Brain System Integration and Message Consistent Health Behavior Change

Mia Jovanova[1], Emily B. Falk[1,2,3], Jacob M. Parelman[1], Prateekshit Pandey[1], Matthew Brook O'Donnell[1], Yoona Kang[1], Danielle S. Bassett[4-9], and David M. Lydon-Staley[1,4,11]

[1]Annenberg School for Communication, University of Pennsylvania, USA

[2]Department of Psychology, University of Pennsylvania, USA

[3]Wharton Marketing Department, University of Pennsylvania, USA

[4]Department of Bioengineering, School of Engineering and Applied Science, University of Pennsylvania, USA

[5]Department of Electrical & Systems Engineering, School of Engineering & Applied Science, University of Pennsylvania, USA

[6]Department of Neurology, Perelman School of Medicine, University of Pennsylvania, USA

[7]Department of Psychiatry, Perelman School of Medicine, University of Pennsylvania, USA

[8]Department of Physics & Astronomy, College of Arts & Sciences, University of Pennsylvania, USA

[9]The Santa Fe Institute, USA

[10]Department of Psychology, The Pennsylvania State University, USA

[11]Leonard Davis Institute of Health Economics, University of Pennsylvania, USA

CReDiT Taxonomy Statement

Conceptualization: M.J, E.B.F, D.L.S, D.S.B, M.B.O, Formal Analysis: M.J, M.B.O, J.P, P.P, Funding Acquisition: E.B.F, Y.K, D.S.B, Supervision: D.L.S, E.B.F, D.S.B, Investigation: Y.K, P.P, E.B.F Methodology: D.L.S, D.S.B, M.B.O, Writing – original draft: M.J, Writing – editing and revising: M.J., D.L.S, E.B.F.

Disclosures and Acknowledgements

D.L.S. acknowledges support from the National Institute on Drug Abuse (K01 DA047417). D.S.B. acknowledges support from the John D. and Catherine T. MacArthur Foundation, the Alfred P. Sloan Foundation and an NSF CAREER award (PHY-1554488). E.B.F, D.S.B & D.M.L acknowledge support from the Army Research Office (Grant Number W911NF-18-1-0244). E.B.F. acknowledges support from NIH/National Cancer Institute Grant 1R01CA180015-01 (to E.B.F. as principal investigator); NIH New Innovator Award 1DP2DA03515601 (to E.B.F. as PI); E.B.F also acknowledges support from the US Army Research Laboratory including work under Cooperative Agreement W911NF-10-2-0022 (to Danielle S. Bassett as PI) and from ARO under MURI contract W911NF-18-1-0244 (to E.B.F as PI); Hope Lab (to Y.K. and E.B.F. as PIs), the Defense Advanced Research Project Agency (DARPA) under contract numbers FA8650-17-C-7712 and 140D0419C0093 (to E. B. F. as PI). The content is solely the responsibility of the authors and does not necessarily represent the official views of any of the funding agencies.

Corresponding authors: Mia Jovanova (email: mia.jovanova@asc.upenn.edu) and David Lydon-Staley (email: david.lydonstaley@asc.upenn.edu), Annenberg School for Communication, University of Pennsylvania, Philadelphia, PA19104.

Positionality Statement

Mindful that our identities can influence our approach to science (Roberts et al, 2020) the authors wish to provide the reader with information about our backgrounds. With respect to gender, when the manuscript was drafted, four authors self-identified as women and four authors as men. With respect to race, six authors self-identified as white, one as South Asian and one as East Asian.

Citation Diversity Statement

Recent work in several fields has identified a bias in citation practices such that papers from women and other minority scholars are under-cited (Dworkin et al. 2020; Dion, Sumner & Mitchell 2016; Zhou et al. 2020; Wang et al., 2020). Here we sought to proactively consider choosing references that reflect the diversity of the field. First, we obtained the predicted gender of the first and last author of each reference by using databases that store the probability of a first name being carried by a woman (Dworkin et al., 2020; Zhou et al. 2020). By this measure (and excluding self-citations to the first and last authors of our current paper), our references contain 17% woman(first)/woman(last), 27% man/woman, 19% woman/man, and 37% man/man. This method is limited in that a) names, pronouns, and social media profiles used to construct the databases may not, in every case, be indicative of gender identity and b) it cannot account for intersex, non-binary, or transgender people. We look forward to future work that could help us to better understand how to support equitable practices in science.

