

PSYCHOLOGICAL SCIENCE

A psychological intervention strengthens students' peer social networks and promotes persistence in STEM

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Retaining students in science, technology, engineering, and math (STEM) fields is critical as demand for STEM graduates increases. Whereas many approaches to improve persistence target individuals' internal beliefs, skills, and traits, the intervention in this experiment strengthened students' peer social networks to help them persevere. Students in a gateway biology course were randomly assigned to complete a control or values affirmation exercise, a psychological intervention hypothesized to have positive social effects. By the end of the term, affirmed students had an estimated 29% more friends in the course on average than controls. Affirmation also prompted structural changes in students' network positions such that affirmed students were more central in the overall course friendship network. These differing social trajectories predicted STEM persistence: Affirmed students were 11.7 percentage points more likely than controls to take the next course in the bioscience sequence, an effect that was statistically mediated by students' end-of-semester friendships.

INTRODUCTION

Science, technology, engineering, and math (STEM) fields face high rates of attrition among students. National estimates suggest that fewer than 40% of undergraduate students in the United States who enter college intending to major in STEM actually graduate with a STEM degree (1). At the same time, the need for STEM professionals outpaces those earning STEM degrees: Economic forecasts predict that, for economic and societal well-being, the United States will need approximately 1 million more college graduates in STEM fields by 2022 than current rates will produce (1). Retaining more students who begin college intending to major in STEM fields is the lowest-cost and most efficient way to meet this need, as increasing retention by only 10 percentage points (from 40 to 50%) over a decade would generate three-quarters of the needed pool of STEM graduates (1). Policy experts have thus identified increasing STEM persistence in college as a national priority.

Traditionally, most research has conceptualized persistence as an individual endeavor, focusing on internal causes and correlates of persistence in creating interventions to help students persevere. For example, researchers have targeted individuals' mindsets about the nature of intelligence, showing that encouraging beliefs that intellectual abilities are malleable as opposed to static can increase persistence in academic settings (2). Other intervention approaches to promote persistence have focused on building "character skills" such as self-control and grit (3), encouraging students to see course material as relevant to their lives (4) and reducing anxiety about belonging in college (5).

Yet, despite this focus on bolstering internal beliefs, knowledge, and skills to help students persevere, persistence is the product of not only individual processes but also relational ones. Social networks, the systems of interpersonal relationships in which individuals are

embedded, may be a powerful force driving perseverance in challenging environments. Research in organizational settings has shown that employees who are more socially connected to friends in their workplace are less likely to quit or change jobs (6, 7). Similarly, cross-sectional analyses of college students' social ties have shown that students were less likely to leave school when they were more integrated into campus social networks (e.g., had more interconnected friendships with peers in their class year; were identified as friends by more peers; knew more classmates; or spent more time with other students in class, sports, and student organizations) (8, 9). In STEM fields in particular, a recent study showed that students who were more centrally positioned in the classroom social network of their introductory physics course were more likely to take a subsequent physics course the following semester, regardless of their performance (10). In summary, social networks may function as "sticky webs" (7), encouraging individuals to persist in challenging environments from which they might otherwise drop out.

Integration in social networks may support persistence through several mechanisms. These include providing access to emotional and informational support needed to overcome challenges; increasing satisfaction with the environment by affording positive social interactions; heightening sense of fit, belonging, and identification with the environment; increasing alignment with core communal goals; adding pressure to persist due to normative influence, role fulfillment demands, and the risk of losing social ties if one left; reducing stress; and increasing self-efficacy (9, 11–17). Social networks may thus be "sticky" because social integration provides both benefits that encourage staying and social deterrents to leaving, increasing the chances of persistence.

The present experiment builds on this emerging evidence of the critical role of social networks in persistence to investigate strengthening students' integration in peer social networks as a means of helping them persevere in academic settings. In doing so, we investigate the possibility of activating a relational pathway to persistence. We use social network analysis, a set of tools for quantifying social networks and individuals' positions in them, to examine whether a randomly assigned low-cost psychological intervention can strengthen students' integration in social networks and, in turn, promote persistence in STEM.

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Despite a growing interdisciplinary science of network interventions (18, 19), processes on which to intervene to strengthen integration in naturalistic social networks remain unclear. In network science, much attention has been devoted to examining the effects of proximity on network formation and maintenance (20), finding that individuals who are spatially proximate because of shared activities have more opportunities to interact and are thus more likely to develop social ties. This work would suggest that STEM students should develop strong social networks over time simply as a result of spending time in classes together.

However, psychological research suggests that proximity is unlikely to breed intimacy in all circumstances. Work on familial, romantic, and workplace relationships suggests that stressful or psychologically threatening contexts can trigger defensive social responses such as relationally destructive behavior and social withdrawal (21–24). These defensive social responses may be particularly strong in domains that threaten one's sense of competence or self-worth (24). These findings suggest that certain environments—such as demanding, high-stakes STEM classrooms—could lead to network erosion, despite proximity. This pattern could be particularly detrimental to persistence because disruption to relationships can in and of itself heighten psychological threat, prompting further social defensiveness, disengagement, and isolation in a downward spiral (25). In this context, an intervention that lessens social defensiveness by reducing psychological threat may offer one route to strengthening integration in social networks.

To address this possibility, we examined the effects of values affirmation on students' social networks. Values affirmation interventions aim to lessen psychological threat in stressful environments by refocusing individuals on an alternative source of self-worth: their core values (26). In these interventions, individuals complete a 10- to 15-min exercise that prompts them to write about their most important personal values (e.g., friends and family or religious values) before an upcoming stressor. Affirmation theory suggests that by bringing into focus these important values, participants in these interventions can better put stressors in perspective, allowing them to shift from self-protective, defensive, and avoidant modes of processing to more open and approach-based orientations (26).

