

Article

Neural mechanisms associated with semantic and basic self-oriented memory processes interact moderating self-esteem

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Highlights

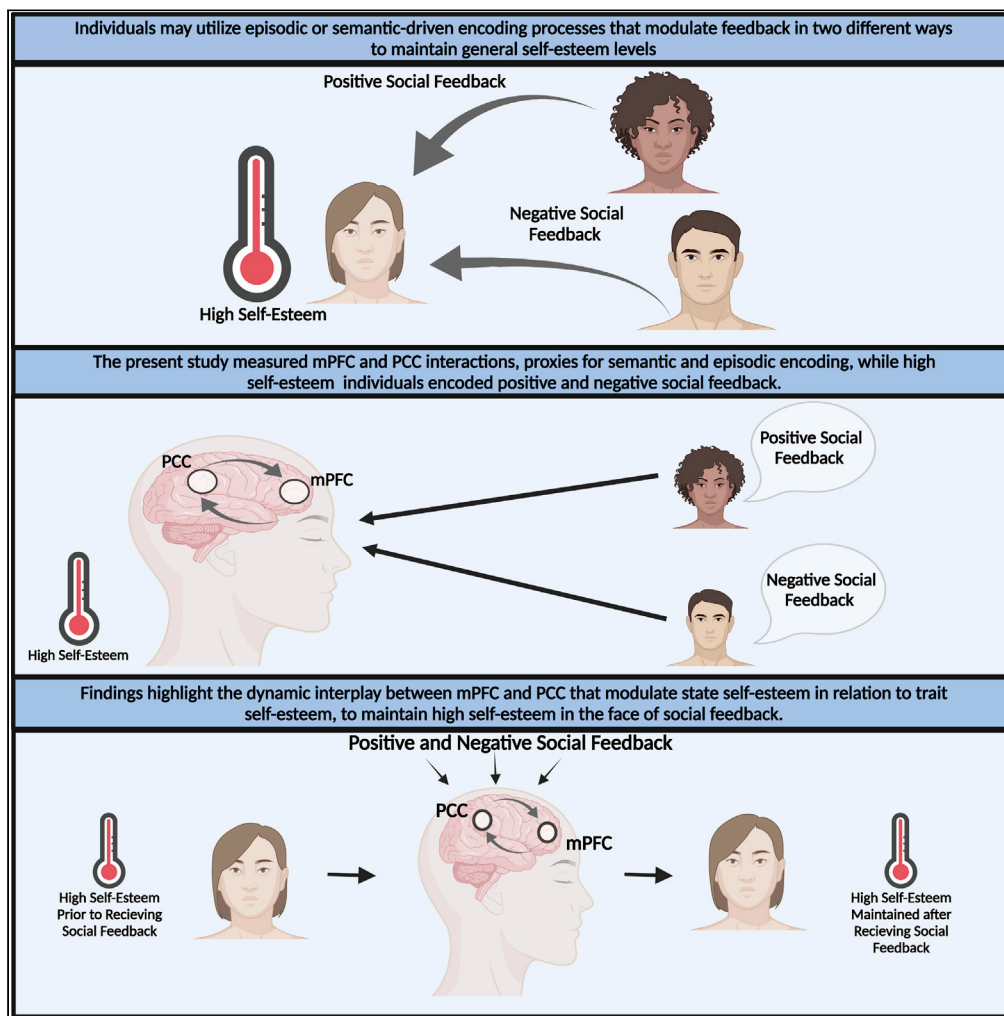
Self-esteem influences the encoding of self-relevant feedback

Medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC) served as proxies for semantic and episodic memory encoding, respectively

Semantic processes were most affected by trait self-esteem

Interactions between episodic and semantic processing maintained high self-esteem

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Article

Neural mechanisms associated with semantic and basic self-oriented memory processes interact moderating self-esteem

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SUMMARY

Individuals constantly encounter feedback from others and process this feedback in various ways to maintain positive situational state self-esteem in relation to semantic-based or trait self-esteem. Individuals may utilize episodic or semantic-driven processes that modulate feedback in two different ways to maintain general self-esteem levels. To date, it is unclear how these processes work while individuals receive social feedback to modulate state self-esteem. Utilizing neural regions associated with semantic self-oriented and basic encoding processes (medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC), respectively), in addition to time-frequency and Granger causality analyses to assess mPFC and PCC interactions, this study examined how the encoding of social feedback modulated individuals' (N = 45) post-task state self-esteem in relation to their trait self-esteem. Findings highlight the dynamic interplay between mPFC and PCC that modulate state self-esteem in relation to trait self-esteem, to maintain high self-esteem in general in the moment and over time.

INTRODUCTION

Individuals appear inherently motivated to maintain positive self-esteem, an integral aspect of the self-concept (Greenwald et al., 1988), and utilize different mechanisms to bolster self-esteem in the face of positive and negative self-relevant feedback (Tesser, 2000). Individuals accomplish this in two main ways. They may initially attend to and encode both positive and negative feedback and then manipulate negative feedback post hoc to maintain high self-esteem (Leary and Baumeister, 2000), or they may encode positive feedback deeper than negative feedback, to bias self-esteem in a more positive manner (Sedikides and Green, 2006). These self-protection mechanisms suggest a dynamic interplay between more semantic-driven self-oriented and basic episodic memory encoding processes. Many of these findings are based on self-report measures collected after feedback is received. Thus, it is unclear how positive and negative self-relevant information is encoded and processed by individuals on-line in relation to more semantic-based trait self-esteem to maintain positive state self-esteem in the moment. The current study examined how individuals encoded positive and negative social feedback on-line using a social neuroscience approach. The study explores how neural regions related to semantic and episodic-based interactions and self-relevant processing during feedback exposure may moderate the relationship between post-task state self-esteem and trait self-esteem. Findings provide evidence for a dynamic interplay between regions related to these processes, mPFC and PCC, that instantiate self-esteem maintenance processes, for example, maintaining high state self-esteem in relation to high trait self-esteem to maintain more positive self-perception.

Social feedback is processed via interactions between semantic self-oriented and basic memory encoding processes

Both abstract information relevant to general self-knowledge (e.g., self-attributes, attitudes, and beliefs), or semantic knowledge, and explicit information about past experiences and behaviors, or episodic knowledge (Kihlstrom et al., 1988) compose a main part of the self-concept. Self-esteem, the subjective feelings of one's self and abilities, in general, has been identified as an integral aspect of the self-concept (Greenwald et al., 1988), and likely a product of semantic and episodic self-knowledge. Self-esteem theoretically should be affected by positive or negative self-relevant information which often comes in the form of social feedback. Social feedback is essential for evaluating whether situational perceptions

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are consistent with current self-esteem levels. Prominent theoretical frameworks contradict this assumption. They indicate that individuals have an innate desire to maintain more positive self-esteem in the aggregate (Leary et al., 1998; Tesser, 2000), suggesting a potential dynamic interplay between self-based semantic and episodic memory processes. Influential theories pertinent to self-esteem maintenance, such as mnemonic neglect (Sedikides and Green, 2006), positive tropism (Swann and Schroeder, 1995), and sociometer theory (Leary and Baumeister, 2000) support this conjecture. Among other things, they argue that situational or state self-esteem may be dependent on self-relevant feedback being processed *post hoc* in ways that make it consistent with more semantic-based positive self-perception (or trait self-esteem). State self-esteem may also be dependent on feedback received *in the moment* in the form of episodic memory-based encoding biases, depending on the valence of the feedback.

According to principles of mnemonic neglect when individuals encounter positive or negative self-relevant feedback, they may utilize basic episodic memory encoding processes to attend to and encode positive information. Here positive, non-threatening information is processed more deeply than negative, threatening, information. In other words, negative self-relevant information and memories degrade over time owing to shallower encoding (Sedikides and Green, 2006). In this case, negative information remains distinct from the stored positive self-concept, facilitating positive self-perception and state self-esteem at the moment that exists regardless of trait self-esteem levels (Sedikides et al., 2016; Sedikides and Green, 2006).

Mnemonic neglect is supported by other studies that suggest negative information is processed differently in comparison to positive information. For example, Kuzmanovic and colleagues (2018) suggest that individuals are more influenced by positive self-relevant information when updating beliefs about themselves. Participants were more likely to update personal beliefs in response to positive self-relevant feedback than negative self-relevant feedback. Moreover, these positivity biases are suggested to occur through the selective neglect and retrieval errors of unfavorable information (Kuzmanovic et al., 2015; Sharot et al., 2011; Sharot and Garrett, 2016). These results support the idea that negative self-relevant information is either neglected or irretrievable thus fostering and maintaining a positivity bias accordingly. In these examples, individuals seem biased toward more positive self-oriented feedback compared to negative self-oriented feedback.

