

**Social Networks and Neural Receptivity to Persuasive Health Messages**

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**Abstract**

*Objective:* Health-related norms in social networks can influence whether people are open to health behavior change. Yet, little is known about how social networks relate to the ways individual brains respond to persuasive health messaging. The current study focuses on ventromedial prefrontal cortex (VMPFC) activity as an index of neural receptivity to health messages that may be related to behavior change. The study tested whether health-related norms and perceived physical activity levels within participants' social networks are associated with neural receptivity to health messages. *Method:* Adults who initially reported under 200 minutes/week of physical activity (N=146) rated the perceived physical activity levels of, and closeness to, each person in their core social network. VMPFC activity was monitored using fMRI while participants viewed persuasive health messages promoting physical activity. Longitudinal changes in sedentary behavior were objectively logged using wrist-worn accelerometers throughout a two-week baseline and the month following the fMRI scan. *Results:* Higher levels of perceived physical activity in participants' social networks were associated with greater VMPFC activity during message exposure, which in turn were associated with greater decreases in sedentary minutes. By contrast, greater closeness to physically inactive social ties was associated with lower VMPFC activity. *Conclusions:* Perceived norms in social networks relate to neural receptivity to health messaging. In particular, closeness to physically inactive ties is associated with lower neural receptivity to health messages encouraging physical activity, which may undermine the effectiveness of health messages.

### Social Networks and Neural Receptivity to Persuasive Health Messages

An individual's health behavior is often influenced by the health behaviors of those around them (Berkman & Glass, 2000; Godin & Kok, 1996; Smith & Christakis, 2008). People tend to follow social norms across a wide range of health behavior domains including physical activity (McNeill, Kreuter, & Subramanian, 2006; Ståhl et al., 2001; Zhang, Brackbill, Yang, & Centola, 2015), smoking (Christakis & Fowler, 2008; Cobb, Graham, & Abrams, 2010; Liu, Zhao, Chen, Falk, & Albarracín, 2017; Powell, Tauras, & Ross, 2005), substance use (Helmer et al., 2014; Long, Barrett, & Lockhart, 2017; Perkins, 2003; Schultz, Nolan, Cialdini, Goldstein, & Griskevicius, 2007), and eating habits (Koestler, 1964; Lally, Bartle, & Wardle, 2011; Louis, Davies, Smith, & Terry, 2007; Marquez, Norman, Fowler, Gans, & Marcus, 2018; Pachucki, Jacques, & Christakis, 2011). Yet, little is known about how social norms relate to processing of health messages in the brain, which might influence downstream health-related outcomes. The current study tested whether social network norms are associated with how the brain receives and processes persuasive health messages. The analysis focused on sedentary behavior, given the evidence linking reduction in sedentary behavior to positive health outcomes and reduced risk of several leading preventable causes of death (Guilbert, 2003; Manley, 1996).

Persuasive health messaging can successfully promote physical activity (Wakefield, Loken, & Hornik, 2010) by highlighting the advantages of active behavior and risks of sedentary lifestyle choices (Bianchini, Kaaks, & Vainio, 2002). However, some individuals are more receptive to persuasive health messaging than others. One possibility is that people may evaluate health messages differently depending on social norms. In particular, one source of normative information is the perceived behavior of people in their close social network. In line with the idea that the perceived physical activity and sedentary behaviors of social network members may

be associated with behavior change, individuals who received social support from friends and family in the form of motivation to participate in sports and physical activity were more likely to be physically active themselves, compared to those who did not receive external motivation (Ståhl et al., 2001). Receiving social reinforcement about physical activity from peers in an artificially structured online community, compared to mass messaging, also led to greater increases in self-reported minutes of exercise and exercise class enrollment (Zhang et al., 2015). Belonging to a highly connected network of physically active peers also increased individuals' likelihood of being physically active themselves (Anderssen & Wold, 1992; Centola, 2010). In sum, the perceived physical activity and sedentary behaviors of social network members may be associated with receptivity to behavior change.

Complementing direct effects of healthy social norms on behavior, individuals might also be more receptive to health messages that encourage behavior that is already exhibited by members of their social network (Scholz, Doré, Cooper, & Falk; 2019). Indeed, social norms can act synergistically or antagonistically with media messages (Jeong & Bae, 2017). In this case, the effect of social network norms would be indirect, by increasing or decreasing receptivity to persuasive messages encouraging behavior change. For example, in social networks where members are particularly active, people might be more receptive to persuasive messages encouraging physical activity (and vice versa for more sedentary networks).