Previous work has shown that affirmation can lessen threat-induced social defensiveness and promote positive social behavior and attitudes, in particular, making this intervention a promising means to instigate change in students' social networks. First, experiments have demonstrated that affirmation improves interpersonal perceptions and anticipated social behavior under psychological threat. Affirmed individuals have reported more positive feelings toward others such as increased love, empathy, and connectedness (27, 28) and a heightened sense of belonging (29) under threat compared to their unaffirmed peers. Insecure individuals who were affirmed (versus unaffirmed) reported decreased intention to defensively distance from a romantic partner following a relational threat manipulation (30). Affirmed people also reported greater willingness to help others in need, instead of defensively downplaying their suffering (31). Second, several experiments have shown that affirmed individuals actually engage in more positive social behavior than their threatened but unaffirmed peers. For example, chronically insecure individuals behaved less tensely in interactions with an experimenter blind to condition both 4 and 8 weeks following an affirmation (versus control) intervention (32). Teachers blind to condition rated affirmed antisocial adolescents as engaging in

more prosocial behavior than their unaffirmed counterparts in the 3 months following intervention (28). Affirmed college students were more likely to help with a (staged) collapsed shelf incident in the laboratory than unaffirmed students (33). Together, this work suggests that affirmation can interrupt defensive social responses to stressful environments and foster positive interpersonal interactions and perceptions. In doing so, affirmation may strengthen students' integration in STEM social networks.

We examined the effect of values affirmation on social network trajectories and persistence in a challenging academic STEM environment: a gateway biology course. This course, a yearlong introductory molecular and cellular biology class, is the required “weed-out” gateway course for all premedical and bioscience majors at the university. It thus marks an inflection point for students who begin college intending to pursue careers in those fields and may be perceived as a make-or-break moment for their aspirations. Previous work suggests that improving students' social experiences in gateway introductory science courses may be key to reducing overall STEM attrition (10, 34), making this high-stakes introductory course an ideal target for intervention. (See the Supplementary Materials for additional details about the course.)

Two hundred and twenty-six students in the first semester of this gateway biology course participated in the present research. Students completed an initial social network questionnaire at the beginning of the fall semester in which they reported the names of their friends in the class and the strength of these friendships. Students were then randomly assigned to complete either a values affirmation or control writing exercise in the third week of the term during their weekly course section. Students in the affirmation condition ranked a list of values in order of personal importance and then wrote for 15 min about why their top-ranked value was important to them. The control condition was designed to be conservative: Students still ranked the list of values and wrote for 15 min about why a value was important. However, instead of writing about a personally important value, students in the control condition wrote about why a value ranked as unimportant to them could be important to someone else. At the end of the semester, 2.5 months after the intervention, students again reported their friends in the class. Lastly, we obtained the enrollment status of each student in the next semester of the biology course sequence.

From students' friendship nominations, we assembled directed, weighted class friendship networks at both the beginning and end of the semester. Friendship networks are an important type of peer social network because friendships provide access to key social support and information, as well as encourage a sense of belonging, shared identity, and attachment to the shared domain (15, 35). The individuals who are best able to access these benefits of friendship networks are those who are socially integrated, or “central,” in two ways. First, they are advantageously positioned relative to others across the whole network: They are connected both directly and indirectly to more individuals, providing broad access to social benefits, resources, and information. Second, they have strong personal relationships with individuals in the network. We examined the effects of the intervention on each of these two forms of social integration.

To address the first type of social integration, advantageous positioning, we measured students' closeness and betweenness centrality (36). Figure S1 offers a graphic representation of these constructs. These forms of network centrality are often considered proxies for social capital and access to information. Closeness centrality

measures the average number of intermediaries needed for a person to connect with each of the others in the network. Fewer intermediaries reflect higher centrality. Individuals high in closeness centrality are widely connected both directly and indirectly, with few people separating them from others in the network. In a classroom, a student high in closeness centrality would be broadly connected, able to reach most other students in the class directly or through friends of friends. Betweenness centrality, on the other hand, measures how often a person rests on the shortest path linking each pair of others in the network together. People high in betweenness centrality serve as a bridge connecting many different individuals in the network. In a classroom, a student high in betweenness centrality would have friendships with many different students who would otherwise be connected more distantly or not at all connected. Those who are central to the network in either closeness or betweenness centrality or who are central along both are thought to be advantageously positioned in the broader network, with access to and control over a greater quantity and range of social benefits, resources, and information (36).

To address the second type of social integration, strong personal relationships, we measured students' degree centrality. Degree centrality is the number of direct ties each individual in a network has (36). It is equal to the sum of out-degree, the number of others who the individual nominates as friends, and in-degree, the number of others who nominate the individual as a friend. For example, if a student nominates three friends in the class (out-degree of 3) and two students nominate her (in-degree of 2), she has a total degree of 5. We also measured the average strength of these "outgoing" and "incoming" ties through students' reports of how interpersonally close they felt to each friend.

The primary research questions we addressed were, first, does affirmation have positive social effects such that affirmed students become more integrated in the classroom social network over time compared with students in the control condition? Second, given previous work associating stronger social networks with increased persistence in difficult environments (7–9), are any intervention effects on students' social network positions associated with persistence in the biology course sequence? Last, we also examined whether any effects differed by race or gender in light of previous affirmation research suggesting that affirmation has stronger effects for groups currently and/or historically marginalized in STEM (26).

