



Neural representations of popularity and leadership status relate to conformity in daily life

Ovidia A. Stanoj^{a,b,1} , Danielle Cosme^{a,b} , Mia Jovanova^{c,d}, Yoona Kang^e, Faustine Corbanif, Amanda L. McGowan^a, José Carreras-Tartak^{a,b} , Anthony Resnick^{a,b} , Peter S. Bearman^g , Zachary M. Boyd^h, Dani S. Bassettⁱ , David M. Lydon-Staley^a , Peter J. Mucha^j , Emily B. Falk^{a,b,k,l} , and Kevin N. Ochsner^{m,1}

Affiliations are included on p. 10.

Edited by Susan T. Fiske, Princeton University, Princeton, NJ; received September 22, 2025; accepted April 30, 2026

Individuals are motivated to increase their social status. To succeed in this pursuit, people must track information about others in their social sphere, monitor group norms, and adjust their behavior strategically. This study employed functional MRI and ecological momentary assessment methods in a sample of 92 college students belonging to 9 social groups to elucidate the neural mechanisms underlying these processes and their relationship to conformity in the context of alcohol use. When young adults passively looked at faces of their real-life social group peers, brain systems implicated in valuation and social cognition spontaneously tracked information about the popularity and leadership status of the social targets in an interdependent manner. Individual differences in these neural valuations were systematically associated with varying levels of conformity. Students who had stronger responses to faces of peers with relatively higher popularity and leadership status than themselves in one key valuation brain region, the ventromedial prefrontal cortex (vmPFC), were more likely to align their drinking behavior with their groups' norms in everyday life. These results provide evidence for how brain systems involved in valuation and social cognition flexibly track information about peers' popularity and leadership status in real-life social groups and contribute to a growing literature on the neural mechanisms through which social comparison processes shape conformity. Our study highlights the vmPFC as a central hub that spontaneously tracks status differences between the self and peers and uses this information to guide behavior to match group norms.

social groups | social status | social cognition | fMRI | conformity

Humans are inherently social, thriving in groups where individuals naturally differentiate themselves in status (1–7). As an example, imagine a school group project. As students collaborate, some quickly become more well-liked than others based on their personalities or behavior. This differentiation reflects sociometric popularity—how much each person is liked by their peers. At the same time, as the group works toward completing the project, one or two members may naturally step into leadership roles by organizing tasks or guiding discussions. These individuals distinguish themselves through their leadership status—how much they are seen as contributing to the group's shared goal. In any organization or group, these two types of status—popularity and leadership—tend to emerge. Popularity reflects how much an individual is liked by their peers overall, while leadership status reflects to what degree they are perceived to influence and coordinate the group's efforts toward a common purpose (8–13).

Between-person disparities in these two types of status are important because they can translate into meaningful differences in outcomes and experiences. For example, popular individuals command more visual attention (14), are often imitated (15, 16), and are generally perceived as more helpful (17). Leaders, in turn, promote behavioral compliance among their group's members (18), are seen as more intelligent and self-confident in day-to-day interactions (19), and can be granted more control over group resources (20). Given the importance of status for social success, it is no surprise that, across cultures, age groups, and genders, humans are motivated to be liked by their communities and attain positions of leadership within them (21, 22).

Achieving and maintaining status requires the ability to monitor the relational dynamics in our social groups (5, 23–27). In fact, being able to discern status differences is so fundamental to goal attainment that it generalizes to most nonhuman primates, who also track hierarchical relationships between members of their group (28–34). Although ample evidence exists for humans' ability to identify popular figures and leaders within their groups, the underlying neural mechanisms remain unclear.

Significance

Two types of status define the standing of individuals within their groups: popularity (how much they are liked) and leadership (how much they are perceived to be leaders). In any social interaction, people may track their own and their peers' popularity and leadership status to decide how to act appropriately. How do we represent this social information and how do these representations relate to behavior? Our findings suggest that brain systems involved in valuation and social cognition spontaneously track information about one's own and peers' popularity and leadership status in an interdependent manner and that these neural valuations influence conformity behavior. This study provides insights into the neural representation of multidimensional social status information and its link to conformity.

Author contributions: O.A.S., D.C., D.S.B., D.M.L.-S., P.J.M., E.B.F., and K.N.O. designed research; O.A.S., D.C., M.J., Y.K., F.C., A.L.M., J.C.-T., A.R., Z.M.B., and D.M.L.-S. performed research; O.A.S., D.C., P.S.B., and P.J.M. contributed new reagents/analytic tools; O.A.S., D.C., and P.J.M. analyzed data; and O.A.S., D.C., D.S.B., D.M.L.-S., P.J.M., E.B.F., and K.N.O. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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¹To whom correspondence may be addressed. Email: ostanoj@falklab.org or ko2132@columbia.edu.

This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2526584123/-/DCSupplemental>.

Published May 27, 2026.

In recent years, functional neuroimaging studies have started to shed light on this question, guided largely by two approaches. The first approach, taken by our labs and others, has examined how the brain enables us to track the sociometric popularity of members of real-life social groups (35–38). To study this, researchers have used naturalistic paradigms in which participants passively view photos of group members in the functional MRI (fMRI) scanner. This approach models the ability to track popularity as an instance of person perception, where viewing a group member's face spontaneously evokes two key processes—valuation and social cognition. Valuation helps people represent the value of interacting with popular individuals, based on previous experiences or observations that link them with positive outcomes. Social cognition enables people to infer the attitudes, emotions, opinions, beliefs, and intentions of these individuals. This is important because, in addition to being highly liked, popular peers often hold significant influence within the group. Consistent with these ideas, neuroimaging studies have shown that activity in neural systems for affective learning/valuation (e.g., ventromedial PFC, striatum, amygdala) and social cognition/mentalizing (e.g., dorsomedial PFC, TPJ, precuneus) track the sociometric popularity of group members (38).

The second approach asks how people learn and make judgments about ranked, hierarchical relationships among individuals such as those you might find in a business, government, or the military. To shed light on this question, researchers have used neuroimaging paradigms in which participants learn about fictitious characters with varying ranks in areas like company power (37, 39–41), naval position (42), incidental skill (43), or financial and moral standing (44, 45). This work has found that acquiring knowledge and making judgments about formal, well-defined but fictional social hierarchies engages regions important for relational encoding (e.g., hippocampus) (5, 39, 40), affective learning (e.g., amygdala, medial PFC) (39, 40, 43–45), and the representation of social distance (e.g., inferior parietal lobule) (42, 44). Notably, these studies have focused only on status hierarchies conferred by formal titles within organizations and institutions, without investigating how people track the degree to which their peers are perceived by the group to be leaders, based on real-life experiences with those individuals in group contexts. In many situations, leadership status that emerges naturally as groups work toward common goals may function similarly to institutional ranks, but the neural systems supporting its perception and tracking may or may not necessarily be the same. Taken together, these two different approaches have provided insight into the processes by which people track status differences in popularity or leadership, but critical questions remain. In this paper, we drew on elements of each approach to address three open questions.

For the first question, we began with the observation that in real-life social groups, people vary in *both* popularity and leadership status at the same time. Although popular individuals can also be leaders, this is often not the case, and success in a group may depend on the ability to monitor both status dimensions simultaneously. For instance, imagine you are choosing a teammate for a project. When deciding with whom to collaborate, you need to consider not only someone's recognized tendency to lead but also their perceived likability (i.e., sociometric popularity). You might decline a project with someone difficult to work with, even if they have strong leadership skills. Despite the relative mundanity of this fact, to date, no studies have addressed the question of whether the neural mechanisms used to represent and track popularity and leadership status are similar or different or what brain regions might represent them in an interdependent manner.