Further, the link between social network norms and individual behavior may depend on the closeness to, or strength of relationship with, members of the network. That is, people may be influenced by behaviors of closer, as compared to more distant, social ties, and by stronger, as opposed to weaker ties. Strength of social ties can be determined by the frequency of interaction with them, perceived emotional closeness to them, and reciprocal exchange of information with them (Granovetter, 1977; Sundararajan, Provost, Oestreicher-Singer, & Aral, 2013). Stronger

social ties are associated with greater influence, owing to greater trust and cooperation among strong ties (Aral, 2011; Coleman, 1988a). The influence of strong and/or close ties extends across behavior domains. For example, social influence on consumer decision making tends to be greater for closer ties, such that consumers are more likely to trust and seek out word-of-mouth referrals by close social ties as compared to distant social ties (Bansal & Voyer, 2000; Brown & Reingen, 1987). Similarly, behavior modeled by close ties, as compared to that of distant ties, can help motivate adoption of healthier behavior in the context of obesity (Christakis & Fowler, 2007), smoking (Christakis & Fowler, 2008; Liu et al., 2017), and eating behavior (Pachucki et al., 2011). It is thus likely that individuals are more receptive to health messages which are consistent with the behavior of strong and/or close ties.

How might such influence work? One possibility is that social network norms might increase the perceived value of certain behaviors, which could be called to mind and reinforced by messages encouraging behavior that are consistent with the social network norms, or decrease the perceived value if social network norms are antagonistic with messaging. Within the brain, the ventromedial prefrontal cortex (VMPFC), a key region associated with self-relevance (Denny, Kober, Wager, & Ochsner, 2012; Murray, Schaer, & Debbané, 2012) and positive valuation (Bartra, McGuire, & Kable, 2013) processing, has been a primary index of neural receptivity to health messages. Past research shows that neural activity, including activity in VMPFC, in response to health message exposure is associated with message-consistent health behavior change across different domains such as smoking behavior (Chua et al., 2011; Cooper, Tompson, Brook O'Donnell, & Falk, 2015; Doré et al., 2019; Falk, Berkman, Whalen, & Lieberman, 2011; Owens et al., 2017; Riddle, Newman-Norlund, & Thrasher, 2016; Wang et al., 2013) and sunscreen use (Burns et al., 2018; Falk, Berkman, Mann, Harrison, & Lieberman, 2010; Vezich, Katzman, Ames, Falk, & Lieberman, 2016). In the context of physical activity,

VMPFC activity during health message exposure was associated with decreases in sedentary minutes in studies that used a separate dataset (Falk et al., 2015) and the dataset reported here (Kang et al., 2018). That is, people who show greater increases in VMPFC activity while viewing persuasive messages go on to change their behavior more (for a review, see Falk & Scholz, 2018). If VMPFC is tracking subjective value of the messages, and social norms are increasing perceived value of the norm-consistent health information, then individuals with physically active peers may show greater VMPFC activity while viewing health messages encouraging physical activity.

### **The Current Study**

The current study tested whether social network norms and closeness to physically active and inactive peers may affect individuals' health behavior change by increasing or decreasing neural receptivity to norm-consistent health information. Participants included individuals who reported having body mass index (BMI) of 25 or above and less than 200 minutes of weekly physical activity. Both immediate neural and subsequent behavioral indices of message receptivity were measured, including VMPFC activity while participants viewed health messages in a functional magnetic resonance imaging (fMRI) scanner, as well as changes in daily sedentary minutes throughout the month following the health messages intervention. Participants also reported their perceptions of how physically active members of their social networks were, and how emotionally close they were to those members. Based on previous work linking social norms and norm-consistent behavior change, it was expected that those in a network of physically active social ties would show greater neural receptivity in the VMPFC to persuasive health messages promoting physical activity, and those in a network of physically inactive ties would show less neural receptivity. Perceptions of physical activity in a participant's social network, irrespective of the objective accuracy of those perceptions, were expected to relate to

neural receptivity to health messages. Further, it was expected that closer social network members would exert greater influence, such that closeness to physically active members would be associated with greater neural receptivity to health messages, and closeness to physically inactive members would be associated with less neural receptivity to health messages. Finally, the study explored the indirect effect of social network norms and closeness to social ties, separately, on behavior change through VMPFC activity during messages.

## Method

### Participants

A community sample of 220 adults (mean age = 33.75 years,  $SD = 11.62$ ; 144 females; 96 Black, 86 White, 16 Asians, 9 Hispanic, 13 Others) was recruited for a “daily activities” study in order to avoid selection bias related to physical activity. Participants responded to flyers and online advertisements by completing a screening survey online. In order to target individuals who were at health risk, the eligibility criteria included: 1) have engaged in less than 200 minutes<sup>1</sup> of walking, moderate, and vigorous physical activity throughout the week prior to the screening (using a short form International Physical Activity Questionnaire [IPAQ]), and 2) have a BMI over 25, derived from self-reported height and weight. Other eligibility criteria included: 1) meet standard fMRI scanning criteria (no metal in body, right-handed, not claustrophobic, not pregnant/nursing), 2) have no history of neurological disorders, coronary artery disease, arrhythmia, or uncontrolled hypertension, 3) have no history of serious psychological/psychiatric/medical conditions, 4) are not currently using psychotropic