RESULTS

To test intervention effects, all end-of-semester (time 2) dependent variables were submitted to a series of multiple regression analyses with intervention condition as the critical predictor. Two covariates were also entered into each model: students' course section and, where applicable, the homologous baseline (time 1) measurement of the dependent variable. Because individual-level network observations are nonindependent, we used nonparametric permutation tests to assess the statistical significance of the effects of intervention condition on network measures. The likelihood of the observed effects occurring by chance (reported two-tailed P_{perm} values) was calculated by comparing the intervention coefficient derived from the multiple linear models fitted to the observed data to coefficients derived from models fitted to 20,000 random permutations of the network. See Materials and Methods for details and fig. S3 for an illustration of this procedure. Means and SEs for all dependent vari-

ables are reported in Table 1, and confidence intervals (CIs) produced by the regression analyses are reported in Table 2. Students' friendship networks at the beginning and end of the semester are shown in Fig. 1.

Classroom network integration

Closeness centrality and betweenness centrality

At the beginning of the semester, before the intervention, students' closeness centrality did not differ by condition. After the intervention, students' positions in the course friendship network diverged: Affirmed students had significantly higher closeness centrality by the end of the semester than their unaffirmed counterparts, indicating that they required fewer intermediaries to connect to other students in the network ($b = 0.009$, $SE = 0.003$, $P_{\text{perm}} = 0.007$). As an indication of effect size, the average affirmed student who began the semester at the mean level of closeness centrality could expect to be 25.0% higher in closeness centrality at the end of the semester than the average unaffirmed student, based on model estimates. Similarly, betweenness centrality did not differ by condition at the beginning of the semester. By the end of the semester, there was a trend such that affirmed students were higher in betweenness centrality than unaffirmed students, indicating that they bridged together others in the network more often, but not significantly so ($b = 0.001$, $SE = 0.001$, $P_{\text{perm}} = 0.10$). As seen in Fig. 2, results indicated that affirmed students held more structurally central positions in the course network

Table 1. Means and SEs for dependent variables. Outcome measures (mean and SE) for affirmation ($n = 118$) and control ($n = 108$) groups. Time 1 = start of semester (baseline), Time 2 = end of semester (after intervention).

Friendship network variable	Control		Affirmation	
	Time 1	Time 2	Time 1	Time 2
Closeness	0.047 (0.002)	0.039 (0.003)	0.045 (0.002)	0.046 (0.002)
Betweenness	0.0023 (0.0005)	0.0015 (0.0004)	0.0017 (0.0003)	0.0019 (0.0004)
Total degree	4.52 (0.32)	3.60 (0.30)	4.81 (0.35)	4.65 (0.31)
Outdegree	2.82 (0.20)	2.26 (0.20)	2.77 (0.21)	2.94 (0.20)
Indegree	1.69 (0.17)	1.34 (0.13)	2.04 (0.18)	1.71 (0.16)
Average total tie strength	2.78 (0.14)	2.66 (0.16)	2.75 (0.14)	2.83 (0.13)
Average out-tie strength	2.62 (0.16)	2.26 (0.17)	2.54 (0.16)	2.66 (0.15)
Average in-tie strength	2.53 (0.18)	2.23 (0.18)	2.42 (0.16)	2.28 (0.16)
Number of old friends	–	1.33 (0.14)	–	1.69 (0.15)
Number of new friends	–	0.93 (0.12)	–	1.25 (0.12)
Proportion of old to new friends	–	0.60 (0.04)	–	0.54 (0.04)

Table 2. Regression results for dependent variables. Multiple linear regression results for all dependent variables plus *P* values calculated through permutation tests, where applicable. $b_{1\text{obs}}$ = the intervention coefficient from the linear models fitted to the observed network for each dependent variable (i.e., b_1 in the model described in Materials and Methods). Effect sizes are given in units of percent change and number of friends in the text.

Friendship network variable (<i>y</i>)	Multiple linear regression on observed data					
	$b_{1\text{obs}}$	SE	<i>t</i>	95% CI	<i>P</i>	P_{perm}
Time 1						
Closeness, normalized	−0.001	0.003	$t(209) = -0.36$	(−0.008 to 0.005)	0.72	0.69
Betweenness, normalized	−0.001	0.001	$t(209) = -1.09$	(−0.002 to 0.001)	0.28	0.17
Total degree	0.47	0.49	$t(209) = 0.97$	(−0.49 to 1.43)	0.34	0.30
Outdegree	0.05	0.30	$t(209) = 0.15$	(−0.55 to 0.64)	0.88	0.88
Indegree	0.42	0.26	$t(209) = 1.64$	(−0.08 to 0.93)	0.10	0.08
Total tie strength	0.06	0.20	$t(209) = 0.31$	(−0.33 to 0.45)	0.76	0.75
Out-tie strength	0.05	0.23	$t(209) = 0.23$	(−0.40 to 0.50)	0.82	0.84
In-tie strength	−0.01	0.24	$t(209) = -0.05$	(−0.49 to 0.47)	0.96	0.95
Time 2						
Closeness, normalized	0.009	0.003	$t(208) = 2.86$	(0.003 to 0.015)	0.005	0.007
Betweenness, normalized	0.001	0.001	$t(208) = 1.50$	(−0.0002 to 0.002)	0.14	0.10
Total degree	0.99	0.30	$t(208) = 3.25$	(0.39 to 1.59)	0.001	0.01
Outdegree	0.78	0.23	$t(208) = 3.41$	(0.33 to 1.23)	<0.001	0.007
Indegree	0.24	0.15	$t(208) = 1.60$	(−0.06 to 0.54)	0.11	0.23
Total tie strength	0.16	0.18	$t(208) = 0.84$	(−0.21 to 0.52)	0.40	0.43
Out-tie strength	0.43	0.21	$t(208) = 2.02$	(0.01 to 0.85)	0.04	0.08
In-tie strength	0.18	0.19	$t(208) = 0.92$	(−0.20 to 0.56)	0.36	0.45
Number of old friends	0.48	0.21	$t(209) = 2.26$	(0.06 to 0.90)	0.02	–
Number of new friends	0.33	0.18	$t(209) = 1.83$	(−0.03 to 0.68)	0.07	–
Proportion of old (versus new) friends*	−0.03	0.06	$t(150) = -0.57$	(−0.15 to 0.08)	0.57	–

*Among those who identified any friends in the course at the end of the semester ($N = 167$).

by the end of the term than unaffirmed students, particularly as measured by closeness centrality.