Abstract

Objective: Modifiable behaviors, including physical activity and sedentary behavior, are important determinants of health. Health messages are important tools for influencing these behaviors. Activity in regions of the brain's default mode and salience systems are independently associated with attending to information promoting health behavior. Interactions between these brain systems support information processing. However, it remains unclear how these brain systems interact during exposure to persuasive messages and how this interaction relates to subsequent behavior change. Here, we examine how the relative integration between default mode and salience systems while viewing health messages relates to changes in health behavior. *Methods:* Using wrist-worn accelerometers, we objectively logged physical activity in 150 participants (mean age=33.17 years, 64% women; 43% Black, 37% white, 7% Asian, 5% Hispanic, and 8% other) continuously for an average of 10 days. Participants then viewed health messages encouraging physical activity while undergoing functional magnetic resonance imaging (fMRI) and completed an additional month where physical activity was logged and the health messages were reinforced with daily text reminders. *Results*: Individuals with higher default mode and salience system integration during exposure to health messaging encouraging physical activity were more likely to decrease their sedentary behavior and increase light physical activity in the month following fMRI than participants with lower brain integration. *Conclusions*: Interactions between the salience and default mode systems are associated with message receptivity and subsequent behavior change, highlighting the value of expanding the focus from the role of single brain regions in health behavior change to larger-scale connectivity.

Keywords: fMRI, functional connectivity, health messaging, health behavior, physical activity, default mode, salience

Brain System Integration and Message Consistent Health Behavior Change

Persuasive messages, such as those used in health media campaigns, can motivate actions that improve health and prevent disease (Wakefield et al., 2010). However, individuals are not uniformly responsive to health-promoting information. Instead, substantial differences exist in how people process and respond to persuasive messages (Orbell et al., 2004). A growing body of neuroimaging research has provided insight into how messages are processed in the brain, and how brain responses to health messages relate to health behavior change (Falk et al., 2010; Falk & Scholz, 2018). Despite progress, more work is needed to provide an understanding of how persuasion unfolds in the brain and how persuasion-related processes translate into differences in real-world behavior change. Here, we apply network neuroscience methods to functional magnetic resonance imaging (fMRI) data captured while participants viewed health messages encouraging physical activity. We link this neuroimaging data to objective logs of physical activity behavior change in the following month captured with wrist-worn accelerometers. This approach allows us to quantify between-person differences in brain activity that may explain why some individuals are more susceptible to changing their behavior in response to health communication efforts than others.

A network neuroscience approach to health communication

The brain and aspects of its organization can be presented as a graph (or network), consisting of nodes often representing anatomically defined brain regions, and edges representing statistical associations between brain regions (Bassett & Sporns, 2017). The network approach allows us to characterize information about the rich interactions of disparate brain regions. Through this lens, brain regions are organized into a number of functionally specialized and densely connected subgraphs or systems (Power et al., 2011). A growing body of neuroscience research has described important between-person differences in the network organization of these brain systems. These studies have linked individual differences in brain network organization to differences in key processes central to health message processing and behavior change (Gallen & D'Esposito et al., 2019), such as attention (Shine et al., 2016), learning (Bassett et al., 2011), and memory (Zhang et al., 2020. Together, prior work suggests that network neuroscience tools may provide new insight about brain function during health message processing that may supplement information provided by more traditional self-report and neuroimaging measures (Fisher, Hopp & Weber, 2020), as well as provide information about persuasion processes more broadly.

Default mode and salience systems in persuasion

Motivated by this work, we examine interactions between two core brain systems that include many regions implicated in persuasion-related processes and message-induced behavior change in prior work: the default mode or medial frontoparietal system and the salience or mid cingulo-insular system (Uddin et al., 2019, Chua et al., 2011; Weber et al., 2015; Ramsay et al., 2013; Cooper et al., 2017; Falk et al., 2015; Wang et al., 2013; Huskey et al., 2017). Activity in the default mode system is associated with valuation, self-referential and social thought processes, and its constituent regions offer key neural markers of receptivity to persuasive messaging (Falk & Scholz, 2018). Increases in activity in key default mode regions, including medial prefrontal cortex, precuneus, anterior cingulate cortex, and posterior cingulate cortex during exposure to persuasive health messages have been linked to increased valuation signals in response to health-promoting stimuli and greater message-induced reductions in smoking (Chua et al., 2011; Cooper, et al., 2015; Falk, et al, 2011; Riddle, et al., 2016), decreases in sedentary behavior (Falk et al., 2015; Kang et al., 2018), and increased sunscreen use (Falk et al., 2010; Vezich, et al., 2017).