Conversely, other theories suggest more nuanced attention and encoding patterns to self-relevant feedback. Indeed, sociometer theory suggests that individuals integrate self-relevant feedback into their self-concept based on situational fluctuations in state self-esteem rather than a general positivity bias. When individuals experience initial reductions in state self-esteem they may accurately attend to both positive and negative social feedback via episodic memory-based encoding processes. Attention to social feedback allows individuals to accurately detect group inclusion and restore state self-esteem (Leary and Baumeister, 2000). In this case, self-esteem serves as a "sociometer" that detects the extent to which one feels included in a valued group. Feelings of exclusion prompt efforts to restore perceptions of inclusion. Sociometer theory also suggests that trait self-esteem may moderate this process. According to Leary, an individual's "sociometer" may be calibrated differently depending on whether they have high or low trait self-esteem (Leary et al., 1995, Study 5). Individuals with low trait self-esteem generally feel as though they experience rejection while those with higher trait self-esteem feel as though they experience acceptance. Similar results have been found in more recent work as well. Vandellen et al. (2011) demonstrated how those with high self-esteem were able to minimize the threat of negative feedback, while those with low self-esteem were less likely to respond to threat in esteem-protective ways. These mechanisms suggest memory may play an integral role in the sociometer theory. Sociometer theory states that self-esteem is an internal, subjective, gauge of interpersonal rejection and acceptance (Leary et al., 1995; Leary and Baumeister, 2000). Ultimately self-knowledge in relation to self-esteem levels is contingent on one's memories of themselves in social situations. One may have more or fewer memories of themselves being accepted or rejected. Thus, the sociometer theory may be inherently rooted in self-relevant memories and depending on the actions one takes to increase or decrease their self-esteem likely affects their memory and encoding accordingly (Leary and Baumeister, 2000). As such, individuals with higher trait self-esteem may have higher state self-esteem regardless of the type of feedback they receive, suggesting that semantic-based trait self-esteem may moderate basic episodic encoding processes involved in on-line conceptualizations of the self to maintain state self-esteem in relation to trait self-esteem.

The type of self-relevant feedback attended to and encoded has also been shown to fluctuate in relation to other trait-oriented features like the fear of negative evaluation (FNE), a defining feature of social anxiety (Button et al., 2015). Past research finds that as FNE increases, participants attend to and encode equal amounts of positive and negative self-relevant information. At lower levels of FNE individuals demonstrate a positivity bias, attending to and encoding more positive self-relevant information over negative self-relevant information. Here FNE acts in a similar manner to trait self-esteem in sociometer theory. Sociometer theory suggests when trait self-esteem is low individuals attend to both positive and negative self-relevant feedback in an attempt to raise state self-esteem levels. Thus, research suggests individuals with high levels of trait self-esteem and those with lower FNE demonstrate a positivity bias in attending to and encoding self-relevant information. Those with low levels of trait self-esteem and high levels of FNE demonstrate less bias, encoding positive and negative information equally. Together these theories suggest a strong top-down influence from trait-oriented processes.

Findings from mnemonic neglect, sociometer theory, and more recent studies on self-maintenance allude to a dynamic interplay between semantic and episodic-based encoding processes in response to positive and negative self-relevant feedback during on-line conceptualizations of state self-esteem. Positive tropism provides additional evidence for this potential interplay (Swann and Schroeder, 1995). According to principles of positive tropism, processing of self-relevant information consists of two phases. Consistent with mnemonic neglect, during the first episodic-based phase of evaluation (or the “positive tropism” phase) motivations to maintain self-esteem result in individuals exhibiting an attentional and encoding bias toward positive self-relevant information. A comparison occurs between initial information and trait self-esteem during the second stage of information processing. Here, positivity biases can change, possibly using more self-oriented semantic processes, if they are inconsistent with trait self-esteem (Chang-Schneider and Swann, 2010). That is, with enough time, semantic-based processes may override basic encoding positivity biases in attention and encoding, suggesting that episodic and semantic processes may interact to maintain state self-esteem levels that are consistent with trait self-esteem.

Thus, episodic and semantic self-oriented processes may interact during the processing of positive and negative social feedback to influence state self-esteem in relation to trait self-esteem. Past studies rely on behavioral and self-report measures. It is unclear how exactly these interactions occur. Semantic knowledge about the self may bias how social feedback is encoded or later recalled (and vice versa), but the assessment of self-related measures before or after receiving social feedback ultimately masks how these processes interact. Neuroscience methodologies, particularly electroencephalogram (EEG) recordings, provide a means to examine this critical time.

Communication between and within posterior cingulate cortex and medial prefrontal cortex may index episodic and semantic interactions concerning trait self-esteem and state self-esteem

One way to gain insight into the role that self-based episodic and semantic memory processes play in biasing encoding of feedback and subsequent state self-esteem is to examine activity within and between neural regions that instantiate encoding (i.e., episodic) and global self-oriented (i.e., semantic) processes on-line, while individuals encode positive or negative feedback. Observing these processes in the moment vs. post-task questionnaires is vital. Post-task questionnaires are not always able to detect these processes. Participants have time to make appraisals about the self-relevant feedback given or they may be unwilling to accurately report their feelings (Nisbett and Wilson, 1977). In other words, in the moment EEG measures allow us to examine specific neural processes that may occur *instantaneously* to self-relevant feedback providing insight that self-report measures cannot. Combining EEG measures with behavioral responses allows us to examine these processes more precisely.

EEG methods allow the present study to explore the proposed self-protection mechanisms via real-time monitoring of the dynamic interaction between neural regions integral for these processes. Recent advances also provide a means for highly accurate source localization of neural activity, especially regarding regions in the default mode network (Gerrits et al., 2019; Canuet et al., 2011; Michel and Brunet, 2019; Lin et al., 2006). EEG also provides a direct and accurate assessment of activity within (i.e., power) and between (i.e., phase locking) regions and thus the effect of regions on one another via measuring oscillations, a direct byproduct of neural activity, on the order of milliseconds. Moreover, while it is true that other modalities such as fMRI have superior spatial resolution compared to EEG (3mm voxels compared to 7mm

voxels; [Cohen, 2014](#)) there are many shortcomings of fMRI with regard to the present study. These include significantly worse temporal resolution compared to EEG and an index of the hemodynamic response, that is, oxygenated blood levels in a given region, which is not a direct index of neural activity. EEG is also much more amenable to mirroring the everyday social contexts our participants face, which allows for superior external validity. In addition to current signal processing analytic advances provide a means to examine brain activity in a way similar to fMRI. All of these factors point to EEG as an optimal methodology with respect to the present study.

Past research has identified a collection of brain regions integral for basic encoding processes including the hippocampus, lateral aspects of the temporal cortex, medial, and lateral aspects of the prefrontal cortex, and the precuneus/posterior cingulate cortex (PCC) ([Svoboda et al., 2006](#)). Of interest to the current study (given its EEG-accessible location in the cortex, [Gerrits et al., 2019](#); [Canuet et al., 2011](#)), the precuneus/PCC has been identified as integral for processes such as attentional allocation, and episodic memory encoding and consolidation ([Northoff et al., 2006](#); [Bird et al., 2015](#)). PCC has also been shown to integrate new information into autobiographical memories during self-reflection ([Van der Meer et al., 2010](#)). Critically, numerous meta-analyses (e.g., [Spreng et al., 2009](#); [Svoboda et al., 2006](#)), as well as the fMRI meta-analytic software Neurosynth, highlight an integral role for PCC in basic episodic memory processes among hundreds of studies (e.g., PCC activation was associated with episodic terms over above semantic terms in a Neurosynth meta-analysis, z score = 4.12, [Yarkoni et al., 2011](#)).

Conversely, medial prefrontal cortex (mPFC), another EEG accessible region in the cortex ([Gerrits et al., 2019](#); [Canuet et al., 2011](#)), is considered a hub for many semantic-based self-oriented processes. These processes include self-perception ([Amodio and Firth, 2006](#); [Hughes and Beer, 2013](#)), self-monitoring, the evaluation of one's direct and reflected self-knowledge ([Rameson et al., 2010](#); [Ochsner et al., 2009](#)), and self-esteem. The mPFC has been identified as a potential "neural sociometer" that plays a direct role in self-esteem moderation ([Eisenberger et al., 2011](#)). Will and colleagues (2017) demonstrated that a subregion of mPFC, vmPFC, directly correlated with online self-esteem updating. Specifically, [Will et al., \(2017\)](#) had participants complete a social evaluation task where they received feedback from 184 strangers sorted into four groups. On each trial, participants were asked to predict whether the rater approved or disapproved of them. Although participants completed the task, participants reported their self-esteem perceptions after every two to three trials. Findings revealed that vmPFC activity exhibited a direct relationship with self-esteem levels and modulated changes throughout the social evaluation task. Together, past research suggests mPFC is vital in self-esteem updating processes, particularly with respect to tasks that provide real-time social feedback. Similarly, mPFC activity has also been correlated with individual differences in state self-esteem and biased perceptions of social feedback estimates, suggesting that mPFC may be a hub for integrating real-time feedback with trait self-esteem during online conceptualizations of state self-esteem ([Somerville et al., 2010](#)). These findings also suggest that mPFC may play a key role in biasing memory recall to maintain self-esteem levels.¹

Given the role these two regions play in self-relevant information and memory processing, assessing communication between PCC and mPFC could provide insight into the degree to which these processes interact during the encoding of social feedback and conceptualizations of state self-esteem in combination with behavioral measures. Indeed, PCC and mPFC are exclusively recruited (along with other regions in the medial temporal lobe network like the hippocampus) during self-related processes such as autobiographical memory reconstruction and prospection ([Spreng et al., 2009](#); [Buckner and Carroll, 2007](#)). This suggests an intimate relationship between the two with respect to self-maintenance processes in general. Importantly, establishing the temporal directionality of this relationship could provide further insight into the nature of these interactions. If a given measure of neural activity in mPFC at one-time point

¹(It is important to note that mPFC and PCC are involved in many self-oriented and cognitive processes, and often co-activated while individuals complete various tasks. Considering these regions are involved in numerous self-oriented processes, it is possible that these regions specific functions aren't self and episodic memory-oriented as ultimately that would require that one rule out the likelihood that self or episodic memory-oriented processes aren't involved in any given task (that is to say, what task *wouldn't* have self or episodic-memory-oriented processes involved?). Given the nature of the current task, which provides self-relevant, social, feedback and the dearth of literature that examines these regions in similar tasks, the authors are confident that looking at these regions in relation to self-relevant tasks can provide meaningful information over and above that of behavioral values. A series of analyses demonstrating these conclusions are located in the supplementary materials ([Figures S1–S4](#)). These analyses include meta-analytic results from [neurosynth.org](#) in addition to regression and machine learning models that demonstrate the construct validity of these two regions within the context of the present study).

predicts a given measure of neural activity in PCC at a subsequent time point, this could be indicative of a more biased memory processing mechanism. The converse could represent a given outcome that was driven by more accurate memory encoding processes. Examining these measures of neural function in relation to the encoding of information associated with social feedback, state self-esteem, and trait self-esteem provides a means to clarify the role that these regions and processes play in the encoding of social feedback and subsequent state self-esteem.