Degree centrality and strength of ties

At the beginning of the semester, there was no significant difference between conditions in degree centrality and participants' total number of friends (i.e., the number of individuals they nominated as friends plus the number of individuals who nominated them). However, by the end of the semester, affirmed students had significantly higher degree centrality than unaffirmed students ($b = 0.99$, $SE = 0.30$, $P_{\text{perm}} = 0.01$). Model estimates suggest that values affirmation led students to have approximately one more friend in the course on average by the end of the semester than students in the control condition (29.2% more friends than the control condition). Descriptively, as seen in Fig. 2, in the absence of intervention, students' friendships eroded; despite spending time in close proximity to classmates during the semester, unaffirmed students lost friends in the course over time. In contrast, values affirmation buffered students against this network erosion, allowing affirmed

students to maintain their net number of friendships over the course of the semester.

Additional analyses indicated that effects on outgoing and incoming ties were directionally consistent such that affirmed (versus unaffirmed) students both nominated more friends and were nominated as friends more often by their peers; both contributed to the overall degree centrality effect. However, this difference between affirmed and unaffirmed students was significant only for the number of ties they nominated (out-degree centrality: $b = 0.78$, $SE = 0.23$, $P_{\text{perm}} = 0.007$; in-degree centrality: $b = 0.24$, $SE = 0.15$, $P_{\text{perm}} = 0.23$). Similarly, whereas the difference between conditions in the strength of incoming ties was not significant ($b = 0.18$, $SE = 0.19$, $P_{\text{perm}} = 0.45$), affirmed students reported feeling marginally closer to those whom they listed as friends than did unaffirmed students ($b = 0.43$, $SE = 0.21$, $P_{\text{perm}} = 0.08$). We examined three potential alternative explanations for the network effects: differences solely in perception of friendships, attention paid to recalling friends in the course, or course attrition by condition. Our analyses did not support these

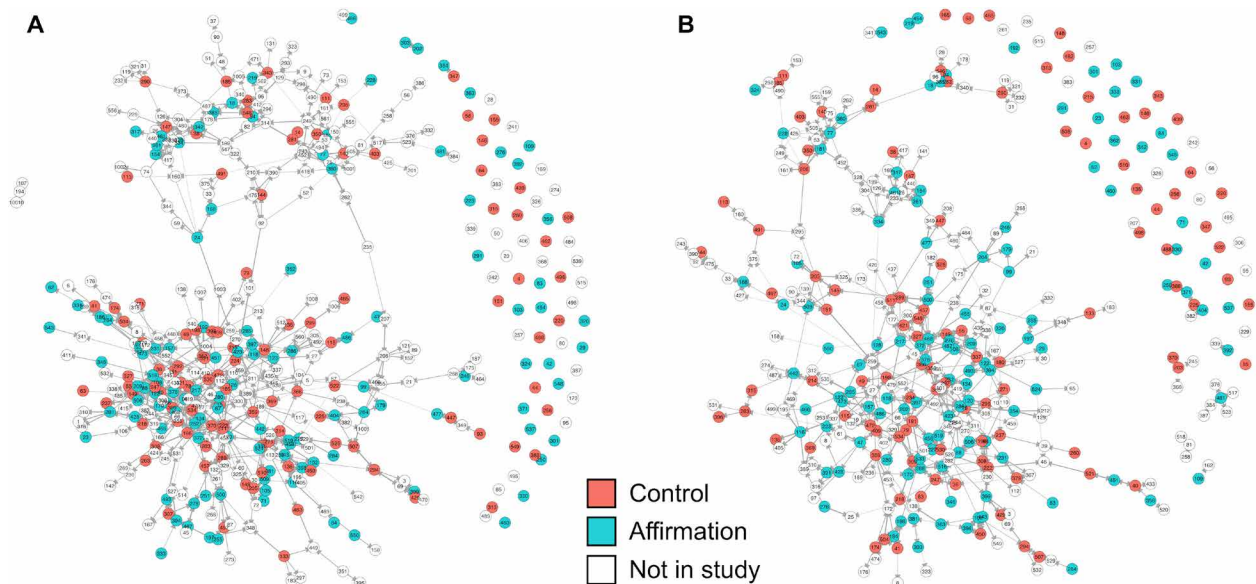


Fig. 1. Course friendship networks. (A) Friendship network at the start of the semester (460 students, 855 ties) and (B) friendship network at the end of the semester (394 students, 629 ties).

