how well participants supported the

patients the next day. Moreover, memory for patients' disclosures partially mediated the relationship between other-focused thought during postencoding rest and subsequent social support. Collectively, these findings point to the important role of memory consolidation during rest in support provision.

Results from Study 1 provide new insight into the role of dMPFC-FPCN$_A$ connectivity in social learning and memory. Past research has found that both of these networks are associated with maintaining and manipulating high-level social information (e.g., information about people's personality traits) over a very brief delay in working memory (i.e., 6 sec [Meyer, Taylor, & Lieberman, 2015; Meyer et al., 2012]). Here, we found that these networks can sustain communication during longer timescales (i.e., 6 min) directly after exposure to new social information and that doing so predicts subsequent social memory performance. Previous work implicates the dMPFC subsystem in interpreting other people (Dixon et al., 2018; Wagner et al., 2016; Van Overwalle & Baetens, 2009; Mitchell et al., 2004; Saxe & Kanwisher, 2003) and the FPCN$_A$ subsystem in regulating internal reflection (Dixon et al., 2018). Thus, the integration of these two processes during postencoding rest may help listeners learn about disclosers after interacting with them. Consistent with this interpretation, in Study 2, we found that other-focused thought during the rest period after patients' disclosures correlated with memory for patients' experiences. Interestingly, the primary neural findings in Study 1 were specific to postencoding rest; although there was evidence of greater connectivity for some networks while participants listened to patient videos versus science videos, it did not relate to subsequent patient memory. These patterns point to the intriguing possibility that idle rest after listening, above and beyond listening in the moment, is important for interpersonal learning and memory.

Graph-based network analyses in Study 1 provide further insight into which and how regions in these two networks help them work together to consolidate memory of disclosures. On average, regions in both the dMPFC subsystem and the FPCN$_A$ subsystem demonstrated higher participation (the extent to which regions can be considered "connector hubs" between networks) during postpatient rest, and their participation during postpatient rest correlated with memory for the patient videos. Of these regions, only the left ATL demonstrated significant participation and links to patient memory at the ROI level of analysis. This finding is consistent with past work showing that the ATL is critical to representing and retrieving information about others in memory (Wang et al., 2017; Olson et al., 2013). However, to our knowledge, this is the first study to reveal that the ATL may play an important role in bridging the dMPFC and FPCN$_A$ subsystems to support social learning and memory during postencoding rest.

Study 1 was also the first to compare consolidation during rest of social versus nonsocial naturalistic stimuli. Both sets of videos present information in a realistic style:

The patient videos are real emotional disclosures posted on YouTube, and the science videos are real course material used by students in Khan Academy. Thus, results from Study 1 lend real-world relevance to past experimental findings with high internal validity but relatively impoverished external validity. In particular, our findings dovetail with past work showing that default network connectivity during postencoding rest helps consolidate basic facts about people (i.e., recognizing photographs of faces and associating traits and roles with them). Collectively, these results suggest one function of engaging the default network during rest may be to learn about the people we interact with day-to-day (Meyer, 2019; Meyer, Davachi, et al., 2019).

In addition, results from Study 1 lend real-world relevance to previous work identifying hippocampal–cortical connectivity in nonsocial memory consolidation. Connectivity between the hippocampus and core subsystem of the default network during the rest period after Khan Academy videos correlated with memory for the science facts communicated in these videos. On the one hand, these findings are at odds with past social neuroscience suggestions that the default network's core subsystem is associated with self-referential processing (Lieberman et al., 2019; Denny et al., 2012). On the other hand, the results align with other memory research implicating connectivity between the hippocampus and the MPFC (a region of the core subsystem) in memory consolidation more broadly (Eichenbaum, 2017; Euston, Gruber, & McNaughton, 2012). For example, hippocampal-MPFC connectivity during rest is associated with updating our knowledge of an unfolding story (van Kesteren, Fernández, Norris, & Hermans, 2010). Future research may reveal whether hippocampal-core subsystem connectivity during postencoding rest plays a general role in updating previous memories across both self-relevant and non-self-relevant stimuli.

Study 2 builds on the primary neural findings in Study 1 by illuminating the cognitive processes during rest that may aid in consolidating memory of emotional disclosures. Other-focused thought was uniquely elevated during rest after viewing videos of patients' disclosures and correlated positively with participants' memory for patients' experiences. These findings add to a growing area of research examining the neurocognitive processes associated with providing social support (Inagaki & Orehek, 2017; Inagaki & Eisenberger, 2012, 2016) and open interesting avenues for future investigation. For example, one direction for future research will be to examine whether (and how) memory consolidation during rest could help us learn about and support individuals in our own social networks. Indeed, one study found that greater dMPFC subsystem connectivity during rest corresponded with greater support-giving to a close other during the following month (Inagaki & Meyer, 2019). Although our findings pertained to learning about and providing support to new individuals, the ability to remember disclosures may also help us maintain our close social connections. The results also have interesting implications for provider–patient relationships. Patients overwhelmingly prefer doctors, nurses, and therapists who respond supportively to their disclosures (von Dietze & Orb, 2000; Ong, de Haes, Hoos, & Lammes, 1995; Miller, 1993; Thompson & Anderson, 1982). Our findings implicate brief rest after listening as a possible route to compassionate care.

Although our findings provide the first evidence to date on the role of rest in consolidating others' disclosures, they are not without limitations. First, our sample size of 40 participants in Study 1 is relatively underpowered to detect individual differences; our fMRI sample size was determined based on available funding, and future studies with larger samples are needed to replicate the correlations observed in Study 1. Second, although our two video-watching conditions vary in the inclusion of disclosure, they may vary on other dimensions as well, such as valence and interestingness, which could impact our results. In our view, these variables may be intrinsic to disclosures, and thus we chose to not control for them in this first study on consolidation of disclosures during rest. Instead, we chose the science videos as the control condition because they also involve hearing someone talk about CF, just not their personal experience with it. Third, it is also possible that the science videos were more challenging to comprehend than the patient videos. However, in our large sample in Study 2, participants' science memory performance was not significantly different from their patient memory performance, suggesting any differences in difficulty did not impact memory. Nonetheless, future research may help clarify the combination of ingredients in disclosures that contribute to their consolidation during rest.

In summary, we found that listeners consolidate information shared by disclosers, in part, by increasing dMPFC-FPCN$_A$ connectivity during rest. Moreover, listeners' ability to consolidate information about disclosers' experiences helped them support disclosers in their time of need. These results point to the critical, although previously overlooked, role of memory consolidation in facilitating supportive relationships. More broadly, the findings suggest that, in our increasingly busy lives, taking the time to briefly rest may not only help us care for ourselves but also help us care for others.

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