Study overview and hypotheses

The current study placed individuals in a context where they received positive and negative social feedback (confederate students accepting or rejecting them) and then assessed the degree to which individuals encoded information associated with positive or negative feedback (faces of supposed students that accepted or rejected them) while continuous EEG activity was recorded. Individuals then completed state self-esteem measures and a memory test for previously seen faces (as well as lures; unseen faces). Activity within neural regions (measured via power analyses), communication between neural regions (measured via phase-locking analyses), and the directionality of this communication (measured via Granger causality analyses) in response to social feedback provided a means to assess the relationship between mPFC and PCC activity to feedback encoding and state self-esteem.

Given self-esteem maintenance processes like mnemonic neglect and sociometer theory may influence memory encoding and recall, the following exploratory analyses were proposed for the behavioral data. Based on principles of mnemonic neglect and past work on positivity biases in general (Kuzmanovic et al., 2015, 2018, Sharot et al., 2011, 2012; Sharot and Garrett, 2016), which suggest individuals are motivated to maintain positive beliefs by attending to and encoding feedback that has a positive subjective value, individuals might exhibit greater memory accuracy for faces associated with positive, as compared to negative, feedback. Greater memory accuracy for positive feedback faces, in turn, may then be associated with higher state self-esteem. In contrast, based on other research in the self-esteem maintenance literature (e.g., Bradley et al., 1995; Leary et al., 1995; Romero et al., 2016; Smith and Petty, 1995; Story, 1998), individuals may not exhibit encoding biases toward a specific face type. Rather, they may encode faces that are consistent with their current self-perception, like self-esteem levels. Depending on one's self-perception, this may not lead to a consistent positivity bias across participants. Thus, no differences in memory accuracy with respect to the valence of the feedback in the aggregate may be seen (H1).²

Specific hypotheses also can be derived for the neural interactions we may observe. In light of literature that highlights the integral role of PCC in memory processes, greater PCC activity to valenced feedback should predict higher memory accuracy for faces associated with said feedback (H1). Likewise, as mPFC and self-oriented processes are often linked in the literature, greater mPFC activity to valenced feedback should predict higher or lower state self-esteem levels in response to positive or negative feedback respectively (H2).

Literature also suggests how mPFC and PCC frequently interact during self-relevant feedback processes. Thus, exploring mPFC and PCC interactions may provide novel insight into how individuals may process and encode self-threatening positive and negative feedback. One possibility is that PCC is involved in accurately encoding social feedback in general, regardless of valence. However, the effect of feedback encoding on state self-esteem may be contingent on the degree to which mPFC becomes involved to manipulate encoded information to maintain trait self-esteem. Therefore, mPFC–PCC interactions may affect memory and state self-esteem such that greater mPFC involvement (higher levels of mPFC–PCC communication) is associated with decreased memory accuracy for faces related to social feedback and higher levels of state self-esteem (H3). Moreover, the communication between these regions may

²(While it is possible that memory performance for faces was not influenced by the valence of feedback presented in conjunction with a given face, that is, memory for faces was independent of feedback processing (e.g., see Will et al., 2017 for an example of this dichotomy), past research suggests that faces are often encoded in conjunction with the information they are explicitly paired with (e.g., Glenberg and Grimes, 1995). These mechanisms are presumed to be instantiated by associative memory processes (Anderson and Bower, 2014). Along these lines, it is important to note in this study that after each (randomized) confederate face presentation, (randomized) feedback (either “accept” or “reject”) was presented in the same font and color across trials and participants, ensuring social feedback stimuli were indistinguishable from one another. Moreover, all faces were previously piloted to ensure they were rated equally in terms of attractiveness, expression, and valence, ensuring face encoding was not likely to be biased by specific facial characteristics. Thus, if recall biases were evident for faces yoked to a specific feedback valence type, and/or outcomes for brain analyses do not differ in any way if using EEG epochs during either face or feedback presentation, as was the case in this study, it would be difficult to presume memory biases for faces were not the product of face feedback pairings. Nevertheless, it is difficult to rule out this alternative possibility entirely).

moderate the relationship between trait self-esteem and state self-esteem to maintain self-perception. Higher communication between these regions may lead to a positive relationship between trait self-esteem and state self-esteem (H4). The directionality of mPFC–PCC communication could provide further insight into how these regions influence one another to bias conceptualizations of the self with respect to the on-line encoding of positive and negative feedback (H5).

RESULTS

For full transparency, sample sizes vary across variables owing to participants identified as outliers via Grubbs test (also known as the extreme studentized deviate method, [Grubbs, 1969](#)). These individuals had Z scores greater than 3.5 (standard deviations) from the grand mean ($p < 0.05$) of the variable of interest. Four participants did not have pretesting measures taken from the beginning of the semester, and eight were unable to complete the state self-esteem questionnaire. For more details and specific numbers please see the supplemental information [Table S2](#).

Performance on the face memory task

Initial t-tests revealed both accepting and rejecting faces were significantly different from chance (represented as a d' score of 0; p 's < 0.001), suggesting that participants reliably encoded accepting and rejecting faces. The repeated measures ANOVA yielded no main effect of memory between accepting and rejecting faces ($p = 0.392$). Thus, participants' memory for faces did not differ as a function of whether faces were associated with accepting or rejecting feedback. Relating these findings back to the self-maintenance theories discussed, findings provide little behavioral support for processes that result in a positivity bias like mnemonic neglect or positive tropism-oriented hypotheses. These results do, however, support self-maintenance processes that do not prioritize one type of feedback over the other, such as sociometer theory.

Performance on the face memory task in relation to trait self-esteem and state self-esteem

Separate analyses regressing state self-esteem and trait self-esteem on to d' scores for accepting and rejecting faces indicated no relationships or interactions between these variables (p 's > 0.20). These findings provide behavioral support for self-maintenance processes that do not favor one valence of feedback over another ([Leary et al., 1995](#), study 5). Considering no behavioral differences were seen between accepting and rejecting social feedback, the following analyses collapsed across accepting and rejecting faces. In other words, the remaining analyses collapse across all faces in general. Analyses specific to accepting and rejecting feedback are available upon request for full transparency.

Medial prefrontal cortex activity correlates to self-esteem

mPFC regression analyses revealed mPFC power was a predictor of state self-esteem in both beta ($b = -0.001$, $t(31) = -2.790$, $R^2 = 0.330$, $p = 0.010$, Standard Error (SE) = 0.29, 95% Confidence Interval (CI): [-0.0015, -0.0002]) and gamma frequency bands ($b = -0.001$, $t(280) = -2.630$, $R^2 = 0.320$, $p = 0.014$, SE = 0.290, 95% CI: [-0.0018, -0.0002]), bolstering work by ([Eisenberger et al., 2011](#)) and strengthening the construct validity for the relationship between mPFC activation and semantic self-processes. These analyses also considered trait self-esteem as a covariate to ensure analyses were tapping into the unique relationship between neural activation and state self-esteem. As mPFC power to feedback (both accept and reject) decreased, state self-esteem increased ([Figure 1](#)). Theta and alpha frequency bands were not significant (p 's > 0.110). mPFC power regressed on trait self-esteem revealed an identical relationship between trait self-esteem and mPFC activity in the theta frequency band ($b = -470.770$, $t(35) = -2.490$, $R^2 = 0.150$, $p = 0.018$, SE = 472.320, 95% CI: [-854.5450, -87.0010]), as trait self-esteem increased mPFC power to feedback decreased. No relationships between trait self-esteem and mPFC power in other frequency bands were apparent (p 's > 0.230). PCC had no relationship with state self-esteem or trait self-esteem in any frequency band (p 's > 0.240).

Posterior cingulate cortex activity correlates to memory accuracy for faces

Results of PCC regressions demonstrated that PCC power was a significant predictor of accurate memory encoding in the beta frequency band ($b = 0.002$, $t(41) = 2.160$, $R^2 = 0.100$, $p = 0.037$, SE = 0.570, 95% CI: [0.0002, 0.0050]).³ Nevertheless, given the *a priori* hypotheses and a large amount of literature supporting

³(This analysis did not reach criterion for multiple comparison testing ($p = 0.037$, FDR cutoff $p = 0.025$)).