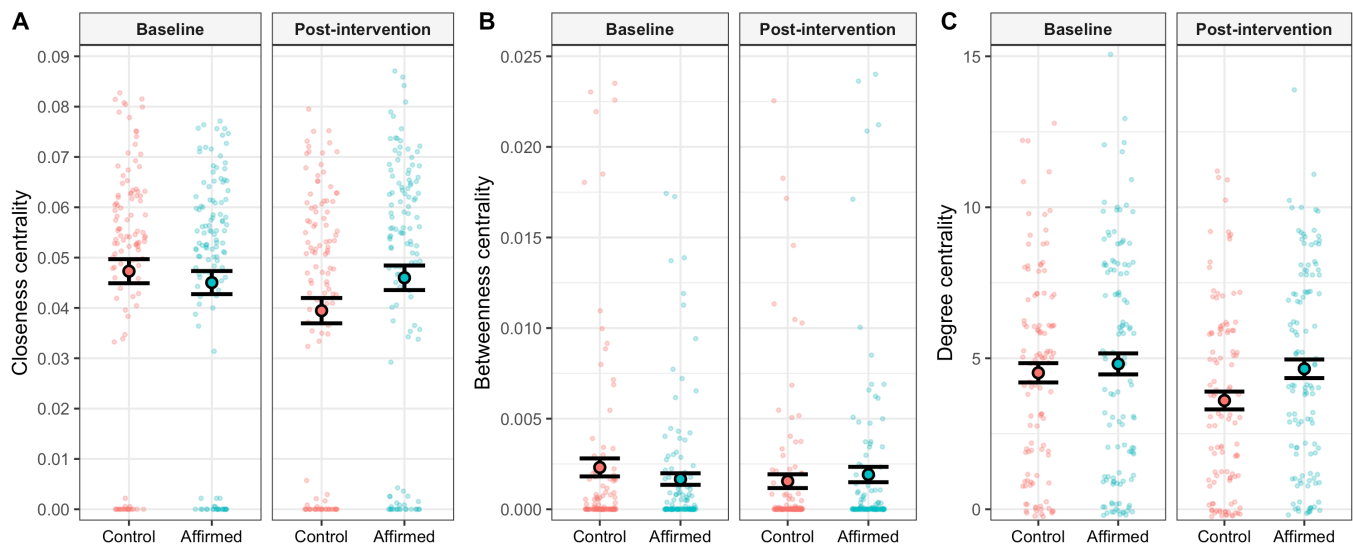


Fig. 2. Effects of the intervention on students' friendship network centrality. There were no significant differences by condition in network centrality at the beginning of the semester (baseline). By the end of the semester (after intervention), however, affirmed students had (A) significantly higher closeness centrality, (B) slightly but not significantly higher betweenness centrality, and (C) significantly higher degree centrality. Points show raw data and means by condition at each time point, and error bars represent ± 1 SE of the mean.

explanations, although the fact that effects on outgoing ties were stronger than the effects on incoming ties could suggest that changes in social perception are part of the mechanism for the social effects of affirmation (see the Supplementary Materials).

Maintaining existing versus forming new friendships

Next, we examined whether values affirmation helped students maintain relationships with the friends they had at the start of the term or helped students form new friendships that replenished lost ties over the course of the semester. To address this question, we examined the extent to which students nominated friends at the end of the semester whom they also nominated at the beginning of the

semester (friendship maintenance) versus nominated friends at the end of the semester whom they did not nominate at the beginning of the semester (friendship formation). (Because these analyses related only to the ties each participant nominated, independent of the ties any other participant nominated, we report standard P values from multiple linear regression analyses in this section.) These analyses revealed that affirmed participants both maintained more old friendships (kept about half an old friend more on average; $b = 0.48$, $SE = 0.21$, $P = 0.02$) and formed marginally more new friendships (made about a third of a new friend on average; $b = 0.33$, $SE = 0.18$, $P = 0.07$) than unaffirmed participants over the course of the semester. The proportion of old versus new friends did not differ by condition

among those who identified any friends in the class ($n = 167$; $b = -0.03$, $SE = 0.06$, $P = 0.57$). Students in both conditions had approximately a 3:2 ratio of old to new friends at the end of the semester. In short, values affirmation did not seem to tip the scales in favor of forming new friends over maintaining old friends or vice versa but rather led affirmed students to broadly engage more in both friendship maintenance and formation over the semester than unaffirmed students.

Mediation of biology track persistence

We next examined whether the observed effects of affirmation on students' social network ties had downstream consequences for persistence. First, we examined the effect of the intervention on persistence in the biology academic track. Affirmed students were 11.7 percentage points more likely to enroll in the next semester of the biology course than unaffirmed students (83.4% of affirmed students enrolled in the next course in the following semester versus 71.7% of unaffirmed students). A logistic regression indicated that this effect was significant ($b = 0.72$, $SE = 0.31$, $P = 0.02$). Next, we tested whether students' end-of-semester social networks mediated the relationship between affirmation and persistence in biology using Bayesian mediation models. Results are reported in Fig. 3, with additional details in the Supplementary Materials. Students' closeness centrality and degree centrality at the end of the first semester of the course both mediated the effect of affirmation on persistence, explaining 31 and 40% of the variance in the effect of the intervention on next-semester enrollment, respectively. The number and strength of the friendships participants nominated also partially mediated this effect (see table S3). We examined an alternative possibility that perhaps course performance rather than or in addition to social network variables mediated the effect of affirmation on persistence in the biosciences, but the intervention did not affect course performance (see the Supplementary Materials). Other examined alternative explanations (changes in grit or growth mindset) also did not explain the effects (see the Supplementary Materials). Together, these findings provide evidence that the positive effects of affirmation on students' friendship networks may confer additional downstream benefits for persistence in STEM.

Race and gender subgroup effects

Lastly, we examined whether effects of affirmation on social outcomes and academic persistence were moderated by gender or by race and ethnicity, given previous findings suggesting stronger positive effects of affirmation among stereotyped racial minorities and women in STEM (26). No significant interactions emerged between intervention condition and gender (see table S5) or between intervention condition and race (see table S6). There was one marginal interaction suggesting that the values affirmation intervention may have led to slightly but not significantly larger gains in incoming tie strength for women compared to men in the class. Otherwise, the results suggested that neither gender nor race significantly moderated the effects of the intervention. We discuss possible explanations for these findings in the Supplementary Materials.