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<sup>1</sup> U.S. Department of Health and Human Services suggests that “adults should do at least 150 minutes (2 hours and 30 minutes) to 300 minutes (5 hours) a week of moderate-intensity, or 75 minutes (1 hour and 15 minutes) to 150 minutes (2 hours and 30 minutes) a week of vigorous-intensity aerobic physical activity.” Based on these recommendations, a threshold of 200 minutes of walking, moderate and vigorous physical activity as the criterion for classifying individuals who might benefit from more activity was set.

medications, 5) have no history of post-traumatic stress disorder, and 6) have not been admitted to a psychiatric hospital within the past year. Research assistants contacted eligible participants via phone to confirm their eligibility and schedule study appointments.

Participants were excluded from neural analyses for the following reasons: attrition before fMRI study appointment ( $n = 10$ ), ineligibilities discovered before fMRI study appointment ( $n = 5$ ; coronary heart disease=1, brain abnormalities=2, metal in body=2), declining to complete scans ( $n=10$ ), and issues with brain data acquisition and quality assessment ( $n=20$ ; technical difficulties=3, frontal distortion=5, excessive motion=7, brain abnormalities discovered during analysis=5). Participants who did not complete the endpoint study appointment ( $n=5$ ) or either declined to wear accelerometers or experienced equipment failure ( $n=16$ ) were excluded from the behavioral outcome analyses. In addition, participants who did not finish the social network survey ( $n=29$ ), or finished the survey without providing information about their social ties' physical activity levels ( $n=24$ ), were excluded from social network analysis. Participants with usable data were included in the final analyses linking social network to neural outcomes ( $N = 146$ ), neural to behavioral outcomes ( $N = 158$ ), social network to behavioral outcomes ( $N = 153$ ), and social network, neural and behavioral outcomes together ( $N = 134$ ). The study was approved by the University of Pennsylvania Institutional Review Board.

### **Procedure**

Participants visited the laboratory at three time points (T1, T2, T3; Appendix A, Figure A1). At the T1 baseline appointment, participants provided informed consent and were fitted with wrist-worn accelerometers to measure the objective levels of their physical activity for the entire duration of the study. Participants also completed a series of questionnaires that are not the focus of the current investigation. At the T2 fMRI appointment, about 10 days after T1 ( $M = 9.60$



days,  $SD = 5.00$ ), participants completed a health messages intervention inside an fMRI scanner<sup>2</sup>. Throughout the T2-T3 post-intervention period, participants received daily text messages reinforcing the health messages intervention (contents were identical to the stimuli in fMRI tasks). About a month after T2 ( $M = 34.91$  days,  $SD = 2.79$ ) at the T3 end-point appointment, participants returned their accelerometer and completed a social network survey that included measures of physical activity norms and closeness.

### Tasks and Measures

**Social network survey.** Participants nominated close others across five different, potentially overlapping domains of life, including 1) family members, 2) friends, and people they recently interacted with through 3) phone calls, 4) texts, and 5) Facebook<sup>3</sup>. Participants reported their perceived levels of physical activity of each member in their core social network, on a five-point scale (-2 'very sedentary', -1 'somewhat sedentary', 0 'neither sedentary nor active', +1 'somewhat active', +2 'very active'). The social network norms measure about physical activity was calculated by averaging the perceived levels of physical activity across all members of the social network. Social network members who were reported as 'somewhat active' and 'very active' were considered as physically active social ties, and the other members were considered

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<sup>2</sup> This was part of a larger study testing the effect of self-transcendence on health message receptivity, as reported in (Kang et al., 2018), in which participants completed a self-affirmation, compassion, or control priming task prior to the health messages intervention. The current analyses controlled for experimental condition in all analysis reported here, and the priming condition did not moderate the effects reported ( $p$ -values > 0.10).

<sup>3</sup> Of the 191 participants who completed the social network survey, for 52 participants, the Facebook Graph Application Programming Interface (API) v1.0 was used to extract a list of top five individuals that the participants recently interacted the most frequently on Facebook in the past week. On April 30, 2015, Facebook disabled this function, and the rest of 139 participants manually entered friends they frequently interacted in the past week on Facebook. Participants who used the Facebook Graph API reported greater number of Facebook friends ( $M = 7.73$ ,  $SD = 17.56$ ), as compared to other participants, ( $M = 2.51$ ,  $SD = 2.79$ ),  $t = -2.13$ ,  $p = .04$ .

physically inactive social ties for this study. Participants also reported the degree to which they felt close to each member, on a seven-point bulls-eye scale (1 'not at all close' to 7 'very close'). These ratings were used to calculate average closeness to physically active and inactive social ties. Further, participants indicated whether each member in the social network knew the rest of the network members.