We hypothesized that there could be two answers to this question. On one hand, in real world groups, learning, thinking, and determining who has emerged as a leader could be similar to the process by which we learn, think, and make judgments about who is highly likable (i.e., popular). From this perspective, the ability to track both kinds of status—separately or interdependently—may depend on valuation systems that build expectancies for future interactions based on a history of positive interaction outcomes [i.e., ventromedial prefrontal cortex (vmPFC), amygdala, striatum], as well as systems for inferring the beliefs, emotions, and intentions of high-status individuals, whether they are leaders, popular, or both (i.e., dmPFC, TPJ) (valuation and social cognition hypothesis). On the other hand, if tracking leadership in real world groups works the same way as tracking formal social hierarchies, then it might depend on systems important for relational learning and representing social distance (i.e., hippocampus and entorhinal cortex) (relational binding hypothesis). This hypothesis would be consistent with theories that the brain represents social relationships in a cognitive map similar to the way it represents space (41, 46, 47).

Our second question was prompted by a related, albeit different observation. People are highly attuned to the status dynamics of their social groups, especially when those dynamics might influence their own standing. Put another way, individuals tend to judge others' popularity and leadership status not in absolute terms, but in relation to their own (5, 23, 48). As Festinger noted in his classic treatise (49), "there exists, in the human organism, a drive to evaluate himself. [...] People most strenuously seek to evaluate performance by comparing themselves to others, not by using absolute standards." Consider, for example, an individual that is fairly popular but does not have a high leadership position in their social group. This person might pay more attention to the group leaders, as the motivation to improve their own standing has the most room to grow in terms of leadership status. Although behavioral research has shown that status differences influence the way we attend to status-relevant cues in others (5, 48, 50, 51), the neural processes involved in tracking these differences in the first place are less well understood. As such, our second question was what brain systems are sensitive to peers with relatively higher popularity and leadership status than the perceiver? We hypothesized that valuation regions, particularly the medial prefrontal cortex, would track differences between the self and others, as these regions are key for assessing the motivational value of others based on how relevant they are to one's goals (52).

Our third question concerned the way in which conformity to group norms may stem from an individual's sensitivity to status differences. Behavioral research has shown that when people feel they lack power, they become more vigilant and responsive to others' perspectives (53, 54). This is in part because low status individuals are more sensitive to group acceptance and rejection, which increases sensitivity to group norms and susceptibility to social influence (50, 55). As such, low status individuals are motivated to know who has higher status because an accurate perception of the group members' popularity and leadership standing should foster the formation of strategic alliances, identification of attributes valued by the group, and modification of their own behavior to help increase their own status (4). Together, these data suggest that those who show greater sensitivity to status differences should be more likely to engage in goal-directed behaviors aimed at improving their position, and these behaviors should, in turn, depend on the local norms of the group (56). Building on prior neuroimaging research examining the neural correlates of social

influence, activation within valuation and social cognition systems is likely to be relevant (57–62). To date, however, no study has used functional imaging to ask how individual differences in neural sensitivity to status differences relate to conformity behavior in daily life.

With this gap in mind, our third question addressed this relationship in the context of a health-relevant behavior—alcohol consumption—in college students. We chose alcohol use in college students as a case study because it is a common behavior in this population with important consequences. In their first year of college, students show a striking increase in drinking (63), which may come at a high cost, including academic difficulties, unintentional injuries, or even accidental deaths (64). Moreover, alcohol use is highly susceptible to social norms and peer influence processes (65–68). These factors make it a valuable case study for how perceptions of status influence behavior. We hypothesized that individuals with higher neural sensitivity to high status peers will be more likely to match their drinking to their groups' norms.

To address these three research questions, we used data from the social health impact of network effects (SHINE) study (69). This research project recruited undergraduate student groups (e.g., sport teams, performing arts groups, Greek life) to complete a comprehensive battery of assessments, including peer ratings, an fMRI scan, and in-the-moment phone surveys for a month. The peer ratings used a round-robin design, in which participants rated how much they liked each member of their group, and how much they thought each member was a leader. We used these answers to quantify each individual's popularity and leadership status as the average rating received from peers on each prompt. Participants also completed an fMRI task adapted from ref. 38 where they passively viewed pictures of group members (SI Appendix, Fig. S1). Finally, for 28 d following the scan, participants answered twice-daily phone surveys about their drinking. All groups represented social contexts where members shared a common goal and

their status varied naturally in terms of popularity and leadership. In this study, we included data from 92 college students belonging to nine close-knit student groups.

Results

Which Brain Systems Represent Peers' Popularity and Leadership Status in Real-Life Social Groups? We tested whether students spontaneously represented information about their peers' popularity and leadership status in brain systems involved in valuation and social cognition vs. relational binding using representational similarity analysis (RSA). RSA compares behavioral and neural representational dissimilarity matrices (RDMs) to understand how differences in stimuli are reflected in different neural representations (70). Because we had strong hypotheses about which brain systems may track popularity and leadership status in real-life social groups, we focused our analyses on 9 regions-of-interest (ROIs) involved in valuation and affective learning (vmPFC, bilateral amygdala, bilateral ventral striatum), social cognition and mentalizing (dmPFC, left TPJ, right TPJ), and relational binding (left hippocampus, right hippocampus, entorhinal cortex) (SI Appendix, ROI Selection and Fig. S2).

For each participant i who completed the fMRI scan, in each of the 9 ROIs, we calculated how dissimilarly they represented any two members of their group whose pictures were presented in the faces task as $1 - \text{Pearson } r$ between the voxel-level responses to the faces of those two peers (Fig. 1A) (71). For each of the 9 student groups, we then used the round-robin ratings completed outside of the scanner to compute all the pairwise distances in popularity and leadership status between each pair of students whose faces were presented in the scanner as the absolute difference between their leadership and popularity status (Fig. 1C).

We estimated how dissimilarly participants represented each pair of peers in the 9 ROIs as a function of that pair of peers' leadership and popularity status distances separately and then as