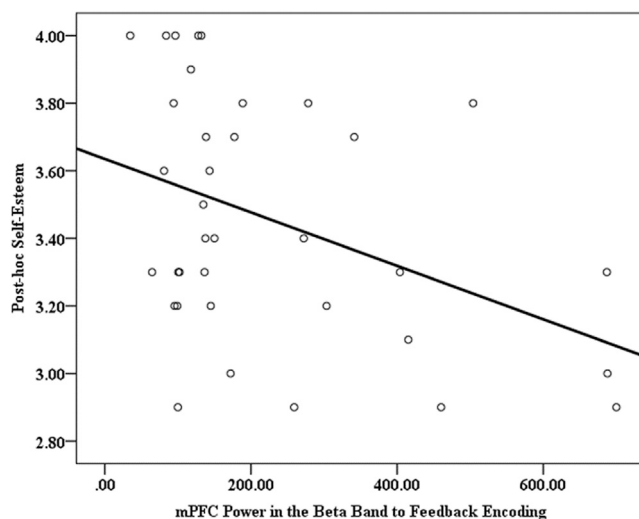


Figure 1. mPFC power and state self-esteem. mPFC power in the beta band to social feedback predicts decreases in post-task state self-esteem ($p = 0.010$).

this basic finding (Bird et al., 2015; Northoff et al., 2006; Spreng et al., 2009; Svoboda et al., 2006), these effects were considered to be informative for the present hypotheses. Additional support for the construct validity of PCC in relation to memory (d prime scores) can be found in the supplemental information. As PCC power to all feedback increased, memory accuracy for all faces increased (Figure 2), replicating prior work (Northoff et al., 2006; Bird et al., 2015) and strengthening the construct validity for the relationship between PCC activation and accurate memory encoding. All other frequency bands were not significant (p 's > 0.11). These patterns were not evident when mPFC power (in any frequency band) elicited during feedback encoding was entered as the predictor (p 's > 0.390).

medial prefrontal cortex and posterior cingulate cortex communication affects self-esteem, and memory accuracy for faces

mPFC–PCC phase-locking values were regressed on trait self-esteem and state self-esteem. These analyses yielded a positive relationship between mPFC–PCC phase-locking in the theta band and trait self-esteem, $b = 0.036$, $t(37) = 2.380$, $R^2 = 0.130$, $p = 0.020$, $SE = 0.040$, 95% CI: [0.0050, 0.0670], Figure 3. To the extent participants had higher trait self-esteem, they exhibited more mPFC–PCC phase-locking during feedback encoding. No other relationships were evident in the other frequency bands (p 's > 0.120) or between mPFC–PCC phase-locking and state self-esteem (p 's > 0.510).

Additional regression analyses regressing memory accuracy for all faces on to mPFC–PCC phase-locking elicited in response to all feedback revealed a negative relationship in the beta frequency band ($b = -5.310$, $t(42) = -3.280$, $R^2 = 0.200$, $p = 0.002$, $SE = 0.540$, 95% CI: [-8.5770, -2.0420], Figure 4).⁴ As mPFC–PCC phase-locking to all feedback increased, encoding memory accuracy to all faces decreased. Theta and alpha frequency bands demonstrated no relationship (p 's > 0.750). Results provide initial evidence that PCC power was associated with basic memory encoding processes. However, this relationship was altered when communication between mPFC and PCC were considered.

Medial prefrontal cortex–posterior cingulate cortex communication moderates the relationship between trait self-esteem and state self-esteem

Moderation results demonstrated that mPFC–PCC phase-locking in the gamma frequency band moderated the relationship between trait self-esteem and state self-esteem ($b = 6.900$, $t(30) = 2.610$, $F = 6.830$, $SE = 2.640$, $p = 0.014$, 95% CI: [1.5061, 12.2907]). Individuals with higher trait self-esteem reported higher levels

⁴(Relationships were also found in the gamma ($b = -3.340$, $t(42) = -2.040$, $R^2 = 0.092$, $p = 0.048$, $SE = 0.580$, 95% CI: [-6.6510, -0.2770]) frequency band. However, this frequency band was not able to detect an effect at 80% power (minimum $b = 3.990$)).

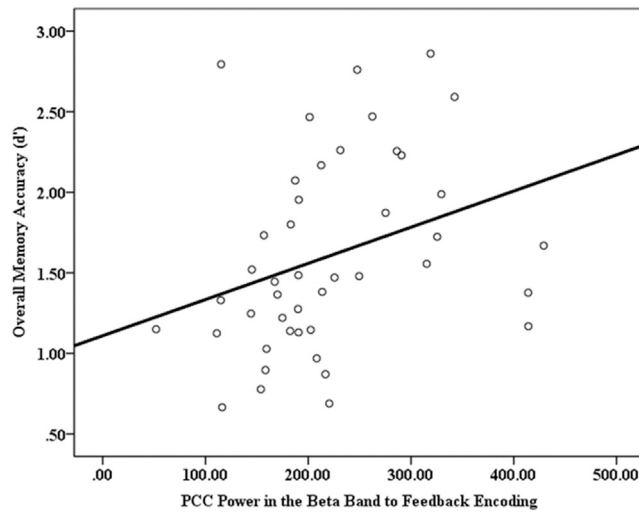


Figure 2. PCC power and memory accuracy. Increases in PCC power in the beta frequency band to social feedback encoding predicts increases in overall memory accuracy ($p = 0.037$)

of state self-esteem to the extent that greater mPFC–PCC communication was observed in response to accepting and rejecting faces during the social feedback task (Figure 5). Simple slopes analyses revealed that whereas at lower levels of mPFC–PCC phase-locking no relationship was observed between trait self-esteem and state self-esteem ($p = 0.670$), at average and higher levels of phase-locking individuals with higher trait self-esteem reported higher state self-esteem ($b_{\text{average}} = 0.310$, $t(30) = 2.430$, $p = 0.020$, 95% CI: [0.0496, 0.5684]; $b_{\text{high}} = 0.700$, $t(30) = 3.410$, $p = 0.0019$, 95% CI: [0.2797, 1.1179]). This pattern was also found in other independent models observing the average and high levels of mPFC–PCC phase-locking in beta ($b_{\text{average}} = 0.370$, $t(30) = 2.580$, $p = 0.015$, 95% CI: [0.0776, 0.6647]; $b_{\text{high}} = 0.710$, $t(30) = 2.770$, $p = 0.0098$, 95% CI: [0.1848, 1.2413]), alpha frequency bands ($b_{\text{average}} = 0.330$, $t(30) = 2.470$, $p = 0.019$, 95% CI: [0.0572, 0.5999]; $b_{\text{high}} = 0.600$, $t = 3.080$, $p = 0.0044$, 95% CI: [0.2027, 1.0020]), and marginally in the theta frequency band $p = 0.110$)⁵.

Evidence for the integral role of medial prefrontal cortex in self-protective mechanisms

Linear regression analysis regressing state self-esteem onto Granger causality values of mPFC activity predicting PCC activity during feedback encoding revealed that individuals exhibited higher state self-esteem to the extent that mPFC activity predicted PCC activity ($b = 18.190$, $t(33) = 2.213$, $R^2 = 0.130$, $p = 0.034$, $SE = 0.340$, 95% CI: [1.4640, 34.9140]; Figure 6). This relationship was not evident when memory accuracy was modeled as the outcome ($p > 0.960$) or with Granger causality values representing PCC predicting mPFC activity ($p > 0.600$). Thus, state self-esteem scores were dependent in part on the extent to which mPFC activity predicted PCC activity in response to evaluative feedback.

DISCUSSION

Many self-maintenance processes such as mnemonic neglect and sociometer theory allude to a dynamic interplay between semantic and episodic-based encoding processes in response to positive and negative social feedback during on-line conceptualizations of state self-esteem. By examining how brain and behavioral measures associated with semantic-based self-knowledge and episodic encoding processes interact in response to social feedback, findings inform how these processes may interact to affect self-perception. Behavioral findings demonstrate no memory encoding biases toward positive or negative feedback, providing evidence against self-maintenance mechanisms that operate through positivity biases, for example, mnemonic neglect. Instead, results provide support for self-maintenance processes that equally attend to all types of feedback. Consistent with past research identifying mPFC as a hub for self-oriented processes, like state self-esteem and trait self-esteem (Amodio and Firth, 2006; Rameson et al., 2010;

⁵(These results were found to be driven by rejecting feedback. Analyses are available upon request.)

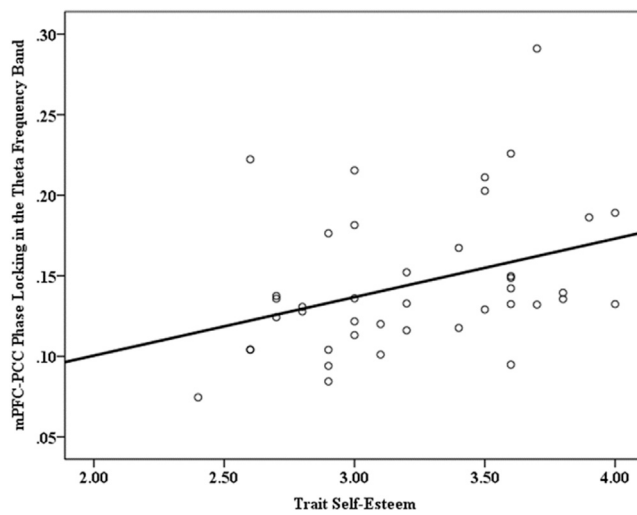


Figure 3. Trait self-esteem and mPFC–PCC phase-locking. Trait self-esteem positively predicts mPFC–PCC phase-locking in the theta frequency band to social feedback ($p = 0.020$)

Eisenberger et al., 2011, Will et al., 2017), mPFC activity (power) elicited in response to all social feedback predicted state self-esteem, but not memory accuracy, for faces associated with social feedback. Conversely, consistent with previous research citing PCC as an integral component in basic memory encoding (Northoff et al., 2006) PCC activity (power) in response to social feedback was associated with increases in memory accuracy for both accepting and rejecting faces, but not a trait or state self-esteem (although this effect was slightly less reliable considering multiple comparison corrections). These relationships were not evident in other sources identified in source localization analyses (e.g., TPJ, STS, ACC), providing evidence for discriminant validity among mPFC and PCC regarding self and memory-based processes in the present data.