The salience system, anchored in the anterior insula and dorsal anterior cingulate cortex, is critical for detecting external information (Menon & Uddin, 2010) and helps direct attention from external stimuli to internally-oriented mental processes (Sridharan et al., 2008). The salience system facilitates the deployment of working memory resources (Seeley et al., 2007) and is implicated in emotional processing (Uddin, 2015). In the health messaging context, brain patterns within regions of the salience system related to affective processing have been associated with increased receptivity to anti-drinking and anti-smoking health messaging (Doré et al., 2019a; Doré et al., 2019b). Further, another study found that more effective anti-drug messages elicited greater activation in salience brain regions associated with emotional arousal relative to less effective messages (Ramsay et al., 2013).

Brain subsystem integration and persuasion

Although activity in individual regions of both the default mode and the salience systems are independently implicated in message consistent outcomes following message exposure, separate lines of research suggest it is important to consider how these large-scale systems interact when persuasive messages are delivered. First, although useful to characterize discrete functional systems of the brain, these subsystems interact to support a wide range of processes essential to health message processing and behavior change. For example, these brain subsystems may work together to direct attention to a health message and to further reflect on and evaluate the message content (Ramsey et al., 2013; Cooper et al., 2018). Indeed, neuroimaging research suggests that activity in the default mode and salience systems often fluctuates together during cognitive task switching, with salience system activity modulating default mode activity in response to externally and internally-oriented task demands (Jilka et al., 2014; Bonnelle et al., 2012).

Similarly, models of persuasion from psychology, health communication, and behavioral decision-making also motivate an examination of how the default mode and salience brain systems work together in the moments during which persuasive messages are delivered. These models highlight the integration of key attentional, affective, and cognitive processes, supported by salience and the default mode activity in the brain, to facilitate successful persuasive communication effects (Dillard and Peck, 2000; Petty et al., 2003; Nabi, 2021). One such prominent model conceptualizes persuasion as a value-based decision making process (Berkman et al., 2017, Berkman, 2018; Falk & Scholz, 2018). From this perspective, subjective value calculations, supported by activity in the default mode system, represent a final common pathway or common currency through which different decision alternatives can be assessed and translated into behavior, for example deciding to take the stairs or the elevator after viewing a physical activity public service announcement (Bartra et al. 2013, Kable & Glimcher 2009).

Several studies provide support for theoretical perspectives that, in the context of viewing health messages, the default mode system may integrate diverse inputs facilitated by the salience system, including attentional, salient, and affective responses, into a summary signal of the subjective value towards the persuasive stimuli (Haber and Knutson, 2010; Roy et al., 2012; Bartra et al., 2013). For example, Cooper et al., (2017) found that associations between the MPFC and the amygdala led to message consistent decreases in sedentary behavior, likely by strengthening subjective positive valuation and salience or affect towards the health messages. Doré et al. (2019b) found that successful persuasive communications elicited salient, emotional reactivity and were mediated by a positive integrative value response in the default mode, highlighting the integration of affective processing and value computations to support message consistent behavior change in the default mode system. In a recent study, Cooper et al. (2018) further observed that greater flexibility of the ventromedial prefrontal cortex (vmPFC) in response to persuasive health messages, defined as the temporal switching of affiliations of the vmPFC across brain systems, was associated with message-consistent reductions in smoking behavior change. Thus, while the importance of integrative process across the default mode and salience systems for persuasive remains to be tested, recent work suggests an investigation of integration of these two systems may be useful in illuminating new insights about health message effects and behavior change.