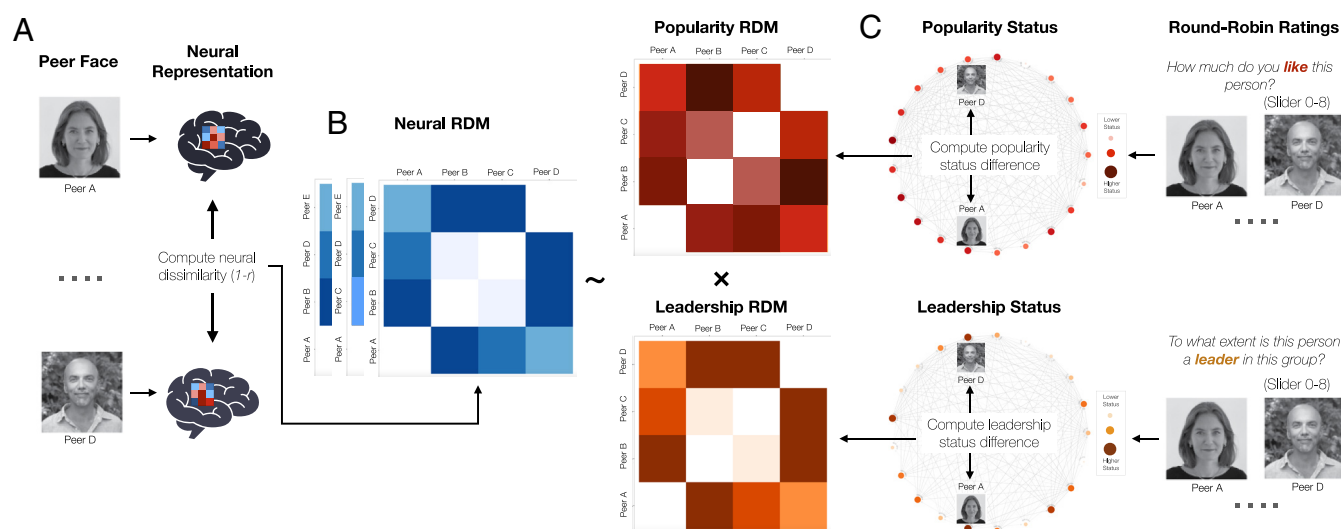


Fig. 1. RSA model design. (A) In the fMRI task, participants passively viewed pictures of their real-life group peers. Participants' neural representation of each peer face was estimated in nine ROIs as voxel-level activity patterns. Next, we computed how dissimilarly participants represented each pair of peers as $1 - \text{Pearson } r$ correlation of their voxel activity values. (B) These values formed a neural RDM, in which each cell reflects how dissimilarly a participant represented two peers. The matrix is symmetrical and excludes the diagonal. Neural RDMs were modeled in a multilevel Bayesian framework as a function of two social status RDMs—popularity and leadership—and their interaction. (C) Popularity and leadership RDMs were constructed from out-of-scanner ratings in which participants evaluated each peer on liking ("How much do you like this person?") and leadership ("To what extent is this person a leader in this group?") on a scale from 0 (Not at all) to 8 (A lot). These ratings were used to compute each individual's popularity and leadership status as the mean rating received from other group members. Pairwise status differences were calculated as the absolute difference in these values and compiled into the popularity and leadership RDMs. These social status RDMs were then compared with the neural RDM in the multilevel model described in (B). Note: Faces shown are of the study authors, not participants.

a function of the two status distance measures together and their interaction (Fig. 1*B*). In effect, our models investigated whether pairs of individuals with similar popularity and leadership status were more similarly represented by their peers at the neural level and whether the relationship between leadership status difference and neural similarity was moderated by differences in popularity status, and vice versa. If a brain region tracks peers' popularity and leadership status in an interdependent manner, then the relationship between neural similarity and difference in leadership status should depend on its distance in popularity status, and vice versa. If the opposite is true, then differences in leadership and popularity status should independently relate to neural dissimilarity, and no interactions should emerge.

We used multilevel Bayesian inference for our analyses, which offers several advantages over traditional statistical methods. First, testing all relationships within a single multilevel model in which we included random slopes for the 9 ROIs nested within their broader brain systems (valuation, social cognition, relational binding) addressed the multiple comparisons issue common in fMRI research (72). Second, partial pooling of variances across ROIs helped account for the interdependence between brain regions and the shared information in our data (73, 74). ROI-specific effects were treated as draws from a shared population-level distribution, resulting in partial pooling of ROI estimates toward the mean, with the degree of pooling determined by the data. Importantly, the multilevel structure does not assume identical effects across ROIs. If an ROI shows a

credible effect in the opposite direction, the model permits this pattern when supported by sufficient evidence. Third, unlike Frequentist statistics, Bayesian inference allowed us to combine data with prior models to generate posterior distributions which can be used to extract measures of uncertainty, like credible intervals, for random effects and simulate predictions for future outcomes.

Throughout the paper, result reports include the median of the posterior distribution (central estimate), its 95% credible interval, and the proportion above or below zero. Because we did not have strong prior expectations above effect sizes, analyses were conducted with the default weakly informative priors from the "brms" and "rstanarm" packages in RStudio (75, 76). All predictors were centered within-group and transformed into z-scores to facilitate interpretability. The R scripts used for analyses are publicly available on GitHub (77) and model descriptions are provided in *SI Appendix, Analysis Plan*.

In the RSAs, in addition to the ROI-level random slopes, we also included random intercepts for participants and dyads nested within groups to account for the hierarchical and repeated structure of the data. Because each dyad comprised two social targets, we also specified a multimembership random effect allowing both members of each dyad to contribute to the variance structure, thereby modeling the nonindependence inherent in dyadic analyses (78, 79).

Neural patterns in none of the 9 brain ROI showed sensitivity to differences in popularity or leadership status alone, regardless

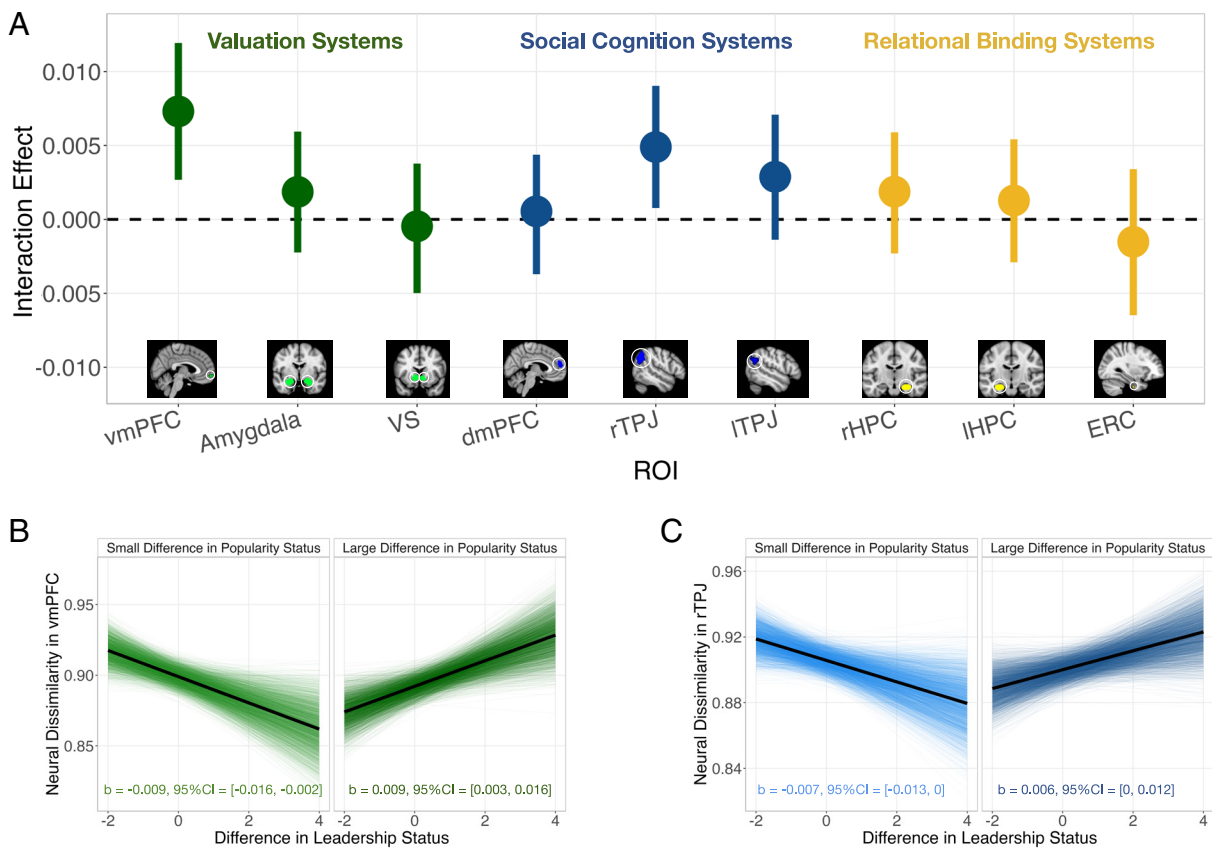


Fig. 2. Neural representation of popularity and leadership status differences. (A) Estimated relationships (standardized betas and 95% credible intervals) between neural dissimilarity and the interaction of popularity and leadership status differences in different ROIs. Neural dissimilarity in the vmPFC and rTPJ was significantly associated with the interaction of targets' leadership and popularity statuses, as indicated by 95% credible intervals excluding zero. (B) Relationship between dyad-level differences in leadership status (centered within-group, z-scored) and neural dissimilarity in the vmPFC, plotted separately for dyads with similar popularity (1.5 SD below the mean; *Left*) and dyads with large popularity differences (1.5 SD above the mean; *Right*). (C) Same as (B), but for neural dissimilarity in the rTPJ. In (B) and (C), black lines show the estimates' posterior medians (best-fit lines); the underlying green and blue lines represent the 4,000 draws from the posterior distribution, reflecting the uncertainty in the estimates. ROIs: vmPFC = ventromedial prefrontal cortex; Amygdala = bilateral amygdala; VS = bilateral ventral striatum; dmPFC = dorsomedial prefrontal cortex; rTPJ = right temporoparietal junction; lTPJ = left temporoparietal junction; rHPC = right hippocampus; lHPC = left hippocampus; ERC = entorhinal cortex.