Thus, the communication between the two regions appeared to be associated with self-esteem and encoding accuracy for all feedback in dynamic ways. Individuals exhibited greater mPFC–PCC communication in response to both positive and negative feedback to the extent they had higher trait self-esteem. Greater communication between these regions was also associated with decreased encoding accuracy of all feedback. These findings provide evidence that interactions between these two regions underscore an interplay between these regions to possibly maintain self-conceptions. Greater communication between these regions, in turn, predicted a positive relationship between trait self-esteem and state self-esteem. Moreover, highlighting how self-oriented processes can directly influence basic encoding to affect state self-esteem, Granger causality analyses indicated that state self-esteem was higher to the extent mPFC power had a direct, causal influence on PCC power during individuals' exposure to social feedback.

Although mPFC and PCC are activated in a myriad of self-related processes, analyses demonstrate construct validity for these regions contributing to semantic and episodic processes. mPFC and PCC activation predicted both their hypothesized dependent variables, self-esteem, and memory accordingly, providing statistical evidence for their construct validity. Moreover, self-esteem and memory accuracy were regressed onto other self-related regions included in the source model (TPJ, STS, ACC) to ensure these relationships were unique to mPFC and PCC. TPJ, STS, and ACC were not able to predict any self-esteem or memory-related behavioral variables. These results are available upon request for transparency. Thus, even if other self-related processes may have been apparent during the social feedback task, the present analyses demonstrate that mPFC played a meaningful role in self-esteem, and PCC played a meaningful role in memory accuracy only.

Consistent with Leary et al., 1995, 2005), the parameters under which mPFC becomes involved in PCC-based encoding may be influenced by the context and valence of trait self-esteem and state self-esteem. According to Leary, individuals with higher chronic trait self-esteem maintain higher levels of state self-esteem by assuming they will be accepted in a given context and thus do not attend to social feedback

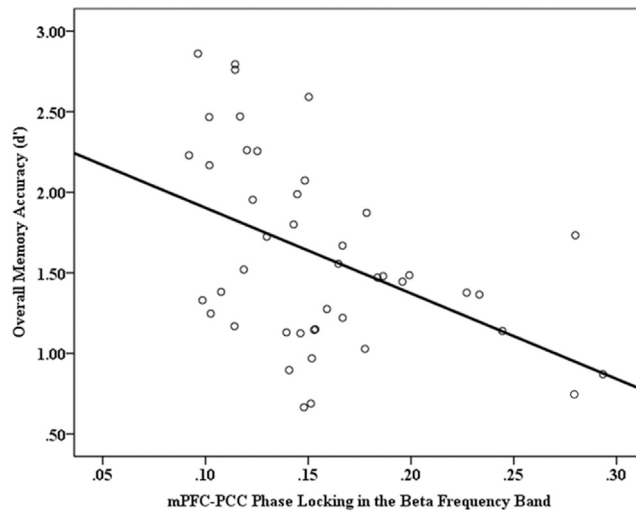


Figure 4. mPFC–PCC phase-locking and memory accuracy. Increases in mPFC–PCC phase-locking to social feedback correlate with decreased overall memory accuracy ($p = 0.002$)

in general. This argument is consistent with findings from the current study indicating that when trait self-esteem was higher, encoding processes did not exhibit any relationships with state self-esteem; individuals' state self-esteem was consistent with their trait self-esteem regardless of whether they were socially rejected or accepted. Moreover, [Leary et al. \(1995\)](#) suggest that while individuals may attend to both accepting-oriented (positive) and rejection-oriented (negative) feedback, individuals tend to be more sensitive to rejection-oriented (negative) feedback specifically. Thus, self-esteem fluctuations might be more pronounced in response to negative than positive social feedback—findings from this study support this conjecture (see footnote 5). Trait self-esteem seemed to influence state self-esteem when phase locking between mPFC–PCC was highest in response to negative feedback (full results are available upon request). However, considering this finding is not consistent across the sociometer theory literature, future work should identify the parameters and contexts that render one type of feedback more influential than the other.

Exploratory analyses suggested that although relationships between mPFC–PCC communication to accepting feedback, trait self-esteem, and state self-esteem were evident, it was the communication between these regions in response to rejecting feedback that appeared to play a larger role in trait self-esteem-based maintenance of state self-esteem. These findings support self-maintenance mechanisms like sociometer theory and positive tropism, suggesting that negative feedback may be manipulated post hoc among high trait self-esteem individuals to maintain high state self-esteem accordingly. Results broaden the understanding of these mechanisms by suggesting that the influence of basic encoding is predicated on individuals' semantic-based trait self-esteem while individuals receive self-oriented feedback. They also provide evidence that actual data are encoded, by the PCC, but the dynamic interplay between mPFC and PCC may ultimately bias how this data is factored into state self-esteem, which is something self-maintenance theories have not clearly explained or expanded upon to date.

These findings also expand on more recent work that demonstrates how self-relevant feedback is processed in different ways to maintain self-perception and beliefs neurally. For instance, work by [Kuzmanovic et al., 2018](#) highlights the essential role of mPFC in filtering self-relevant information to preserve self-beliefs. Participants were given feedback about how likely they were to experience an adverse life event (e.g., how likely they were to be diagnosed with cancer) and asked to estimate their own personal risk before and after each trial. They found that the interaction between vmPFC and dmPFC during negative feedback (higher likelihood of experiencing the adverse life event) drove positivity biases in participants' estimates of their own personal risk. In other words, the more these two regions interacted during the trial, the less participants rated themselves as more at risk for experiencing an adverse life event. Furthermore, work by [Van Schie et al., 2018](#) suggests that participants who had high or low self-esteem utilized different neural regions to process positive and negative self-relevant feedback. Individuals with higher self-esteem

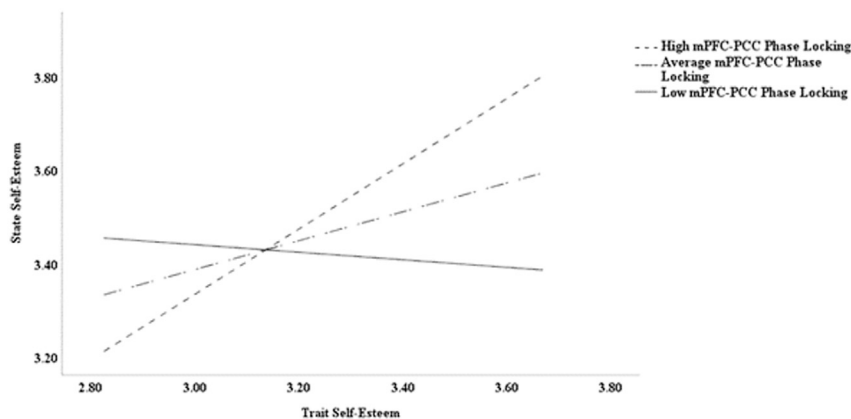


Figure 5. Trait self-esteem and state self-esteem are moderated by mPFC–PCC phase-locking in the gamma frequency band. Individuals with higher trait self-esteem reported higher levels of state self-esteem to the extent that greater mPFC–PCC communication was observed in response to accepting and rejecting faces during the social feedback task ($p = 0.014$)

presented increased activation in the PCC and precuneus activation for applicable negative feedback while individuals with lower self-esteem presented decreased mPFC, insula, anterior cingulate cortex, and PCC activation during positive feedback. Results suggest that self-esteem and the congruency of feedback and self-perception can influence affective and neural responses to social feedback.

The present results add to these findings in two ways. First, they inform past work by suggesting the interactions between vmPFC and dmPFC may be part of a larger network that includes regions involved in more episodic memory processes including PCC. In light of findings suggesting the coupling of PCC and mPFC activity was associated with the maintenance of higher self-esteem, it's possible that vmPFC and dmPFC interactions found in [Kuzmanovic et al. \(2018\)](#) represent filtering of PCC-dependent episodic information (although other regions such as hippocampus would likely be integral as well) to maintain positivity biases accordingly. This is consistent with work suggesting that PCC and vmPFC are co-active while individuals exhibit positivity biases in information processing ([Blair et al., 2013](#)). Moreover, results suggest it is not only the connectivity between mPFC and PCC that may be integral for these processes but also the precise manner in which these regions interact as well. Those who are more prone to positivity biases (e.g., have higher trait levels of self-esteem), may exhibit network interactions consisting of mPFC regulating interactions with PCC (and other regions) in order to maintain self-views accordingly (which would also be consistent with general frameworks that suggest a hierarchical organization across cortex with prefrontal structures representing the top or regulating component of the hierarchy; e.g., [Badre and D'Esposito, 2007](#); [Koechlin and Jubault, 2006](#)). Importantly, findings from this study help bridge the gap between past research that primarily examines state self-esteem via pre and post self-report measures independent of what individuals encode in a given context, and social neuroscience studies that did not examine how multiple regions integral for semantic self-knowledge and episodic encoding processes interact and/or directly influence one another to affect state self-esteem with respect to trait self-esteem.

Findings also replicate and expand upon past research. For instance, similar to [Will et al. \(2017\)](#), which found a direct role for aspects of mPFC (vmPFC specifically) in the real-time modulation of self-esteem levels during a social feedback task, findings from this study suggest that mPFC activity is also related to state self-esteem levels and may help moderate state self-esteem levels in accordance with more stable trait self-esteem levels. That is, trait self-esteem and state self-esteem were highly correlated with the extent mPFC, and PCC was communicating with one another during feedback presentation. Furthermore, follow-up Granger causality analyses demonstrated that it was the mPFC's influence on PCC that predicted state self-esteem levels, specifically, suggesting that mPFC may play an integral role in self-esteem maintenance processes in general.