DISCUSSION

Two primary findings emerged from this research. First, social networks were responsive to a brief psychological intervention. A values affirmation intervention strengthened students' social network

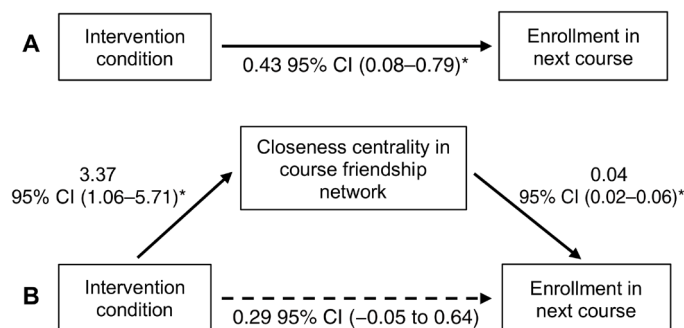


Fig. 3. Mediation analysis. Path diagram with point estimates (posterior means) of effect parameters and associated 95% credible intervals, using Bayesian estimation with default settings in Mplus (uninformative priors and two Markov chain Monte Carlo chains). Reported $p_{\text{positive-effect}}$ values indicate the probability that the effect is not greater than 0 so can be interpreted similarly to a one-tailed P value. This model controls for baseline closeness centrality, but results do not differ meaningfully when the baseline covariate is omitted. **(A)** The total effect of intervention condition on enrollment in the next course was 0.43, $SE = 0.18$, 95% CI (0.08 to 0.79), $P_{\text{positive-effect}} = 0.008$. **(B)** There was an indirect effect of intervention condition on enrollment in the next course through closeness centrality at the end of the semester [estimated effect of 0.13, $SE = 0.06$, 95% CI (0.04 to 0.28), $P_{\text{positive-effect}} = 0.003$], while the 95% credible interval for the direct effect dropped to include 0 [estimated effect of 0.29, $SE = 0.18$, 95% CI (–0.05 to 0.64), $P_{\text{positive-effect}} = 0.05$]. This suggests that the greater likelihood of affirmed students taking the next biology course was, in part, explained by affirmation-induced increases in closeness centrality in the course friendship network: Closeness centrality at the end of the semester explained 31% of the variance in the effect of intervention condition on enrollment in the next course.

positions and ties in a challenging weed-out gateway biology course. In contrast to untreated students, who seemed to socially withdraw from the classroom friendship network over time, affirmed students preserved more friendships they had at the start of the term and formed marginally more new friendships over the semester. In terms of effect size, affirmation increased number of friends in the course by an estimated 1 friend ($b = 0.99$), or by 29%, compared to the control condition. In addition, the intervention led to structural changes in students' network positions such that they became more central in the overall course network, potentially giving them greater access to social and informational resources important for success (37).

Second, experimentally induced differences in social trajectories shaped persistence in the biology track: Affirmed students were 11.7 percentage points more likely than unaffirmed students to take the next course in the biosciences/biomedical sequence, an effect that was statistically mediated by students' end-of-semester social networks. To put this work into perspective, economic projections suggest that increasing the retention of college students intending to major in STEM by 10 percentage points (from 40 to 50%) over a decade is the most efficient way to meet the United States' increasing demand for college graduates in STEM fields (1). Interventions to help students build and maintain social connections in introductory STEM classes may thus be one promising route forward to aid students in meeting their personal goals while also helping to alleviate the societal shortage of STEM graduates.

In addition to its implications for practitioners working to increase persistence in STEM, this research makes key theoretical contributions to distinct literatures: the field of intervention science and research on network change and relationships. Most research on interventions designed to increase persistence has focused on

individual, internal mechanisms. In addition, most research on network interventions has focused either on strategies that do not attempt to change network structure or on artificial networks where structure can be experimentally controlled (18, 38). This study demonstrated that psychological interventions can be leveraged to alter not only individual-level psychology but also broader real-world social structure—in this case, student's social networks—and that these structural shifts may play a key role in shaping downstream persistence. Our findings dovetail with other recent experimental work showing that individual-level psychological interventions can trigger ecological shifts in the social systems of treated individuals, which can promote lasting positive change (5, 39–41).

Moreover, our work suggests that changes in the social networks of treated individuals could be an important mechanism by which the effects of affirmation and potentially other interventions in educational settings propagate over time. Although researchers have typically focused on intrapsychic mechanisms as the drivers of intervention effects, if these interventions strengthen individuals' social ties, this could afford many other extrapsychic benefits to treated individuals that could help to maintain and promote positive effects, such as heightened access to support and social capital. Other ongoing research supports this idea: Students who received an intervention to bolster their sense of belonging in college were more likely to establish relationships with mentors in college, which, in turn, promoted their long-term success (40).

This work also makes a theoretical contribution to research on the social ecology of network change and relationships. Previous research on social networks has suggested that a group of individuals in a shared environment will become more connected over time as people spend time together in the same space (20). Research on people's tendency toward homophily suggests that this should be particularly true among individuals who are similar to one another (42), as the students in the current study were along age, education, interests, and goals. However, we observed that students in the control condition seemed to become less connected in the classroom friendship network over time, despite spending time in close proximity to classmates during the course of the semester. These untreated students lost friends on average over time, even to the point where more of these students were completely friendless in class at the end of the semester than at the beginning (15.7% had zero friends at the beginning of the semester versus 22.2% at the end of the semester, whereas the percentage of affirmed students with zero friends decreased from 16.9 to 13.6% over the course of the semester).