of whether we held constant differences in the other dimension or not (*SI Appendix, Tables S1–S4*). We did find, however, that neural activity in the vmPFC and in the rTPJ tracked interactions between the two (*Fig. 2A* and *SI Appendix, Table S5*). When participants passively viewed photographs of members of their real-life social groups, neural patterns in the vmPFC ($b = 0.007$, 95% CI = [0.003, 0.012], 99.9% posterior > 0) and in the rTPJ ($b = 0.005$, 95% CI = [0.001, 0.009], 99.1% posterior > 0) were associated with interactions between peers' popularity and leadership status. The relationship between leadership status differences and neural similarity depended on differences in popularity status, and vice versa. The presence of an interaction in the absence of main effects indicates that these regions do not encode either status dimension independently; rather, neural representations were sensitive to the conditional relationships between the two.

To understand this moderation effect better, we estimated the relationship between differences in leadership status and neural dissimilarity in the vmPFC and rTPJ separately for individuals close in popularity status (operationalized as 1.5 SD above mean) and for individuals distant in popularity status (operationalized as 1.5 SD below mean) (*Fig. 2B and C*). As expected, group members who differed in both popularity and leadership status were more distinctly represented than their peers who differed only in popularity or leadership ($b_{vmPFC} = 0.009$, 95% CI = [0.003, 0.016], 99.9% posterior > 0; $b_{rTPJ} = 0.006$, 95% CI = [0, 0.012], 96.7% posterior > 0). These results are consistent with an additive model, in which larger status differences are reflected in more distinctive neural patterns. Nonetheless, we also found that individuals who were similar in both leadership and popularity status were more dissimilarly represented than those who differed in popularity or leadership status alone ($b_{vmPFC} = -0.009$, 95% CI = [-0.016, -0.002], 99.7% posterior > 0; $b_{rTPJ} = -0.007$, 95% CI = [-0.013, 0], 98.2% posterior > 0), suggesting that the vmPFC and rTPJ might engage in cortical processes of pattern separation by enhancing small differences between very similar individuals to maintain separate representations of them (80). Exploratory categorical analyses (*SI Appendix, Exploratory Analyses*) showed greater differentiation among low-status individuals, potentially reflecting more varied pathways to low-status than high-status roles.

We also considered other variables that could explain our results. Popular individuals were judged as more attractive by their peers (Kendall's $\tau = 0.44$, $P < 0.001$), while students with higher leadership status tended to be more senior ($r = 0.31$, $P < 0.01$) and to come from households with higher parental education ($r = 0.15$, $P = 0.02$) and higher income ($r = 0.12$, $P = 0.06$). The stimuli in our fMRI task also included significantly more individuals self-identifying as women (73%) than men (27%). Since all these factors have been shown in previous research to influence neural valuations of faces (81–86), we reran the analyses above while including in the models an expanded set of covariates. This set included the dyads' average popularity and leadership statuses to mitigate the possibility that effects attributed to status differences could be driven by particular types of dyads (e.g., both high-status or both low-status targets), as well as whether the members of the dyad were the same gender, and the difference in their attractiveness as judged by independent raters, college year, household income, and parental education. We also held constant the same characteristics for the perceivers: attractiveness, gender, college year, household income, and parental education level. We additionally controlled for participants' own popularity and leadership status to ensure that the observed neural effects were not driven by the perceivers' status, given evidence that status perceptions vary as a function of one's own standing (38, 87–91). Finally,

we controlled for the difference in the perceivers' individual liking and leadership judgments of each dyad. We added this last control variable to ensure that results reflected neural representations of how peers are collectively liked and seen as leaders by the whole group and not merely individually liked or seen as leaders by the perceiver (38) (*SI Appendix, Measures*).

There were no meaningful changes in our results when we ran our analyses including these covariates. The relationship between neural dissimilarity in the vmPFC and rTPJ and interactions between popularity and leadership status remained almost identical ($b_{vmPFC} = 0.007$, 95% CI = [0.002, 0.012], 99.9% posterior > 0; $b_{rTPJ} = 0.004$, 95% CI = [0, 0.09], 97.8% posterior > 0) (*SI Appendix, Table S10*). Just as before, neural dissimilarity in none of the 9 ROIs tracked differences in popularity or leadership status alone (*SI Appendix, Tables S6–S9*). These results support the idea that valuation and social cognition brain systems track others' popularity and leadership status in an interdependent manner. Notably, these interactions did not replicate in a sensitivity analysis in which RDM were constructed from perceivers' own idiosyncratic liking and leadership ratings (*SI Appendix, Exploratory Analyses*), suggesting that vmPFC and rTPJ represent interactions between sociometric status dimensions rather than between subjective evaluations. We did not find evidence for the relational binding hypothesis, as peers with comparable popularity and leadership status were not more similarly represented in the bilateral hippocampus or in the entorhinal cortex.

Which Brain Systems Track Peers' Popularity and Leadership Status Relative to One's Own? Next, we investigated whether and how participants spontaneously responded to the relative popularity and leadership status of their peers (compared to their own status). People track others' social status in order to make the social comparisons that tell them which cooperative relationships to pursue to achieve their social goals (5, 23, 48, 49). Thus, we posited that, when passively viewing pictures of college peers, students' neural responses will depend on their own status as well.

To test this hypothesis, following prior work (35, 38, 92), we investigated which brain systems responded to faces of peers with higher relative popularity and leadership status in a Bayesian multilevel univariate analysis. While RSA provides insights into the content of neural representations by examining distributed patterns of activity across multiple voxels (93), univariate analyses, which track changes in average neural activity in response to a stimulus, are better suited to answer questions about the contexts in which specific types of neural processing are engaged. We estimated participants' mean neural response to peer faces in the 9 ROIs as a function of the peers' 1) popularity status and 2) leadership status, while holding constant the perceivers' own popularity and leadership status. By including the perceivers' own status in the model, the parameter of the relationship between the target's status and neural activity provides an estimate of participants' mean responses to the targets' status relative to their own. We included random slopes for the 9 ROIs nested within brain systems as well as random intercepts for peer faces and participants, nested within their student groups (*SI Appendix, Analysis Plan*). Sensitivity analyses using a difference-score measure of relative status, reported in *SI Appendix, Tables S38 and S39*, found attenuated effects of dmPFC for relative popularity and bilateral amygdala for relative leadership, but the overall pattern of findings remained unchanged.

Students had stronger neural responses to faces of more popular peers in the vmPFC ($b = 0.28$, 95% CI = [0.09, 0.50], 100% posterior > 0), the amygdala ($b = 0.21$, 95% CI = [0.04, 0.37], 99.2% posterior > 0), the dmPFC ($b = 0.22$, 95% CI = [0.06,

0.41], 99.5% posterior > 0), the left TPJ ($b = 0.20$, 95% CI = [0.03, 0.38], 99.1% posterior > 0), as well as the right HPC ($b = 0.20$, 95% CI = [0.01, 0.36], 98.1% posterior > 0), the left HPC ($b = 0.20$, 95% CI = [0.03, 0.37], 98.8% posterior > 0), and the ERC ($b = 0.22$, 95% CI = [0.03, 0.39], 99.1% posterior > 0), partially replicating previous findings from our group (39) and from ref. 47 (SI Appendix, Table S11).