Additionally, the present study provides important insight into self-esteem maintenance dynamics, particularly as it pertains to different neural systems that may play critical roles in this process. For instance,

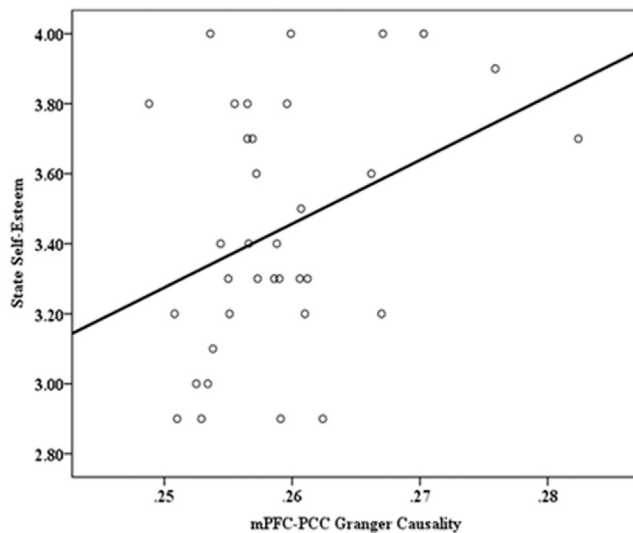


Figure 6. mPFC influence on self-esteem maintenance. State self-esteem scores are dependent on the extent to which mPFC activity predicted PCC activity in response to social feedback, suggesting an encoding mechanism driven by mPFC ($p = 0.034$)

findings from Will et al. (2017) suggest that self-esteem maintenance processes may, in part, be dependent on implicit learning processes instantiated by the basal ganglia system. Recall in this study that participants learned over numerous trials what groups were more likely to accept or reject them and that ultimately social prediction errors correlated with activity in the ventral striatum, a region in the basal ganglia integral for implicit learning processes (Everitt et al., 1999; Mattfeld and Stark, 2011). In contrast, the present study focused exclusively on declarative, that is, hippocampal-based, episodic, and semantic-based memory processes (although again, the use of EEG precludes our ability to assess hippocampal activity specifically). Participants engaged in a passive viewing task and were then asked to recall whether they had seen previously presented faces amongst several unseen lures. Indeed, our findings yielded neural patterns more specific to regions integral for declarative memory processes, like PCC, that are not involved in implicit learning processes (Lega et al., 2017; Papma et al., 2017). Thus, both studies contribute to the self-esteem maintenance literature by highlighting how implicit learning and declarative (episodic and semantic) memory systems may play separable roles in on-line self-esteem maintenance processes. Although (Will et al., 2017) focused more on the extent to which social expectations influenced information processing and subsequent state self-esteem levels, our findings suggest that one of the downstream consequences of how this feedback is processed is biased memory encoding. Notably, the differences between these two works highlight an integral next step in self-esteem maintenance research. For instance, the basal ganglia and hippocampal systems often cooperate or compete with one another during learning and memory processes (Myers et al., 2003; Retailleau et al., 2012; Seger et al., 2011). Given this, it would be fascinating for future research to tease apart the contributions (or detractions) of these two systems on self-esteem maintenance processes.

While no *a priori* hypotheses were established for specific frequency bands, it is worthwhile to note that different findings appeared to be driven by activity in beta and gamma frequency bands. Whereas analyses focusing on activity within regions typically found effects in the beta and gamma frequency bands, some phase-locking analyses suggested effects were specific to the theta frequency band (although most analyses provided evidence that all frequency bands were trending in the same direction except for the alpha frequency band). There is still much debate in the literature regarding what exactly different frequency bands correspond to neurally and psychologically; however, findings from this study are consistent with current theoretical accounts. Neuronal oscillations are an essential part of the brain's design, suggesting functional relevance for each frequency band (Buzsáki and Draguhn, 2004). Frequency bands have been associated with different brain states and processing mechanisms including attention and memory (Klimesch, 1999; Kopell et al., 2000; Buzsaki, 2006), and can be characterized by the neural area activated. For instance, higher frequency oscillations have been considered representative of smaller neural networks

in a given cycle (i.e., activity within a brain region) while lower frequency oscillations have been considered representative of more extensive network interactions (i.e., activity between brain regions; [Buzsaki, 2006](#)). Ultimately all frequency bands have been shown to temporally coexist within the same neural structures; however, as a given neural structure performs operations locally as well as in relation to larger networks. These patterns of oscillations and functional architecture of the brain allow multiple cognitive processes to be carried out at once, possibly in a hierarchical manner ([Buzsáki and Draguhn, 2004](#)). Thus, analyses confined to activity within a region or driven by a single region (e.g., like those found for mPFC and self-esteem, and PCC and memory accuracy) would be expected to yield meaningful results in higher frequency bands such as beta or gamma. Likewise, analyses focusing on activity between regions (e.g., mPFC–PCC phase-locking analyses) should yield meaningful results in lower frequency bands like theta, consistent with findings from this study.

The present results focus on the behavioral data from the memory part of the task. Given the study was designed to measure what subjects spontaneously encode; that is, encode without explicit directions to do so, participants were given accepting and rejecting feedback and only asked to indicate whether the confederate accepted or rejected as an attention check. Although this attention check was not intended to be an integral part of the study or a variable included in behavioral analyses, having participants answer this question on each trial ensured participants saw and encoded the feedback. Having participants answer this question on each trial also allows us to monitor if participants demonstrated a systematic bias in the type of faces they accurately recalled. For example, if individuals acknowledge seeing rejection feedback but then exhibit a systematic bias in the type of faces they accurately recall, it allows us to more confidently assume that memory encoding for specific faces was disrupted after the initial stages of information processing, perhaps because of semantic influences from mPFC. Future studies should examine how these self-esteem maintenance processes change on a moment-to-moment basis in relation to participant expectations, that is, do they expect the confederates to accept and reject them. By measuring participant expectations prior to each trial studies could examine how expectancy violations may influence these self-esteem maintenance processes. Expectation violations have a significant impact on what is encoded and recalled and may likely influence the maintenance processes at hand ([Murty and Adcock, 2014](#); [Sherman et al., 2004](#); [Sun and Yu, 2014](#)).

In summary, findings from this study highlight the parameters under which mPFC-oriented processes (perhaps indicative of more self-oriented semantic processes) and PCC-oriented processes (perhaps indicative of more episodic memory processes) interact to moderate state self-esteem in relation to trait self-esteem. Although behavioral findings provide evidence for self-esteem maintenance theories suggesting that most self-oriented feedback is encoded regardless of valence (e.g., sociometer theory), online assessments of neural activity suggest self-esteem maintenance processes might be much more nuanced and dynamic. For example, when trait self-esteem is higher, mPFC appears to play an integral role in modulating how social feedback is recalled, such that memory accuracy for socially accepting and rejecting individuals, that is, the actual “data,” does not appear to influence the extent to which higher state self-esteem is associated with higher trait self-esteem. To the extent mPFC may play a role in more semantic-based trait self-esteem processes, findings suggest that trait self-esteem moderates the extent to which basic encoding processes are employed in evaluative contexts (mPFC influencing PCC activity $n+1$ trials) to maintain state self-esteem levels that are consistent with trait self-esteem levels. Findings provide additional support for self-maintenance theories that argue for semantic and episodic processes’ importance and extend upon these theories by suggesting that much more might be going on in the brain concerning these processes. These dynamics are not typically captured in typical post-task self-report measures, but they have significant ramifications for said measures nonetheless.

Limitations of the study

Specific to study limitations, as, with an EEG study that utilizes a source localization approach, it is always important to encourage caution with respect to conjectures based on specific regions of the brain given limitations in spatial localization associated with the methodology. Nevertheless, standards practiced in this study, for example, using a high-density EEG array for data collection and restricting sources to the outer cortex, have been shown to provide reasonably precise measurements of specific brain regions (with EEG regional source voxel clusters around seven cubic millimeters in size as opposed to three cubic millimeters for fMRI; [Cohen, 2014](#)). Given the number of sources present in the model, it is also possible that any combination of sources could provide a good representation of the global EEG signal. Although

true, a theoretical approach was taken in selecting these sources. Prior knowledge of regions integral in social cognition was used to constrain spatial parameters of the model (Scherg and Berg, 1991). It is also important to note that only *a priori* defined mPFC and PCC sources exhibited any hypothesized relationships with behavioral outcomes of interest. No less, these behavioral outcomes map directly onto hypothesized functions of the *a priori* regions of interest. That is, mPFC activity predicted self-esteem but not memory measures, and PCC activity predicted basic memory but not self-esteem measures, providing an element of construct and discriminant validity to the above basic findings. MSPS analyses bolstered confidence in source locations by revealing activation around *a priori* regions as well. Nevertheless, future research should replicate this study utilizing combined EEG–fMRI methodologies to allow for both optimal temporal and spatial resolution to bolster claims accordingly.

It should be noted that there were some limitations with respect to the study design. The present study and methods were utilized to observe the spontaneous mechanisms behind self-relevant information processing in high self-esteem individuals. Understanding how individuals process social feedback naturally, without any explicit directives, was deemed integral for our study goals. However, as noted in footnote 2, this design does not allow us to rule out the possibility that ultimately information presented directly after faces was not encoded in conjunction with a given face. Nevertheless, exploratory patterns found in this study were in accordance with tenets of associative memory processes (Anderson and Bower, 2014), suggesting that feedback valence may influence the encoding of specific faces yoked to said feedback. That is, exploratory analyses suggested mPFC–PCC phase locking to negative feedback may have been driving the presented effects despite the randomized nature in which these stimuli were presented to people. All significant effects from brain-memory analyses were evident regardless of whether face or feedback presentation epochs were used. However, future studies would be necessary to definitively parse out these processes and mechanisms as they pertain to self-esteem maintenance processes (e.g., sociometer theory).