These findings highlight the importance of considering psychological climate in future research on how social networks change over time and in network interventions. Whereas in some environments, spending time together may lead group members to strengthen existing relationships and form new ties, our research suggests that threatening environments may undermine social connection, even between individuals who might otherwise gravitate together because of their similarities and shared fate. This idea is supported by recent research in high-pressure Fortune 500 work environments showing that when these companies transitioned from traditional office spaces to open floorplans in an attempt to increase collaboration, employees paradoxically engaged in less face-to-face social interaction (43). This work underscores that interventions that simply create more opportunities for people to be together can backfire without consideration of psychological climate. Although some types of stressors may promote affiliation (44), psychologically threaten-

ing or competitive environments may inhibit positive social ties with others.

Interpretations of this work should keep in mind that our results do not indicate that unaffirmed students were globally less socially engaged or more isolated than affirmed students during the semester of study. For example, unaffirmed students could have grown closer to roommates, romantic partners, families, or other individuals outside the class who supported them in times of stress. We focused on students' social ties in the class because previous work suggests that relationships within challenging environments may uniquely drive “sticky web” benefits for persistence in those environments (7), but the role of other relationships would be an interesting expansion for future research.

In addition, although we aimed to maximize external validity by conducting this work in a real STEM setting with high stakes for students, replication studies are needed to determine the robustness and generalizability of the observed social network effects. Future research shedding light on the conditions under which values affirmation leads to positive social and persistence effects either broadly among affirmed students, as in this study, or specifically among members of marginalized groups, as in previous research, would be particularly valuable. Moreover, although performance was not the focus of the present analyses, we examined condition differences in course grades as an alternative explanation for the observed effects on persistence and did not find an effect of affirmation on course performance. Given this lack of replication of previous findings, further research into the conditions under which affirmation improves performance is also critical. Lastly, future work could leverage proximity sensor technology or videotape student interactions to gain insight into the changes in social behavior that may underlie network effects.

The relational systems in which people are embedded may play an important role in shaping processes that are commonly thought of as individual and internal, such as persistence. This research suggests that, with an understanding of the psychological mechanisms that underlie social behavior, it is possible to experimentally intervene at the individual level to strengthen social network ties and structure. In turn, these strengthened social network positions may give rise to important real-world benefits. Efforts to attend to and strengthen the social integration of students in STEM and others in challenging environments may offer a promising route forward to increasing persistence.

MATERIALS AND METHODS

Experimental design

This research was conducted to examine the social and academic effects of values affirmation. All research procedures were performed in accordance with relevant ethics regulations and were approved by the Institutional Review Board at Columbia University. Informed consent was obtained from all participants after the nature and possible consequences of the study were explained. Data and analysis code are publicly available in an Open Science Framework (OSF) repository (<https://osf.io/tpwvn/>).

Participants

All undergraduate and postbaccalaureate students enrolled in a gateway biology course (a total of 552 students) were invited to participate in the study. A detailed description of the course is included in the Supplementary Materials. Following online and in-person

recruitment in the first 2 weeks of the course, 328 students (59% of total enrollment) consented to participate. Of these participants, 290 (88%; 145 affirmed, 145 control) were present in class the week that the intervention was administered and thus completed the intervention, and 226 (69%; 118 affirmed, 108 control) completed both the baseline and end-of-semester measures in addition to the intervention. Condition did not predict attrition (see the Supplementary Materials for details). All 226 participants who completed the study were included in the present analyses (aged 18 to 44, $M_{\text{age}} = 20.6$ years, $SD = 3.4$; 151 women, 72 men, 3 gender-fluid or other; 71 Asian, 16 Black, 25 Latinx, 2 American Indian, 70 White, 36 multiracial, 6 other or declined to report). There were no data exclusions.

Procedure

The data presented in this paper were collected as part of a larger study; relevant portions of the procedure and measures are discussed here, with additional details included in the Supplementary Materials. First, all participants completed an online start-of-semester (baseline) questionnaire assessing demographics, social networks, and a set of psychological measures during the first 2 weeks of the semester.

Next, participants were randomly assigned to complete either a values affirmation or control writing exercise. Participants' assigned writing exercises were distributed in envelopes by teaching assistants in students' weekly sections during the third week of the course, as in previous research (45). The envelopes concealed the existence of multiple conditions for students, and teaching assistants and instructors were unaware of students' condition assignments. In both conditions, participants first ranked a list of 11 values (e.g., creativity, relationships with friends or family, and religious values) in order of personal importance and then wrote a short essay for 15 min. In the affirmation condition, participants wrote about the value they had ranked as most important. In the control condition, participants wrote about why the value they ranked as ninth most important might be important to someone else. As such, students in both conditions wrote about why a particular value was important, but the exercise was only self-relevant for students in the affirmation condition. The exercise was presented as a course assignment by the professors and teaching assistants and was not tied to the research team.

In the last week of the course, participants were sent an end-of-semester online questionnaire similar to the baseline assessment, including social network items. Participants completed the end-of-semester questionnaire by the end of finals period. During the subsequent semester, we obtained the enrollment status of each participant in the second half of the biology course to determine next-semester biology track retention.

Measures

Friendship network. We administered two items to assess students' friendship networks, consistent with established social network methods (46): (i) a fixed-choice free recall name generator, in which participants listed the full names of up to six students from the class whom they considered to be their friends, followed by (ii) a name interpreter in which participants provided a rating of how close they felt to each friend listed (from 1 = Not very close to 5 = Very close). Participants answered these questions at both the beginning and end of the semester, yielding valued, directed social network data for each time point. Responses to these questions allowed for the calculation of the following measures.

Centrality measures

Network centrality measures quantify how well-connected, important, or prominent each individual is within their social network (46).