Activity in the vmPFC, amygdala, dmPFC, TPJ, HPC, and ERC was also positively correlated with peers' relative leadership status ($b_{vmPFC} = 0.40$, 95% CI = [0.21, 0.59], 100% posterior > 0; $b_{amygdala} = 0.22$, 95% CI = [0.05, 0.38], 99.4% posterior > 0; $b_{dmPFC} = 0.30$, 95% CI = [0.14, 0.48], 100% posterior > 0; $b_{rTPJ} = 0.17$, 95% CI = [0, 0.34], 97.8% posterior > 0; $b_{lTPJ} = 0.27$, 95% CI = [0.11, 0.45], 99.9% posterior > 0; $b_{rHPC} = 0.17$, 95% CI = [0, 0.33], 97.7% posterior > 0; $b_{lHPC} = 0.20$, 95% CI = [0.04, 0.36], 99.1% posterior > 0; $b_{ERC} = 0.20$, 95% CI = [0.02, 0.37], 98.7% posterior > 0) (SI Appendix, Table S12). Our results suggest that the same brain regions are important for representing popularity and leadership status, even though human reports of perceived status were only moderately correlated ($\tau = 0.36$, $P < 0.01$) (SI Appendix, Fig. S1).

Importantly, depending on their own goals, people might pay more attention to differences in popularity in one case and more attention to differences in leadership status in another case. For example, an individual who is well liked but does not occupy a position of leadership in their student group might pay more attention to the leaders of the group as they are motivated to improve their own leadership standing. As such, we hypothesized that the vmPFC—a region important for computing valuations of things and individuals in the current context (52)—might show a stronger response to the faces of peers who occupy a relatively higher status than the perceiver—not only in popularity and leadership status separately but also in a dual social space in which popularity and leadership status are evaluated together in an interdependent manner.

To address this possibility, following ref. 47, we examined leadership and popularity status as two separate dimensions of a social space represented as a scatterplot in which participants' popularity and leadership statuses are plotted on the x- and y-axes. We then calculated, for a given participant i , each peer j 's relative dual status as the difference between the area covered by the participant i and the target j together and the area covered by the participant i alone in this dual status social space (SI Appendix, Measures and Fig. S3). Conceptually, this measure captures how much more a participant i 's status would need to increase to match that of the target j . We then estimated participants' mean neural response to peer faces as a function of this measure of peers' relative dual status in a Bayesian multilevel model with random slopes for ROIs nested within brain systems and random intercepts for peer faces and perceivers nested within groups (SI Appendix, Analysis Plan). Consistent with predictions, participants showed stronger neural responses to faces of higher status peers in the vmPFC ($b = 0.36$, 95% CI = [0.19, 0.54], 100% posterior > 0) and the dmPFC ($b = 0.16$, 95% CI = [0, 0.33], 97.8% posterior > 0) (SI Appendix, Table S13).

To account for other variables that could explain these results, we repeated our analyses while holding constant different target and perceiver characteristics that have been associated with neural valuations of faces in past research (81–86): perceived attractiveness, gender, college year, household income, and parental education. When we included these covariates in the model, only neural activity in the vmPFC ($b = 0.22$, 95% CI = [0.04, 0.44], 99.3% posterior > 0) and in the dmPFC ($b = 0.17$, 95% CI = [0, 0.35], 97.6% posterior > 0) was associated with relative popularity status (Fig. 3A and SI Appendix, Table S14). Activity in the

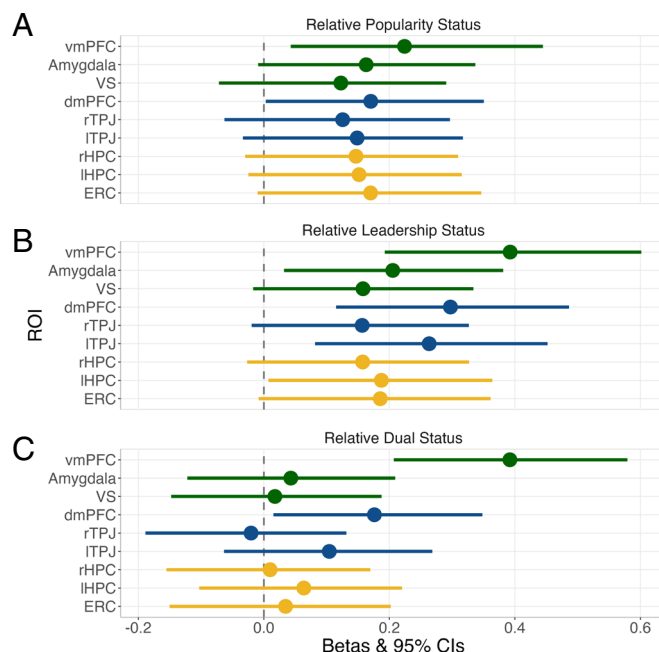


Fig. 3. Effects of peers' relative status on participants' neural responses across ROIs. Standardized betas and 95% credible intervals from univariate ROI analyses showing associations between participants' neural responses to faces of peers and those peers' (A) relative popularity, (B) relative leadership, and (C) relative dual status across valuation (green), social cognition (blue), and relational binding (yellow) systems. ROIs: vmPFC = ventromedial prefrontal cortex; Amygdala = bilateral amygdala; VS = bilateral ventral striatum; dmPFC = dorsomedial prefrontal cortex; rTPJ = right temporoparietal junction; lTPJ = left temporoparietal junction; rHPC = right hippocampus; lHPC = left hippocampus; ERC = entorhinal cortex.

vmPFC, bilateral amygdala, dmPFC, left TPJ, and left HPC, however, remained positively correlated with peers' relative leadership status regardless of whether or not control variables were included in the model ($b_{vmPFC} = 0.39$, 95% CI = [0.19, 0.60], 100% posterior > 0; $b_{amygdala} = 0.21$, 95% CI = [0.03, 0.38], 99% posterior > 0; $b_{dmPFC} = 0.30$, 95% CI = [0.12, 0.49], 100% posterior > 0; $b_{lTPJ} = 0.26$, 95% CI = [0.08, 0.45], 99.8% posterior > 0; $b_{lHPC} = 0.19$, 95% CI = [0.01, 0.36], 97.9% posterior > 0) (Fig. 3B and SI Appendix, Table S15).

For the dual status analyses, the effects on neural activity in both the vmPFC ($b = 0.39$, 95% CI = [0.21, 0.58], 100% posterior > 0) and the dmPFC ($b = 0.18$, 95% CI = [0.02, 0.35], 98.4% posterior > 0) were unchanged (Fig. 3C and SI Appendix, Table S16). In accordance with our hypothesis, this finding suggests that, when viewing pictures of their peers, the participants spontaneously engaged in processes of social comparison on goal-relevant dimensions. These tacit relative comparisons involved both valuation (vmPFC) and social cognition (dmPFC) regions, but not relational binding areas (hippocampus or entorhinal cortex). In a final step, we compared the predictive accuracy of the relative dual-status model against two control models indexing targets' popularity or leadership status alone (SI Appendix, Exploratory Analyses). Leave-one-out cross-validation showed that the dual-status model predicted vmPFC responses better than the popularity-only model. Nonetheless, the leadership-only model performed similarly and even slightly better. This pattern suggests that vmPFC responses to peers' faces were driven primarily by leadership status information in this sample.