**Health messages intervention task.** Participants underwent fMRI while viewing 30 health messages, including messages highlighting the advantages of increasing physical activity and reducing sedentary behavior (e.g., "You can live longer to enjoy the things you love if you start to sit less."; n = 10), how one can implement such a lifestyle (e.g., "Make a habit of walking up and down the stairs whenever you can."; n = 10), and the risks of a sedentary lifestyle (e.g., "You are more likely to die early if you stay inactive."; n = 10)<sup>4</sup>. Health messages were presented across two runs in a block design, where each block consisted of a health message with text and illustration (8s), followed by a relevance rating (1 'not relevant' – 4 'relevant') (4s). Each block was followed by a fixation period of 3 seconds, and longer fixation period of 12 seconds after every fifth block. These health messages, drawn from the corresponding fMRI tasks, were reinforced via daily mobile text messages from T2 leading up to T3.

**Physical activity.** Physical activity of participants was monitored using wrist-worn accelerometers. Accelerometer data were collected using a triaxial GENE A accelerometer (Esliger et al., 2011) worn on the left wrist (all participants were right-handed). Participants were encouraged to wear the accelerometer throughout the entire duration of the study, between T1 and T2 (the *baseline period*), and between T2 and T3 (the *post-intervention period*).

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<sup>4</sup> In addition to messages related to physical activity, stimulus blocks were included with advice regarding other daily activities unrelated to physical activity that are not the focus of the current report (n = 30; task timing same). Refer to <https://github.com/cnlab/PhysicalActivity2> for further details.

Individual specific sedentary and moderate/vigorous cut points were defined according to measurements taken during the T1 baseline calibration in which participants performed a range of activities including inactive (i.e., completing surveys while seated at a computer terminal for at least 30 min) and active behavior (i.e., walking/climbing up and down the stairs at their usual pace). The third quartile (75th percentile) of the activity during the inactive period for each participant was used as a sedentary threshold for that participant, such that activity below that threshold was tagged as "sedentary," consistent with prior published reports on this dataset (Kang et al., 2018), and with the idea that individualized cut points can benefit this type of research, based on accelerometer calibration studies (Esliger et al., 2011; Ozemek et al., 2013).

For accelerometer data analyses, periods in which participants were sleeping or were not wearing the accelerometers were tagged by three research assistants blind to condition assignments. Using the sedentary threshold, the proportion of daily sedentary minutes was computed throughout the pre and post-intervention periods. Percentage change in daily sedentary minutes during post-intervention periods as compared to pre-intervention periods was used as the measure of behavior change in the current analyses (for more details, see Appendix B).

**Demographics and self-report measures.** Participants reported their age, gender, ethnicity, and years of education. The ethnicity variable was converted into a binary variable indicating Black (the mode, 41.62% of the current sample) vs. non-Black status. In all three visits, participants also completed a modified version of a health-behavior change survey (Fishbein et al., 1992), which asked participants to estimate the “overall percentage” of (a) their friends, and (b) people in general, who are trying to change their physical activity behavior (which is hereon referred to as “aggregate norms”; see Appendix C for additional details)<sup>5</sup>.

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<sup>5</sup> These surveys were embedded in other tasks not reported here. Refer to <https://github.com/cnlab/PhysicalActivity2> for further details on scanner tasks.

## Analysis

A series of linear regression models tested the relationships between social network norms about physical activity, brain activity during message exposure, and changes in sedentary behavior. All regression analyses controlled for the condition assignment (which is orthogonal to the results reported here). The significance of main effects<sup>6</sup> does not change after controlling for demographics (see Appendix C). Analyses relating to social network data also controlled for the mode of network data collection (an indicator variable indicating if Facebook Graph API was used or not). Regression analyses with behavior change as the dependent variable also controlled for baseline sedentary minutes. The coefficient of determination ( $R^2$ ), beta coefficients ( $\beta$ ), and 95% confidence intervals (CI) are reported. All reported p values are two-tailed. All analyses were performed in R (v3.0.1, [www.r-project.org](http://www.r-project.org)) using the R-studio interface (v0.98.1103).

**fMRI data acquisition and preprocessing.** Structural and functional magnetic imaging of the brain was conducted using 3-Tesla Siemens Trio scanners (see Appendix B for details on scanning parameters). Brain activity was monitored as participants completed various tasks inside the scanner. In addition to six motion parameters (three for translation and three for rotation), the health messages task was modeled with four regressors -- one for each message type (why to be less sedentary and more active, how to be less sedentary and more active, and risk messages about health) and one for the corresponding response periods<sup>7</sup>. A contrast was computed for each participant by averaging across the 30 health messages of different types and comparing activity during those messages to rest. Second-level random-effects models were constructed by averaging across participants and were submitted to a further ROI analysis.