Closeness centrality is a measure of distance between each participant and all others in the network such that individuals high in closeness centrality require few intermediaries to connect with others in the network (36). We used a variant of closeness centrality adapted for use in disconnected networks, harmonic centrality, calculated by summing the inverse of the shortest path lengths between the participant and all others (47). Higher values indicate less distance from the participant to others in the network. We calculated total harmonic closeness centrality based on the weighted network using the "CINNA 1.1.53" package in R and normalized it to account for differences in network size across time points by dividing by $N - 1$, where N is the number of nodes in the network (48). Total harmonic closeness centrality disregards direction of ties. Betweenness centrality is a measure of how often each participant rests on the shortest path linking two others in the network together (36). Higher betweenness centrality indicates that the participant connects more pairs of students in the network. We calculated normalized betweenness centrality based on the weighted, directed network using the "igraph 1.2.4.1" package in R. Betweenness centrality was also normalized to account for differences in network size across time points (48). Degree centrality is the number of direct ties each participant has in the network (36). Degree centrality is the sum of two components: out-degree, the number of peers a participant nominated as friends, plus in-degree, the number of peers who nominated the participant. We calculated total degree centrality and its components, in-degree and out-degree, using the igraph 1.2.4.1 package in R. These three centrality measures are illustrated in fig. S1.

Average strength of friendships

Strength of friendships was measured by participants' interpersonal closeness ratings for each friend. These ratings were averaged for both incoming ties (mean of ratings of felt closeness to the participant reported by all peers who nominated that participant as a friend) and outgoing ties (mean of felt closeness ratings to all friends reported by the participant). Higher tie strength indicates greater interpersonal closeness. We calculated average total strength, average in-strength, and average out-strength of ties, by calculating total strength, in-strength, and out-strength using the igraph 1.2.4.1 package in R and then dividing by total degree, in-degree, and out-degree, respectively.

Number and proportion of old and new friends

Old friends were defined as friends who were nominated at the end of the semester who were also nominated at the beginning of the semester. New friends were defined as friends who were nominated at the end of the semester who were not nominated at the beginning of the semester, suggesting that the friendship developed between time points.

Study and support networks. We also measured students' networks of study partners and support providers in the course to assess different types of academic relationships, but there was extremely high overlap between these two networks and the friendship network: Across time points, 95 to 99% of classmates nominated as study partners or support providers in the course were also nominated as friends. See the Supplementary Materials for study and support network methods, results, and visualizations (fig. S2), as well as descriptive properties of the three networks (tables S1 and S2).

Biology track persistence. The biology course under study in this experiment was the first half of a two-semester course, both semesters of which are necessary for completing bioscience majors (biology, biochemistry, biophysics, and neuroscience) and prehealth requirements at the university. Next-semester persistence in the biosciences

was measured by whether students enrolled or did not enroll in the second semester of the course, according to the course roster the following semester.

Alternative explanations of persistence. We examined three alternative explanations of persistence. First, we examined course performance. Course performance was operationalized as students' final point total for the course on which the professors based the letter grades they awarded, calculated from the curved scores students received on the four class exams. Next, we examined two measures commonly used in psychology as predictors of persistence: grit and theories of intelligence. To measure grit, we used the Short Grit Scale (49), which includes eight items assessing participants' grit, defined as "the tendency to sustain interest in and effort toward very long-term goals." A higher composite score indicates higher grit. To measure theories of intelligence, we used the three-item implicit theories of intelligence questionnaire (50). A higher composite score indicates greater agreement with an entity theory of intelligence (i.e., intelligence is fixed; fixed mindset), whereas a lower composite score indicates greater agreement with an incremental theory (i.e., intelligence is malleable; growth mindset). Analyses concerning these measures are largely reported in the Supplementary Materials.

Statistical analysis

Model specification

The multiple linear regression analyses reported in this manuscript estimated the following model to test intervention differences:

$$y_1 = b_0 + b_1Z + b_2S + b_3y_0$$

In this model, y_1 is the posttreatment value of the dependent variable of interest (e.g., closeness centrality at the end of the semester); b_0 is the intercept of the regression equation; b_1 is the coefficient of Z , the intervention condition; b_2 is the coefficient of covariate S , the students' course section; and b_3 , where applicable, is the coefficient of y_0 , the pretreatment (baseline) value of the dependent variable (e.g., closeness centrality at the beginning of the semester).

Permutation tests

Network data challenge the independence assumption required for parametric tests by reflecting relationships between participants. Because of this inherent nonindependence of our network dependent variables (the y s in the model outlined above), we used permutation tests with 20,000 randomizations of network nodes to assess the statistical significance of effects of intervention condition on students' social networks in the course. The goal of these permutation tests is to compare observed results to a null model based on randomization of the data. The null hypothesis in this case is that the effects of intervention condition on students' social network positions, as indicated by the coefficient of intervention condition in the multiple linear regression models outlined above, do not differ from chance (i.e., if individuals in each condition were randomly distributed across the network).

For each dependent variable, we thus constructed a null model by permuting individuals across nodes in the network 20,000 times and running the same multiple linear regression model outlined above on each of the permuted networks. We extracted the b_1 coefficient of the effect of intervention condition from each of these regressions, yielding a distribution of b_1 estimates under the null against which we compared the observed b_1 (i.e., $b_{1\text{obs}}$). A two-sided P value was calculated as the proportion of node permutations where $|b_1| \geq |b_{1\text{obs}}|$.

Thus, if $b_{1\text{obs}}$ falls outside the middle 95% of the distribution of calculated b_1 for each of the 20,000 node permutations, we rejected the null hypothesis that there is no significant difference between conditions in the social network dependent variable; if $b_{1\text{obs}}$ falls within the middle 95% of the distribution, we fail to reject the null (see fig. S3 for an example). See (51) for a generalized overview of these steps. See Table 2 for all multiple linear regression statistics and P values calculated through permutation tests. The code used for these tests is included on the OSF page for this project.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/6/45/eaba9221/DC1>

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