How Do Neural Valuations of Relative Status Relate to Behavioral Conformity in Daily Life? We hypothesized that individuals showing greater vmPFC sensitivity to peers with higher relative

dual status will also tend to conform more with the norms of their group (57, 59, 62, 94). To test this hypothesis, we first computed for each participant an index of their vmPFC sensitivity to peers' relative dual status (*SI Appendix, Analysis Plan*). We then tested two predictions. First, we examined whether vmPFC sensitivity was associated with a self-report measure of susceptibility to peer influence (95). Second, we tested whether vmPFC sensitivity moderated the extent to which participants' drinking behavior in daily life aligned with their group's norms around alcohol use. Group norms were operationalized as the average of all group members' answer to the prompt "How strongly does your group as a whole approve of binge drinking?"

We estimated the participants' likelihood of drinking and the number of drinks consumed during the 28-d ecological momentary assessment (EMA) period following the fMRI scan as a function of the interaction between their vmPFC sensitivity to peers with higher relative dual status and their group drinking norms. Because the alcohol use EMA data included many observations (85%) at zero, we used a multilevel hurdle model, which combines logistic and negative binomial regression to separately estimate 1) the likelihood of alcohol consumption at any given time and 2) the number of alcoholic beverages consumed on an occasion when the individual drinks (96). To account for the structure of our data which involved repeated observations for each participant, intercepts were nested within individuals and their respective groups. Analyses were implemented in the "glmmTMB" package in RStudio (97) (*SI Appendix, Analysis Plan*).

In keeping with our predictions, participants who exhibited stronger vmPFC responses to faces of peers who had higher dual status than themselves also scored higher on our self-reported measure of susceptibility to peer influence ($b = 0.10$, 95% CI = [0.02, 0.18], 99.6% posterior > 0) (Fig. 4A and *SI Appendix, Table S17*). This susceptibility to peer influence translated into important differences in drinking behavior in daily life as a function of group attitudes toward alcohol consumption: students who had a stronger vmPFC response to faces of peers who had higher status than themselves were also more likely to align their drinking behavior to match the injunctive norms of their social groups.

vmPFC sensitivity to peers' relative dual status did not moderate the relationship between group norms around alcohol use and participants' likelihood of drinking in daily life ($b_{interaction} = -0.02$, 95% CI = [-0.47, 0.43], $P = 0.70$), but it did moderate the

relationship between group norms and the number of drinks consumed when participants drank ($b_{interaction} = 0.32$, 95% CI = [0, 0.63], $P = 0.05$). For students whose groups approved of binge drinking, higher vmPFC sensitivity to status differences was associated with more drinks consumed in daily life. The reverse was true for students whose groups disapproved of binge drinking. For them, higher vmPFC sensitivity to relative status predicted fewer drinks consumed in daily life (Fig. 4B and *SI Appendix, Table S18*). The relationship between vmPFC sensitivity to higher dual status and both self-reported susceptibility to peer influence and the strength between group norms and drinking behaviors remained significant when we controlled for potential confounds (*SI Appendix, Tables S19 and S20*). These results suggest that the vmPFC is an important hub through which social comparison processes steer conformity of drinking behavior in young adults.

In a final set of analyses, we examined whether our conformity measures were related to participants' vmPFC sensitivity to higher popularity and leadership status, assessed separately. vmPFC sensitivity to peers with higher popularity or leadership status alone was not significantly associated with scores on the Resistance to Peer Influence scale or with susceptibility to social influence on drinking (*SI Appendix, Tables S21–S24*).

Discussion

People live and thrive by effectively interacting with others in social groups and social status differences influence how they act. Here, we used fMRI in the real-life social groups of college student to address three core questions about the mechanisms underlying these interactions: 1) How do people mentally represent the status of their peers in terms of popularity and leadership? 2) How do neural responses to peers vary as a function of one's own status (i.e., track status disparities between peers and self)? 3) How do individual differences in neural sensitivity to popularity and leadership status disparities relate to conformity and susceptibility to social influence in daily life? Our last question was addressed in the context of alcohol consumption, which is a common social activity among college students with potentially harmful consequences.

In answer to these questions, we found that neural patterns in the vmPFC and in the right TPJ represented information about social targets' popularity and leadership status in an interdependent manner. Moreover, the strength of the neural activity in the vmPFC and dmPFC positively correlated with status

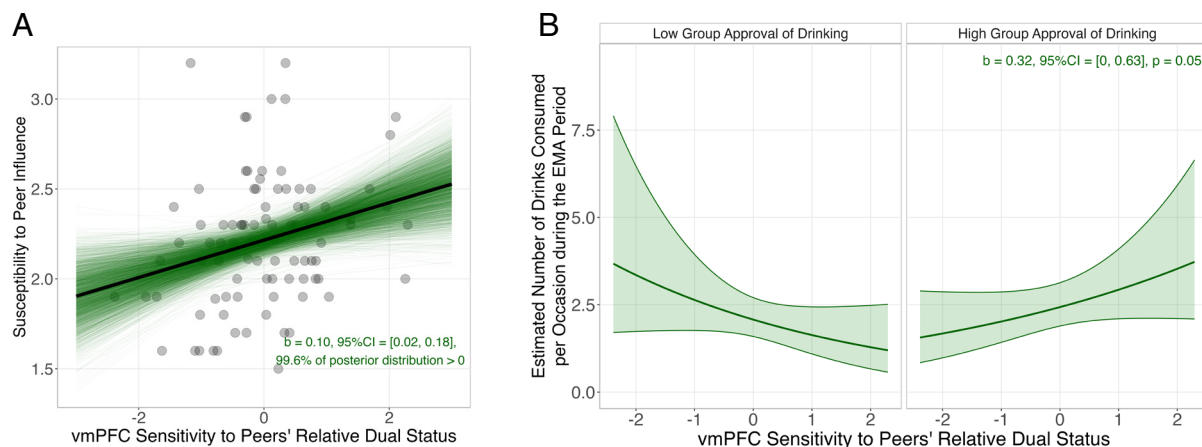


Fig. 4. vmPFC sensitivity to peers with higher dual status predicts conformity. Stronger vmPFC responses to peers with higher relative dual status were associated with (A) greater self-reported susceptibility to peer influence and (B) lower daily alcohol consumption in groups with low approval of drinking, but higher consumption in groups with high approval. In (A), the black line shows the posterior median (best-fit line), while the underlying green lines are the 4,000 posterior draws, representing the estimated uncertainty. In (B), the relationship between vmPFC sensitivity and the number of drinks consumed on a given occasion is estimated separately for students belonging to groups with low (1.5 SD below the mean) versus high (1.5 SD above the mean) approval of drinking.

differences between peers and self in a dual social space of popularity and leadership. Participants who exhibited a stronger vmPFC response to faces of peers with higher dual status than themselves were also more likely to consume alcohol in ways similar to their social groups' injunctive norms. That is, for students whose group approved of drinking, higher vmPFC sensitivity to peers' higher status in a dual popularity $\times$ leadership space translated into more drinks consumed in daily life, but the reverse was true for students whose group disapproved of binge drinking. Our results provide insight into how individuals' neural valuations of status dynamics modulate their susceptibility to social influence outside of the laboratory. The vmPFC emerged as a central hub that connects social comparison processes to conformity.

Taken together, these findings offer insight into how individuals navigate and benefit from participation in everyday social groups. First, our findings may shed light on what it takes to be a successful social agent. Cognitively, people must be able to represent information about others' status in accordance with their goals and motivations, as revealed by studies showing that people value popular individuals in their communities and seek their proximity (98, 99). At a neural level, we found that these processes are supported by brain systems associated with affective learning and valuation as well as social cognition and mentalizing. As such, our results contribute to a growing literature on the neural mechanisms of social status representation by showing that valuation and social cognition regions track not only the popularity of members of real-world social groups but also their leadership status.