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<sup>6</sup> For the regression analyses in the current manuscript, effects of p-values  $< 0.05$  are considered to be significant, and p-values  $\leq 0.10$  to be marginally significant.

<sup>7</sup> The model included an additional regressor for control messages, which are not the focus of the current report.

**Region of interest (ROI) analyses linking neural receptivity in VMPFC to social network norms and behavior change.** As an index of neural receptivity to health messages, neural activity was extracted from a VMPFC ROI drawn from a previous study that linked VMPFC activity and health behavior change (Falk et al., 2010; Figure 1a). Parameter estimates of activity (percent signal change) were extracted within the VMPFC ROI during the 30 health messages compared with rest for each participant. Linear regression analyses then tested the association between individual differences in social network norms and activity within VMPFC ROI. Furthermore, replicating previously reported data (Kang et al., 2018) with the current subset of participants, separate linear regression models verified the association between activity within the VMPFC ROI and behavior change in the current participants.

**Whole Brain Analysis.** In addition to testing neural activity within previously defined ROIs associated with behavior change, an exploratory whole-brain analysis identified brain regions associated with changes in sedentary behavior in the current data. Linear regression analyses then tested relationships between activity within these regions in response to health messages, and variables related to perceived physical activity in the social network (results in Appendix B).

## Results

### Social Network Characteristics

Participants reported a network of people they interacted with throughout the past week, with varying network characteristics: network size ( $M = 19.91$ ,  $SD = 12.57$ ,  $range = 2 - 101$ ); social network norms, or average levels of perceived physical activity in social network ( $M = 0.36$ ,  $SD = 0.59$ ,  $range = -1.42 - 2.00$ ); average closeness to physically active social ties ( $M = 4.96$ ,  $SD = 0.96$ ,  $range = 1.50 - 7.00$ ); and average closeness to physically inactive social ties ( $M =$

= 4.49,  $SD = 1.03$ ,  $range = 1.00 - 7.00$ ). Participants' baseline levels of physical activity were not significantly associated with any aforementioned network characteristic,  $ps > .25$ .

### **Social Network Norms and Neural Activity During Health Messages**

Our primary analysis tested the link between individuals' social network norms about physical activity and VMPFC activity during health messages. Brain activity in a functionally defined region of VMPFC previously associated with message-consistent behavior change (Falk et al., 2010; Figure 1a) was used as the outcome variable. Higher (vs. lower) levels of social network norms promoting physical activity were associated with greater increases in VMPFC activity during health messages,  $\beta = 0.17$ ,  $t(142) = 2.04$ ,  $p = .04$ ,  $R^2 = .05$ , 95% CI [.00, .08] (Figure 1b).

Next, the link between VMPFC activity and closeness to physically active and inactive social ties was tested. Closeness to physically inactive social ties was negatively associated with VMPFC activity,  $\beta = -0.21$ ,  $t(137) = -2.45$ ,  $p = .02$ ,  $R^2 = .06$ , 95% CI [-0.05, -0.01] (Figure 1c), such that individuals who were closer to physically inactive social ties had lower VMPFC activity during message exposure. Closeness to physically active social ties was not associated with VMPFC activity,  $\beta = 0.002$ ,  $t(138) = 0.02$ ,  $p = .98$ ,  $R^2 = .03$ , 95% CI [-0.02, .02].

### **Brain Regions Associated with Behavior Change**

In prior work, Kang et al. (2018) reported that VMPFC activity was associated with decreases in sedentary behavior over the month following the scan; these analyses were repeated and verified with the sub-set of participants who had complete data for the current investigation. A similar relationship between activity in VMPFC and decreases in sedentary behavior in this sub-sample was found,  $\beta = -0.20$ ,  $t(154) = -2.62$ ,  $p = .01$ . Further, within the current sub-sample, additional brain regions were identified in a whole brain search that were most robustly

associated with sedentary behavior change, including a cluster in VMPFC that extends near ventral striatum (VS) (see Appendix B).

### **Indirect Relation between Social Network Norms and Behavior Change via Neural Activity**

Next, the relationship between social network norms and changes in physical activity was tested. It was predicted that those who have more physically active ties, are closer to physically active social ties, or are less close to physically inactive ties, would show decreases in sedentary behavior following health messages intervention. However, regression analysis revealed that social network norms were not directly associated with changes in sedentary behavior,  $R^2 = .06$ ,  $\beta = -0.08$ ,  $t(148) = -1.01$ ,  $p = .31$ , 95% CI [-0.03, 0.01]. Similarly, being closer to physically active,  $R^2 = 0.08$ ,  $\beta = 0.002$ ,  $t(144) = 0.02$ ,  $p = .98$ , 95% CI [-0.01, 0.01], or inactive social ties,  $R^2 = 0.06$ ,  $\beta = 0.07$ ,  $t(140) = 0.88$ ,  $p = .38$ , 95% CI [-0.01, 0.02], was not directly associated with sedentary behavior change.