One final limitation was the characteristics of our sample. Our sample included only individuals with high trait self-esteem ($M = 3.22$, $SD = 0.44$). Although ideal for the present hypotheses surrounding self-maintenance theories that favor individuals maintaining positive self-esteem, such as mnemonic neglect, the sample does not address the self-maintenance mechanisms behind those with lower levels of trait self-esteem. This is an important detail as subjects with lower trait self-esteem have also been found to seek negative feedback in line with their self-perception (Vandellen et al., 2011; Swann, 2011; Van Schie et al., 2018). Future research should consider these alternative self-maintenance theories in a sample that has more variable levels of trait self-esteem.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2022.103783>.

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AUTHOR CONTRIBUTIONS

Rachel Amey: Conceptualization, Methodology, Formal Analysis, Writing
Jordan Leitner: Resources, Data Curation
Mengting Liu: Resources
Chad Forbes: Writing, Visualization, Supervision

CONFLICTS OF INTEREST

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Raw data and experiment code	This study	https://osf.io/jgwev/?view_only=a8874870a45c44af9fa099bccfa02d38
Software and algorithms		
SPSS 24	IBM SPSS Statistics	https://www.ibm.com/products/spss-statistics?utm_content=SRCWW&p1=Search&p4=43700050715561164&p5=e&gclid=Cj0KCQiAzMGNBhCyARIsANpUkzNTD5VLIKGMZ7aP7TpSvHHBSGzWD3TxHqgm6t-kPNZe_4QhHjEWtjlaAuUFEALw_wcB&gclsrc=aw.ds
BESA	Brain Electrical Source Analysis	https://www.besa.de/
Python	Python	https://www.python.org/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Rachel Amey (Rachel.C.Amey.civ@army.mil).

Materials availability

This study did not generate new unique reagents.

Data and code availability

De-identified human data have been deposited at osf.io. They are publicly available as of the date of publication. DOIs are listed in the key resources table.

All original code has been deposited at osf.io and is publicly available as of the date of publication. DOIs are listed in the key resources table.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Participants

Sample size was determined and fully collected before any data analysis. Forty-five white introductory psychology students (23 male, 22 female; Mage = 18.54, SDage = 0.74 years) participated for partial course credit. All participants were screened for head trauma, neurological disorder, and drug/medication use prior to participating. No additional participants were collected after data analysis. This information was collected from an IRB approved prescreening survey. All participants and had given consent to partake in the study and have their pictures taken in an approved university IRB document.

METHOD DETAILS

Materials and procedure

The study's hypotheses were examined using raw data from [Leitner et al. \(2014\)](#). In that study, participants reported to the lab and were informed that the researchers were ostensibly investigating facial features that promote social interactions. Participants were told that they would be interacting with and receiving feedback from individuals across the country who would view their facial photo on an online social network system. In reality, there was no social network, and confederate faces were used from the Eberhardt Face Database, Center for Vital Longevity Database ([Minear and Park, 2004](#)), MORPH Longitudinal database ([Ricanek and Tesafaye, 2006](#)), and from [Hehman et al. \(2013\)](#). Participants had their photos taken and were told that it would be uploaded to the social network system to corroborate the cover story. They were

then prepared for EEG recording. Next, participants completed the supposed social feedback task (see below) and were led to believe that confederates were deciding in real time whether to accept or reject the participant's personal profile based on their picture that had just been uploaded to the database. Participants were then given a surprise memory test to measure the extent to which individuals encoded confederate faces that were yoked with either positive or negative social feedback (i.e., accepted or rejected the participant). Finally, participants completed measures of state self-esteem and were debriefed. All measures, manipulations, and exclusions in these studies are reported.

Social feedback task

The social feedback task provided a means to administer adequate amounts of positive and negative social feedback in conjunction with different confederate faces. Importantly, this task allows for the spontaneous encoding of confederates and feedback, that is participants are not instructed to explicitly encode information. Thus, this task provides a veridical assessment of what aspects of social feedback individuals naturally attend to and encode, and how, in turn, encoding accuracy of this feedback modulates state self-esteem in relation to trait self-esteem levels. Each trial began with a fixation cross presented in the middle of the computer screen for 250ms, followed by a confederate face for 2000ms, a black screen for 1000ms, and then feedback indicating whether the confederate accepted them for 2000ms (either "ACCEPT" or "REJECT" was presented in the middle of the screen).

As an attention check, participants were asked to indicate whether the confederate accepted or rejected them with a corresponding button press that would advance them to the next trial. Participants were shown 100 faces randomly paired with feedback (50 faces associated with accept feedback, 50 faces associated with reject feedback). Confederate gender was always matched to participant gender (e.g., males saw only male confederate faces) to increase the amount of stimuli control in the study, i.e., being rejected by the opposite sex may be more arousing than being accepted or rejected by the same sex (Dion, 1975).

Memory test

Participants were given a surprise memory test consisting of previously seen confederate faces (100 faces; 50 accept, 50 reject) and lures of other confederate faces (50 lures) they had not seen previously. Following the presentation of a confederate face, participants were asked if they had previously seen the confederate on a scale from one to six (where one indicated that they definitely did not see the confederate in the previous task and six indicated that they definitely did see the confederate in the previous task). If participants had been exposed to the confederate during the social feedback task, responses of four to six were classified as a hit while responses of one to three were classified as a miss. Trials that presented confederates with faces that had not been seen in the previous task were classified as a false alarm if the participant responded with a four to six, and as a correct rejection if the participant responded with a one to three. To examine participants' sensitivity to faces that were associated with social acceptance vs rejection feedback, separate d' scores were calculated for faces associated with accepting feedback and faces associated with rejecting feedback. D' , a measure argued to be a more sensitive assessment of memory encoding (Wickens, 2002), was derived by subtracting z scores for false alarm rates from z scores for hit rates. Larger d' values indicate better ability to discriminate seen from unseen faces. In the present study d' will serve as the operationalization of memory accuracy within all analyses.

Trait self-esteem and state self-esteem

The Rosenberg self-esteem scale (RSE, Rosenberg, 1965) was administered during a pretesting session conducted at the beginning of the semester as well as immediately post-experiment. The experimental session took place toward the middle and end of the semester. This allowed researchers to compare trait ($\alpha = 0.66$) and state ($\alpha = 0.84$) self-esteem. The RSE scale given during pretesting to assess trait self-esteem framed the questions regarding participants' *overall feelings* i.e., "On the whole, I am satisfied with myself" while the RSE scale given post-task to assess state self-esteem framed the questions regarding how participants felt in the moment, i.e., "At this moment, I am satisfied with myself". Both versions of this scale have been implemented in previous literature to measure trait and state self-esteem accordingly (Rosenberg, 1965; Kernis et al., 1993; Greenier et al., 1999; Robins et al., 2001). Participants answered ten questions on a one to four scale (where one equaled "strongly disagree" and four equaled "strongly agree"). Question answers were averaged together. Final scores ranged from one to four with higher numbers indicating higher trait self-esteem and state self-esteem.

EEG recording

Continuous EEG activity was recorded using an ActiveTwo head cap and the ActiveTwo BioSemi system. Recordings were collected from 64 scalp electrodes, an electrode density high enough for source localization (Michel and Brunet, 2019). Two electrodes were placed under and on the outer canthus of the right eye to record ocular movements. Data were re-referenced to the original average reference for all analyses offline, and EEG signals were band-pass filtered (0.3–75 Hz) and stimulus-locked to the feedback presentation portion of all trials. EEG signals were stimulus-locked to feedback per previous studies utilizing similar paradigms (Leitner et al., 2014; Somerville et al., 2006). All participants' data were scanned for artifacts using BESA's artifact scanning tool, and ocular artifacts were corrected via the adaptive algorithm implemented in BESA. All participants included in analyses had at least ten epochs for all trial conditions.

Source localization

The goal of this study was not to employ a typical EEG/ERP based approach, which relies on examining evoked activity in response to stimuli within a confined frequency space that collapses across multiple frequency bands and localizing a neural generator for a given ERP of interest. Instead, the current study sought to analyze data in a manner that more closely resembles what fMRI studies typically achieve but with the added benefits afforded to EEG, e.g., examining electrical activity stemming directly from neural activity on the order of milliseconds as opposed to indexing indirect markers of neural activity consisting of blood flow in a given region on the order of seconds. That is, both spontaneous and evoked activity within specific neural sources across distinct frequency bands thought to reflect different neural processes (e.g., excitatory compared to inhibitory neural processes) were analyzed. Source and time-frequency analyses were conducted with Brain Electromagnetic Source Analysis (BESA) 5.3 software (MEGIS Software GmbH, Grafelfing, Germany) to model spontaneous and evoked activity; MATLAB was utilized for Granger Causality analyses. BESA source localization utilizes a planted dipole approach in which precise coordinates located in specific neural regions are used, as opposed to regions on the scalp, to parse apart the variance in the EEG signal not unlike a typical principal components analytic (PCA) approach (see Scherg, 1990 for mathematical proofs). The primary difference between the two approaches is that whereas PCA is constrained by the mathematical components of the variance within the data, BESA's approach bases constraints on volume conduction theory and head geometry (Scherg, 1990, 1992). This allows one to model principal components as hypothesized sources instead of unique voltage patterns defined by the algorithm. This dipole technique has been cited in notable papers aimed at addressing the inverse problem in EEG source analyses (Scherg, 1990; Grech et al., 2008) and identifying neural generators of specific ERPs in addition to dipole source localization (Jentzsch and Sommer, 2001; Santiago-Rodriguez et al., 2002).