Second, our results help ground our understanding of leaders' central role in coordinating activity and maintaining group cohesion (18), which requires recognizing the leaders in our communities and being motivated to pay attention to them (100–102). We show that the same neural mechanisms underlying popularity perception also support leadership status perception. Further, valuation and social cognition regions appear to represent information from both status dimensions in an interdependent manner. This integrative form of representation likely serves an adaptive function, as people must be able to represent popularity and leadership information strategically in any given moment depending on their current goals.

Follow-up analyses revealed a U-shaped relationship between differences in popularity and leadership status and neural similarity in the vmPFC and rTPJ. Dyads who were either highly similar or highly different in both status dimensions were represented more dissimilarly, whereas dyads with a large difference in one dimension but small difference in the other were represented more similarly. This pattern departs from a simple additive linear model and suggests that social representations may reflect categorical, stereotypical thinking—quickly identifying others as “leaders” or “popular” individuals—when status differences are pronounced in one domain (103). At the same time, the enhanced neural dissimilarity for dyads who are very similar in both dimensions resembles pattern separation processes described in memory research, which serve to maintain distinct representations of highly overlapping inputs (80). Such neural differentiation may help perceivers keep track of socially important individuals, raising broader questions about when status similarities and dissimilarities matter most for social cognition. One possibility is that vmPFC and right TPJ activity reflects the relevance of individuals to the perceiver's goals or context, prioritizing those who warrant individuation. Another is that similar individuals may actively work to differentiate themselves and maintain distinct social identities. Future behavioral work could test whether individuals who are similar in both popularity and leadership status dimensions seek

to differentiate themselves in the context of the group, and how peers detect and encode these distinctions at a neural level.

Third, this study also highlights that we may gain different insights when studying status representation for status in real-life social groups as compared to hypothetical or artificial lab-based stimuli. Here, it is notable that some prior studies (41, 46, 47) have asked participants to learn novel hierarchical relationships between hypothetical individuals, observing engagement of the medial temporal lobe regions (e.g., hippocampus and entorhinal cortex) known to be important for the initial learning and binding together of related pieces of information. By contrast, we examined mental representations of well-known members of long-standing groups and observed engagement of systems for affective valuation and social cognition. The presence of the valuation system activity may reflect the motivational relevance of group members as compared to strangers or hypothetical others (52). The lack of a robust medial temporal lobe involvement, with the exception of the left hippocampus for relative leadership status, could also reflect the fact that representations of well-known group members have been consolidated in cortical regions (104), and the medial temporal lobe is no longer required for retrieval and use of this information. Also notable is the way in which we probed for mental representations of status, which involved the passive perception of faces of group members. We did not ask participants to make explicit judgments of status or to compare/contrast different kinds of status, processes that may depend on parietal regions important for representing social distance (36, 42) and/or medial temporal lobe regions involved in holding in mind and comparing different stimulus features (relational working memory) (105, 106).

Another difference lies in our operationalization of social status using sociometric measures derived from peer ratings aggregated at the group level, rather than assessing participants' second-order perceptions of status (e.g., “How much do you think the group likes this person?” or “How much do you think the group sees this person as a leader?”). Although prior work suggests that individuals' status perceptions often align with group consensus, individuals may nonetheless vary in how accurately they perceive others' standing within the group (35, 38, 89, 91, 107, 108). Future research that directly measures these second-order perceptions alongside sociometric assessments will be important for disentangling neural representations of sociometric status from idiosyncratic beliefs. More broadly the SHINE dataset includes round-robin ratings which can support various social network analyses. Future work can leverage these data to test bidirectional relationships between individuals' structural position in their groups and social perception.

Our second core question concerned the way in which peoples' valuations of others' status in a group also depends on their own status within that group. Our results revealed that relative self-other status differences were tracked by activity in the vmPFC and in the dmPFC, two regions thought to lay at opposite ends of a functional gradient in person perception, ranging from value-based, self-referential processing (vmPFC) to abstract, inferential reasoning about others (dmPFC) (109, 110). These findings are consistent with previous work from our lab and others (38, 88) showing that neural valuations of popularity are influenced by the perceiver's own popularity status, such that low status individuals value all group members higher in status than themselves equally, while high status individuals preferentially allocate attention to other, similarly high-status individuals. Since people seem to orient toward higher status members, we focused our analyses on students' sensitivity to the status of individuals higher in status than themselves. We replicated the

findings of ref. 38 and expanded them to leadership status perception as well. Analyses of relative leadership status revealed consistently greater activity in valuation (vmPFC, amygdala), social cognition (dmPFC, left TPJ), and relational binding (left hippocampus) systems for faces of peers who held higher leadership positions than the perceiver, even after controlling for potential confounds such as attractiveness or demographic factors.

Here we can also note that, although our model that regressed vmPFC neural activity on targets' relative dual status had more explanatory power than an equivalent model in which we regressed vmPFC neural activity on targets' popularity alone, a third equivalent model in which we regressed neural activity on targets' leadership status alone performed slightly better. Taken in the context of all our results, this suggests that, when viewing photos of their peers, students spontaneously engage in processes of social comparison on goal-relevant dimensions; however, in the current sample of college groups, these relationships were driven most strongly by students' responding to differences in their peers' leadership status.

Several factors could explain this pattern of results. First, we studied student groups in which participation was voluntary (e.g., performing arts groups, Greek life, recreational sports teams) and in which individuals tended to like each other relatively well (summary statistics for popularity status were $M = 5.40$, $SD = 1.14$ relative to the leadership status summary statistics, $M = 3.96$, $SD = 1.90$). Thus, people might pay more attention to leadership status simply because there is relatively less variability in peers' popularity. Second, leadership status might be particularly relevant to social groups with well-defined roles and hierarchical structures like the ones included in this study—perhaps because leadership signals influence, decision-making authority, and access to group resources. In informal groups of friends, different dimensions might take the central stage. Third, although we instructed participants to respond naturally when watching the photos of their peers, they might have inferred the purpose of the task to be hierarchical status judgments. To help clarify when popularity becomes more significant to people's social lives, future studies should compare communities in which participation is voluntary or mandatory, formal or informal, and explore different task instructions.

Our third core question examined how individual differences in neural valuations of relative dual (popularity $\times$ leadership) status related to conformity behavior in daily life. We theorized that individuals showing higher sensitivity to status differences in both popularity and leadership will also change their behavior more to meet their group norms. We tested this hypothesis in the context of alcohol consumption, a consequential health behavior that is highly susceptible to social influence in college students. Participants who exhibited a stronger vmPFC response to faces of peers who had higher dual status than themselves were also more likely to align their drinking behavior with their groups' norms. That is, for students whose groups approved of binge drinking, higher vmPFC sensitivity to peers' higher dual status translated into more drinks consumed in daily life, but the reverse was true for students whose groups disapproved of binge drinking. Our results provide insight into how individuals' neural valuations of status dynamics modulate their susceptibility to social influence outside of the laboratory. The vmPFC emerged as a central hub that connects social comparison processes to conformity. Notably, our results were specific to a relative dual status measure that simultaneously took into account both popularity and leadership; students' sensitivity to popularity or leadership status alone did not moderate the relationship between group norms and drinking behavior. Thus, neural sensitivity to goal-relevant status information was

the determining factor for conformity in our study. These results highlight sensitivity to status differences as a potential avenue for interventions to decrease alcohol consumption. Decreasing the value attached to higher status individuals in a group with high endorsement of drinking could create a path to change.

Broadly, this research highlights that studying people as members of real-world social groups is essential to understanding their behavior and decisions in everyday life. Our results point to a flexible neural system in which brain systems involved in valuation and social cognition spontaneously represent information about peers' popularity and leadership status in an interdependent manner, giving weight appropriately to the status dimensions more relevant to one's social goals in the moment. These neural representations in turn play a key role in guiding behavior to achieve social success.