As an additional exploratory analysis, the indirect effect of social network norms on behavior change through VMPFC activity was tested. Bootstrapped estimates (1000 samples) of the indirect effect of social network norms on behavior change through VMPFC activity were marginally significant, such that those with higher (vs. lower) levels of perceived physical activity in their social networks showed greater reduction in sedentary behavior over time,  $\beta = -0.003$ , CI(-.01, .00),  $p = .10$ . Although the indirect effect of closeness to physically inactive social ties on sedentary behavior change via VMPFC activity was similar to the prior analysis, the effect was not statistically significant,  $\beta = 0.002$ , CI(-.00, .01),  $p = .13$ .

### **Discussion**

Individuals' health behaviors are influenced by the people who surround them; yet, the neurobiological mechanisms of this type of social network influence on health behaviors are unclear (cf., Nook & Zaki, 2015). Data from the current study focus on adults reporting under

200 minutes of weekly physical activity, who thus might benefit from additional physical activity. Within this sample, those who perceived that their social ties were more active showed higher neural receptivity to persuasive health messaging, indexed by greater activity in a region of VMPFC previously associated with positive valuation and message consistent behavior change (Falk et al., 2010). Further, being close to physically inactive social ties was associated with decreased neural receptivity to the health messages. Greater neural receptivity to health messages was also associated with objectively logged, message consistent changes in physical activity levels in the following month.

Associations between perceived social network norms and VMPFC activity suggest that individuals who perceive their social ties to be more active might find information encouraging physical activity more valuable and self-relevant than those who perceive their social ties to be less active. Activity in VMPFC has previously been associated with positive valuation (Bartra et al., 2013) and self-relevance processing (Denny et al., 2012; Murray et al., 2012; Wagner, Chavez, & Broom, 2019). VMPFC activity is also associated with message-consistent behavior change in the current data (Kang et al., 2018) as well as previous independent datasets (Chua et al., 2011; Cooper et al., 2015; Falk, et al., 2010, 2011, 2015; Riddle et al., 2016).

The relationship between social network norms and receptivity in VMPFC was particularly strong for people who reported being close to people they perceived to be relatively sedentary. Being close to sedentary social ties was associated with less VMPFC activity in response to health messages; however, being close to physically active social ties was not associated with VMPFC activity. Closeness or significance of interpersonal relationships can moderate adoption of norm-consistent, new behaviors (Aral & Walker, 2014; Bakshy et al., 2012; Bond et al., 2012). For health behaviors, close peers exert greater influence on individual behaviors than more distant peers (Christakis & Fowler, 2007, 2008; Liu et al., 2017; Pachucki et



al., 2011). Based on this prior work, it was predicted that close peers would also exert influence on receptivity to health messages, such that closeness to physically active peers would increase receptivity to health messages, and closeness to physically inactive ties would be associated with a decrease in VMPFC activity. However, the effect of closeness was isolated to physically inactive ties, which were associated with decreased activity in VMPFC. There are several possibilities for these results. Growing evidence suggests that influence from social network ties and from media can be either synergistic or antagonistic in its effects on targeted behaviors (Scholz et al., 2019). For example, conversations generated by mass media campaigns have a positive effect on campaign targeted outcomes overall if the media message and peer norms are in the same direction (Jeong & Bae, 2017). By contrast, these conversations can have an antagonistic effect on campaign-targeted behaviors if the media messages and peer norms contradict one another (Jeong & Bae, 2017). Our results are consistent with an antagonistic peer influence effect, such that participants who are closer to those who exhibit message-inconsistent behavior also show lower neural receptivity towards health messages. As all of our participants reported less than 200 weekly minutes of walking, moderate or vigorous physical activity at recruitment, their activity levels and valuation of physical activity could be strongly influenced by close ties who are also relatively sedentary. Indeed, past work shows that social ties with similar behavior have greater influence on individual behavior change (Centola, 2011; Rao, Rogers & Singh, 1980). Close social ties who have activity levels similar vs. dissimilar to the participants could contribute to stronger perceived normativity of sedentary behavior, greater valuation of sedentary behavior over physical activity, or greater resistance to physical activity.