This *a priori* hypothesis-driven source localization approach consists of the following steps: 1) electrode space is transformed into a reference-free source space. 2) Dipole sources specific to a region of interest are fitted in both orientation and location to best model current flow in a given dipole, independent of other dipoles. 3) This source space is then transformed into time-frequency space, providing a means to virtually model oscillations in a specific frequency band within a specific source that is theoretically independent of oscillatory activity in other sources. Again, much like the PCA approach, but in this case the principal components are sources with specific coordinates identified per the present hypotheses as opposed to principal components comprised of spatially unique voltage patterns located at the scalp.

Given that prior knowledge of a neural system of interest can be utilized to constrain spatial parameters of a source model (Scherg and Berg, 1991), the goal was to model and isolate time-frequency activity in sources of interest while also accounting for typical artifacts present in any EEG study (e.g., eye blinks) as well as basic cognitive and perceptual processes that are likely active during any basic cognitive task. Furthermore, because of the social nature of the task, it is possible that other social cognitive processes, e.g., attribution/theory of mind processes, were evoked but irrelevant to study hypotheses as well. Thus, to account for basic visual and perceptual processes like eye movements and eye blinks, multiple sources were initially planted in the left and right eyes, bilateral occipital cortices, and bilateral cerebellum following previous literature (Eisenberger et al., 2011; Hanslmayr et al., 2008). Dipoles were also planted in regions associated with social interactions and social feedback (Behrens et al. 2009), including the right Temporal Parietal Junction (TPJ, mental state representation, Saxe, 2006; Molenberghs et al., 2016), bilateral Superior Temporal Sulci (STS, social perception, Allison et al., 2000; Adolphs, 2001), and Anterior Cingulate Cortex (ACC, social rejection (Somerville et al., 2006; Eisenberger and Lieberman, 2004). Although social rejection

regions were accounted for, regions associated with social reward, i.e., caudate, ventral striatum, and nucleus accumbens were not accounted for due to the difficulty inherent in measuring activity in these regions via EEG and the inverse problem. Final dipoles were then placed in mPFC and PCC in accordance with study hypotheses.

Coordinates for social cognitive processes and hypothesized ROIs were taken from various meta-analyses and relevant works of interest (rTPJ: [Van Overwalle \(2009\)](#); right and left STS: [Grosbras et al. \(2012\)](#); [Iacoboni et al. \(2004\)](#); ACC: [Rotge et al. \(2015\)](#); PCC ([Bird et al., 2015](#); [Maddock et al., 2001](#); mPFC: [Ochsner et al., 2009](#); [Van Overwalle, 2009](#); [Mitchell et al., 2005](#)). The coordinates from the meta-analyses were then verified using Neurosynth meta-analyses to locate the most appropriate Talairach coordinates for use in the final source model ([Yarkoni et al., 2011](#)). The corresponding Talairach coordinates are presented in [Table S1](#). The dipoles from these sources were converted into regional sources with three orientations, each of which was analyzed as a separate dipole. This source model accounted for 98% of the total variance in the EEG signal; no other dipoles could be planted to account for the other 2% in the model. While a model with this many sources in any given brain region would likely account for 98% of the variance, it's important to note that by applying the approach outlined here, much like a PCA approach and standard fMRI region of interest analysis. This technique essentially applies a spatial filter to the data that allows the examination of spontaneous and evoked activity in specific frequency bands in ROIs that are theoretically independent of time-frequency activity in other neural regions that are not of interest to the study (i.e., noise). That is, the source model optimized prior knowledge of neural systems to accurately extract signal from theoretically driven ROIs ([Scherg and Berg, 1991](#)).

Finally, to validate the source model, a multiple source probe scan (MSPS) was performed in BESA following past studies using similar techniques ([Hanslmayr et al., 2008](#); [Sehatpour et al., 2006](#)). The MSPS model displayed activity around all sources in the source model, suggesting the source model was an adequate representation of the EEG data.

Time-frequency analysis

EEG data were then transformed into time-frequency space using complex demodulation ([Papp and Ktonas, 1977](#)) within BESA 5.3 using the source model above. Samples were taken from frequencies ranging from 4 to 50Hz in 2-Hz increments. Theta frequencies were operationalized as 4–8 Hz, alpha as 8–12Hz, beta as 12–30Hz, and gamma as 30–50Hz ([Sauseng and Klimesch 2008](#)). Samples were taken from a -500 to 1500ms epoch in 25ms steps. Epochs of interest were extracted from stimulus presentation (0 ms) to 500 ms post-stimulus, specifically from accepting feedback, rejecting feedback, and all feedback presentations (collapsing across accepting and rejecting feedback). This epoch length was chosen for several reasons. One, epochs of 500ms typically helps avoid contaminating the results with edge artifacts. Two, by using a more extended time segment it is possible to have better frequency precision and resolution. With a time of 500ms, two cycles of the lowest frequency of interest (500ms for a 4-Hz oscillation) can be extracted while still capturing higher-frequency activity accurately ([Cohen, 2014](#)). Larger time windows are also less susceptible to muscle artifacts, outliers, and other non-brain interference ([Bastiaansen et al., 2011](#)).

Phase-locking values were obtained for all frequencies above by calculating the correlation of two normalized spectral density functions ([Forbes and Leitner, 2014](#)). All phase-locking analyses used mPFC source as the source reference given its essential role in self-related processing. Power was calculated by obtaining the instantaneous envelope amplitude of each source from the model as a function of frequency and latency, following the procedures of [Hoechstetter et al. \(2004\)](#) and [Forbes and Leitner \(2014\)](#). The absolute power in each source with respect to the baseline was then averaged over all trials.

Time-variant granger causality

To gain insight into how self-oriented memory processes interacted, be they basic encoding processes influencing self-oriented processes (PCC to mPFC directionality) or self-oriented processes influencing basic encoding processes (mPFC to PCC directionality), Granger causality (GC) analyses were conducted to assess the directionality of the mPFC and PCC time series. GC is an analytic approach used to quantify the existence and direction of causal influence of time series neural activity from multiple regions. In this study, linear regressive predictive models were first used to calculate independent time series for mPFC and PCC. Time series from either PCC or mPFC were then incorporated into the other using multi-regressive models. If one region has a causal influence on another, then the predictive ability of the model should

be improved when incorporating the time series from that neural source. The full mathematical descriptions of the models are available upon request. In this study, time-variant GC was utilized for 0-500ms post-stimulus presentation and more positive GC values represent mPFC activity influencing PCC activity to a greater degree while more negative values indicate PCC activity better predicts mPFC activity.

QUANTIFICATION AND STATISTICAL ANALYSIS

Analytic plan

The following steps were taken to address the five hypotheses. For each analysis, sensitivity analyses using G*Power were conducted to ensure each analysis was powered to 80%. All analyses that contain neural variables controlled for multiple comparisons given that all four frequency bands were tested with no *a priori* hypotheses. The Benjamini–Hochberg False Discovery Rate procedure (Benjamini and Hochberg, 1995) was utilized using a q-level of .1 (Singh and Phillips 2010; Pintzinger et al., 2017; Ewald et al., 2012). All descriptive statistics of variables used are located in supplemental information Table S1. All statistics were conducted using SPSS software.

H1: To determine how individuals may encode and recall self-threatening or non-threatening social feedback, the following analyses were conducted. A one-sample t-test was first conducted. This test compared participant's memory accuracy for both accepting and rejecting faces to chance. Following, a repeated measures ANOVA with repeated measures on memory scores for accepting and rejecting feedback was conducted to observe if participants remembered accepting or rejecting faces to a greater extent. Finally, to address the behavioral question of whether memory accuracy correlated with state self-esteem, regression analyses were conducted to assess whether there was any relationship between state self-esteem and memory accuracy for accepting and rejecting faces independently.

H2: After the behavioral analyses, neural analyses were conducted to provide discriminant validity for the study's *a priori* regions. If a particular region is integral for a specific psychological process, we might expect activity within that region to fluctuate during tasks that recruit given psychological processes. To examine the role of PCC activity in memory-oriented processes, independent linear regression analyses (conducted in all frequency bands for four total models), regressed memory scores on to PCC power elicited in response to accept and reject feedback. To examine the role of mPFC activity in self-oriented processes, independent linear regression analyses (conducted in all frequency bands for four total models) regressed state self-esteem scores, and then trait self-esteem scores on to mPFC power elicited in response to accept and reject feedback.

H3: Previous analyses will provide insight into what social psychological processes are occurring behaviorally and whether there was discriminant validity for mPFC and PCC power in relation to behavioral variables. Analyses specific to H3 address the interactions concerning behavioral and neural responses by examining how trait self-esteem, state self-esteem, and explicit memory are impacted by mPFC-PCC communication (phase-locking). Taking a similar approach to H2, we first regressed mPFC-PCC phase locking (in all frequency bands) on to trait self-esteem. Explicit memory and state self-esteem were then regressed on to mPFC-PCC phase locking to determine whether behavioral differences exist as a function of altered communication between these two regions.

H4: After determining whether mPFC-PCC communication could influence behavioral outcomes, it is important to explore its effects on self-perception maintenance. Moderated regression analyses were conducted by deriving unstandardized regression coefficients and 95% bias-corrected confidence intervals (CIs) from 10,000 bootstrap estimates using PROCESS (Hayes, 2017; model 1). Trait self-esteem was represented as X, state self-esteem was represented as Y, and mPFC-PCC phase-locking to feedback was represented as the moderator, M.

H5: Finally, to determine whether memory accuracy or state self-esteem was driven by mPFC communication or PCC communication, a series of linear regression analyses were conducted utilizing these variables and the product of the time-variant Granger causality analyses conducted on the mPFC and PCC time series elicited during feedback presentation. In two linear regressions, state self-esteem was regressed on to the Granger causality values of mPFC on PCC, and PCC on mPFC, during feedback encoding to determine this relationship.