Materials and Methods

This study used data from a multisite longitudinal project called SHINE, which examined how interactions between mind, brain, and community give rise to health and well-being (69). The SHINE study includes extensive behavioral, social network, neuroimaging, ecological momentary, and longitudinal assessments. The present paper focuses on a specific subset of these data relevant to neural representations of social status and conformity to group norms. Other publications using SHINE data, but addressing different research questions, include refs. 111–120. A comprehensive list of all measures collected as part of SHINE is available in the publicly available protocol paper ref. 69.

The participants in this study were 92 undergraduate students (mean age = 20.13 y; 67% women, 33% men, 0% nonbinary; 54% White, 32% Asian, 5% Latino/a, 1% Black, 8% mixed race) from nine close-knit student groups at two universities in the Northeastern United States. Groups varied in size from 21 to 87 members and represented a range of social contexts (e.g., sports clubs, performing arts groups, fraternities). All interested participants who consented to participate completed a baseline survey, individual-difference measures, and a functional MRI task in which they passively viewed pictures of their group members, followed by a round-robin peer-rating procedure. Subsequently, they engaged in a 28-d ecological momentary assessment protocol assessing their drinking behavior in daily life. The University of Pennsylvania served as the Institutional Review Board of record, following reliance agreements and local context review approvals at Columbia University. This study was approved by the University of Pennsylvania Institutional Review Board (Protocol #830189) and the Army Research Office's Human Research Protection Office (Protocol #ARL 18-157). Informed consent was obtained from all participants. A full description of the study procedures is provided in *SI Appendix*.

Measures.

Popularity and leadership status. Popularity and leadership measures were aggregated from individual round-robin ratings that participants completed outside of the scanner after the fMRI task. Participants were presented with photos of their group members (including themselves) and asked to rate each one on a scale from 0 (Not at all) to 8 (A lot) on the following prompts: "How much do you like this person?" and "To what extent is this person a leader in this group?". After removing all self-ratings, we calculated each individual's popularity and leadership status as the mean rating received on the liking and leadership prompts from their peers who completed the fMRI scan (popularity status: $M = 5.4$, $SD = 1.14$, range = [1, 8]; leadership status: $M = 3.96$, $SD = 1.9$, range = [1, 8]). The Kendall rank correlation between participants' popularity and leadership status was $\tau = 0.37$, $P < 0.01$ (*SI Appendix, Fig. S4*).

Estimation of neural responses to peer faces. Neural responses to peer faces were measured in an fMRI passive face perception task adapted from a method used in ref. 38, variants of which have been used in other studies as well (35, 92). In this task, participants viewed portrait photographs of the members of their social group while in the scanner (*SI Appendix, Fig. S1*). These photos were uploaded by peers themselves during the baseline survey. The task consisted of two runs during which participants viewed their own face, peer faces, and control images (red dot), appearing one at a time. Most participants viewed 162

face trials presented in an event-related design with the following timing: face or dot presentation (1 s); jittered fixation cross ($M = 5.5$ s, $SD = 2.8$). Faces were presented in random order 3 times per run. Details of task design, data acquisition, preprocessing, and first-level modeling are provided in *SI Appendix*.

Conformity Measures.

vmPFC sensitivity to peers with higher dual status. To obtain participant-specific estimates of vmPFC sensitivity to peers with higher relative dual status, we fit a Bayesian multilevel model restricted to vmPFC activity. Neural responses to peer faces were modeled as a function of each peer's relative dual status, with participant-level slopes nested within groups and random intercepts for social targets. Individual sensitivity was defined as the posterior mean of the person-level effect linking vmPFC responses to relative dual status. These estimates were standardized and used in subsequent models (*SI Appendix*).

Susceptibility to peer influence. Outside of the scanner, participants completed a measure of susceptibility to peer influence: the Resistance to Peer Influence scale (95). This scale asks respondents to choose the statement that describes them best from 10 pairs of statements (e.g., "Some people think it's more important to be an individual than to fit in with the crowd" BUT "Other people think it is more important to fit in with the crowd than to stand out as an individual"). After choosing the statement that described them best, participants were asked whether that description was "Really True" or "Sort of True" of them. We coded answers on a 4-point scale, ranging from 1 (Really true) for one statement to 4 (Really true) for the other statement, took the average and reverse scored it, such that higher scores indicate greater susceptibility to peer influence ($M = 2.78$, $SD = 0.37$, range = [1.8, 3.5]). The 10 items had high internal consistency (Cronbach's $\alpha = 0.83$).

Group norms around alcohol use. Each group's norms around alcohol use were measured during the baseline survey by aggregating group members' responses to the prompt "How strongly does your group as a whole approve of binge drinking?" rated on a scale from 0 (Strongly disapprove) to 4 (Strongly approve). Binge drinking was defined as the consumption of 5 or more alcoholic drinks for men and 4 or more for women within a 2-h period. Participants were instructed that one drink could be anything from a 12 oz can or bottle of beer to a 5-oz glass of wine or one shot of liquor. These ratings were aggregated across group members to yield a single score for each student group. The group average ranged from 1.29 to 3.25 ($M = 2.19$, $SD = 1.16$).

Drinking behavior in daily life. We used EMAs to examine dynamic, intraindividual fluctuations in alcohol consumption in daily life. For 28 d following

the fMRI task, participants received two surveys on their smartphones via the LifeData application (<https://www.lifedatcorp.com/>) at 8 AM and 6 PM. Participants were first asked whether they had consumed any alcohol since the previous survey (a binary yes/no question). If they answered yes, then they received an additional set of questions assessing the number of bottles or glasses of beer, the number of shots of liquor, and the number of glasses of wine consumed. These answers were summed to create a score of the total number of drinks. Implausibly high values for the number of alcoholic drinks consumed since the previous survey were trimmed (i.e., winsorized) to the next highest plausible value (69). Participants reported having consumed alcohol on 15% of the surveys with the number of drinks varying between 0 and 16 ($M = 3.37$, $SD = 2.92$).

Data, Materials, and Software Availability. The R scripts used to implement analyses have been deposited on GitHub (https://github.com/ostanoi/Popularity_Leadership_Status_Perception_Conformity) (77). De-identified data are available upon request. The data have not been made publicly available due to the risk of participant identification in small college groups based on the combination of two or more sensitive data points such as social network metrics, year in college, or gender.

ACKNOWLEDGMENTS. Research was sponsored by the Army Research Office and was accomplished under Grant W911NF-18-1-0244. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the US government. The US government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation herein.

Author affiliations: ^aAnnenberg School for Communication, University of Pennsylvania, Philadelphia, PA 19104; ^bAnnenberg Public Policy Center, University of Pennsylvania, Philadelphia, PA 19104; ^cSchool of Medicine, University of St. Gallen, St. Gallen 9000, Switzerland; ^dCentre for Digital Health Interventions, Department of Management, Technology and Economics, ETH Zürich, Zurich, Switzerland; ^eDepartment of Psychology, Rutgers University, Camden, NJ 08102; ^fDepartment of Psychology, Princeton University, Princeton, NJ 08540; ^gDepartment of Sociology, Columbia University, New York, NY 10027; ^hDepartment of Mathematics, Brigham Young University, Provo, UT 84603; ⁱDepartment of Bioengineering, University of Pennsylvania, Philadelphia, PA 19104; ^jDepartment of Mathematics, Dartmouth College, Hanover, NH 03755; ^kDepartment of Psychology, University of Pennsylvania, Philadelphia, PA 19104; ^lWharton Business School, University of Pennsylvania, Philadelphia, PA 19104; and ^mDepartment of Psychology, Columbia University, New York, NY 10027

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