The current data also lend novel insights into the ways that social norms might implicitly affect people's attitudes and behaviors. Prior social network research has linked social network variables such as positive reinforcement from randomly assigned peers (Zhang et al., 2015), and

being situated in highly connected network of healthy individuals (Anderssen & Wold, 1992), to downstream physical activity behavior. Likewise, experimentally manipulating peer feedback can change people's valuation of stimuli, such that stimuli highly approved by peers are valued more and elicit increased activity in the brain's value system, including VMPFC (Klucharev, Hytönen, Rijpkema, Smidts, & Fernández, 2009; Nook & Zaki, 2015; Zaki, Schirmer, & Mitchell, 2011). Taken together with past work, the current data are consistent with the idea that people's perceptions of health behaviors in their real-world social networks are associated with neural receptivity to health messaging. That is, social norms may influence health behavior by changing neural receptivity to health messages within one key component of the brain's value system.

It is also possible that people who find more value in health messages might also then notice the healthy behavior of others more, resulting in an increase in message consistent behavior. In other words, although the health messages used as stimuli in the current study were not normatively framed (i.e., didn't directly comment on what others do or think), norms established in participants' social networks were related to their brains' message receptivity. This adds to the findings from research on 'social-norms marketing' campaign messages, which use normative information as a primary tool to motivate socially relevant behavior. This has been investigated in domains such as environmental protection (Cialdini, 2003), energy conservation (Nolan, Schultz, Cialdini, Goldstein, & Griskevicius, 2008; Schultz et al., 2007), and health behaviors like alcohol consumption (Neighbors, Larimer, & Lewis, 2004), drug abuse (Donaldson, Graham, & Hansen, 1994), and physical activity (Slaunwhite, Smith, Fleming, & Fabrigar, 2009). Manipulating social norms can activate norms about healthy behavior, thus establishing standards against which the audience may compare and assess their own behavior (e.g., "Most people at the university take the stairs. Be active, take the stairs."; Slaunwhite et al.,

2009), and conform to the normatively framed messages (Schultz, Tabanico, & Rendón, 2008). Health messages in the current study were informational without explicitly activating social norms (e.g., “The more you sit, the more damage it does to your body. When you sit for long periods of time, your body can’t handle sugar and fat—this can mean higher risk for disease”). This suggests that even when health messages are not normatively framed, norms established in one’s social network can influence message receptivity.

Although marginal, an indirect effect of social network norms was observed on sedentary behavior change through neural receptivity. However, there was not a direct effect of social network norms on objectively logged behavior change. The lack of a direct effect runs counter to a substantial body of literature establishing the effects of norms on behavior change (Anderssen & Wold, 1992; Centola, 2010; Liu et al., 2017; Ståhl et al., 2001; Zhang et al., 2015). This discrepancy might be because the study focused on a narrow population of individuals reporting under 200 minutes per week of moderate or vigorous activity at baseline and BMI 25 or higher. The neural measure of receptivity may have been more sensitive to variation in receptivity than the overall direct effect. Future research that explores parallel effects with participants who vary more widely in their baseline physical activity will provide valuable insight in this regard.

The findings of this study should be interpreted in the context of its main strengths and limitations. Strengths of the study include a novel combination of social network analysis, neuroimaging and objectively logged behavior using accelerometers, all tested over a large sample size of participants. The measure of social network norms provides an overall estimate of the subjective perceptions of physical activity of social connections. Limitations of the study include lack of objective measurement of physical activity levels of social ties. Our core hypotheses were centered around perceptions of physical activity in social networks. An additional measurement of confidence in those perceptions, or additional measurements of

activity of social ties (e.g., objective or self-reported by the social network member themselves), would add nuance to the analysis. Further, tie strength was unidimensionally operationalized using a self-report measure for emotional closeness, whereas tie strength is a multidimensional construct that can be characterized by the amount of time spent together, emotional closeness and reciprocal exchange of information, advice, and support (Granovetter, 1977; Sundararajan, Provost, Oestreicher-Singer, & Aral, 2013). Other operationalizations of tie strength might yield similar or different results; for example, frequency of interaction (Bond et al., 2012; Coleman, 1988b) is one key metric of tie strength, and it has been suggested that emotional closeness is associated with frequency of interaction, such that emotionally close peers reported shorter time since last contact (Roberts & Dunbar, 2011). Another limitation to our findings was that the social network norms were measured at the third visit, roughly a month after the intervention. It is possible that participants who showed higher VMPFC activity in response to health messages found the messages valuable, and thus paid more attention to the physical activity of their social peers over the post-intervention period, influencing their perception of others' behaviors. Our dataset cannot determine the directionality of this relationship. The results of the study are also limited in generalizability, since the study data do not include individuals with more than 200 minutes of weekly physical activity and BMI greater than 25.

The current study focused on participants' subjective perceptions of other people in their social networks. Future research could address this limitation by more directly and objectively logging the behavior of social connections. Future research could also distinguish between direct social support (e.g., a friend inviting the participant to workout) and indirectly observed norms (e.g., seeing a friend go to the gym). Several other ways of perceiving physical activity could also be considered, like the extent to which social ties talk about physical activity, the frequency with which a participant observes physical activity behaviors of social connections, or how often

then engage in physical activity with others in the social network. Future research may also explore if emotional closeness and other metrics of tie strength, e.g., frequency of interaction, show similar associations with neural receptivity to health messages. Additionally, to address the limitation that all tests in the current work are correlational, laboratory experiments with carefully controlled manipulation of peer influence, or in vivo randomization of social contexts, can be used to establish the causal effect of social network norms on neural receptivity to health messages. Causal manipulations of active and inactive social network ties with presence and absence of health messages could help establish stronger causal pathways between social network norms and change in physical activity following persuasive messaging.

### **Conclusion**

Audiences exposed to mass-communicated health messages are situated in a complex web of social contexts, including the norms conveyed by social network ties. As such, considering the influence of social network norms can help understand individual differences in message receptivity. Evidence from neuroimaging studies suggests that VMPFC activity in response to campaign messages tracks subsequent message-consistent behavior. Here, VMPFC activity also tracks influence of real-life social contexts on message receptivity, such that having physically active social ties is associated with higher VMPFC activity, while closeness to sedentary peers is associated with lower VMPFC activity. These findings highlight a neural pathway through which social influence might influence health relevant outcomes.

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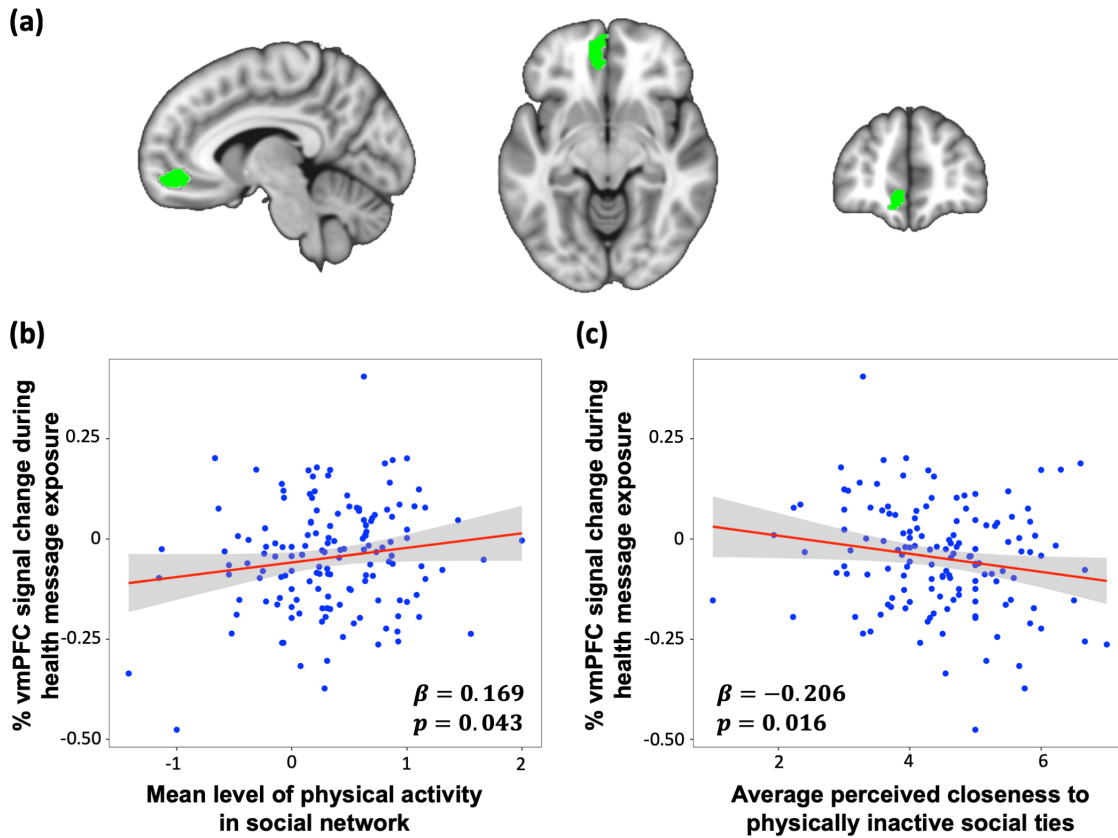
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**Figure 1.**

*Social Network Norms Associated with Neural Receptivity to Messaging.*



*Note.* (a) VMPFC region-of-interest (in green), as defined in Falk et al. (2010) to be associated with health behavior change. (b) The perceived physical activity in participants' social networks was associated with increased activity in VMPFC activity during health messages exposure. (c) Closeness to social ties perceived to be physically inactive was negatively associated with VMPFC activity during health message exposure.