The present study

The present study builds on findings suggesting that effective persuasive message processing simultaneously relies on specialized connections within individual systems in addition to between-system cross talk, in order to integrate salient and affective responses in response to external stimuli into value computations. The current investigation examined the extent to which effective message processing that leads to desired health behavior change was supported by functional integration between the default mode and salience systems. We examined the association between default mode and salience brain system integration during exposure to health messages and subsequent longitudinal changes in physical activity. To do this, we first measured the functional connectivity within and between the default mode and salience systems while participants viewed persuasive health messages. Then, to capture individual differences in functional integration, we created a subsystem integration measure to quantify the relative difference in the connectivity strength between the default mode and the salience system relative to the connectivity strength within each of the two systems. We tested the extent to which between-person differences in integration are associated with message-induced changes in the amount of time spent in sedentary activity, performing light activity, and performing moderate-to-vigorous activity. In line with previous findings that showed that more flexible connectivity patterns relate to persuasion susceptibility (Cooper et al., 2018), we hypothesized that stronger between system integration relative to within-system segregation would be associated with greater message-consistent changes in objectively logged physical activity following message exposure.

Methods

We used data from a larger study testing the effect of self-transcendence on health message receptivity (see Kang et al., 2018 and Pandey et al., in press, for details).

Participants

Adults with low physical activity levels and body mass index (BMI) over 25 were recruited using online advertisements and flyers (*N* =220; mean age=33.75 years, *SD*=11.62; 144 females; 96 Black, 86 white, 16 Asian, 9 Hispanic, 13 Other). To reach individuals at increased health risks from physical inactivity (Guilbert, 2003), eligibility criteria screened for self-reported body mass index (BMI) over 25 and engagement in less than 200[1] minutes of moderate to vigorous physical activity and walking throughout the week prior to the screening, derived from the International Physical Activity Questionnaire (IPAQ; Madison et al., 2007). Further, individuals were screened for standard fMRI scanning criteria including no metal in body, not claustrophobic, not pregnant/nursing, right-handed, no history of serious psychiatric/medical conditions, and no current use of psychotropic medications.

Participants were excluded from analyses due to attrition before the fMRI appointment (*n* = 10), ineligibilities discovered before the fMRI 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* = 28; technical difficulties = 3, frontal distortion = 5, excessive motion defined as 1 mm spikes and/or more than 3 mm average displacement across runs = 15, brain abnormalities discovered during analysis = 5). Participants who did not complete the endpoint study appointment (*n* = 4) or either declined to wear accelerometers or experienced equipment failure (*n* = 13) were further excluded from the behavioral analyses. The sample with usable brain data included 167 participants and the final sample with both neural and behavioral data included 150 participants. Participants included and excluded from analyses did not differ significantly across gender, age, and race/ethnicity (all *p*-values >.05).

Study procedure

Upon recruitment, participants were randomized into three between-subject intervention conditions designed to manipulate receptivity to health messaging as part of the parent study

[1] U.S. Department of Health and Human Services recommends 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, and to account for over-reporting of physical activity in the screening process, a threshold of 200 minutes of walking was set as the inclusion criterion for classifying individuals who might benefit from more activity.

(see Supplementary Figure 1 for study protocol and Kang et al., 2018 for details). Although the intervention manipulation is not the focus in the current study, we controlled for the effects of the three conditions (affirmation, compassion and control) in all analyses.

Participants visited the laboratory for 3 separate appointments: a baseline appointment (T1), a subsequent fMRI appointment (T2) approximately 10 days later (mean = 9.60 days, SD = 5.00), and a final appointment (T3) a month following T2 (mean = 34.91 days, SD = 2.79). All participants provided informed consent and completed accelerometer calibration during the first appointment (T1), completed a health messages intervention task in the fMRI scanner during the second appointment (T2), and wore accelerometers from the baseline period until their final appointment (T3). Further, throughout the T2-T3 post-intervention period, participants received daily text messages reinforcing the health messages intervention, with content identical to the stimuli presented during the fMRI task. At the last appointment, participants returned the accelerometers and were debriefed, paid, and thanked for their participation. Participants completed additional fMRI tasks and self-report assessments not reported here. The study was approved by the University of Pennsylvania Institutional Review Board.

fMRI health messages task

During an fMRI scan, participants viewed 30 health messages encouraging physical activity (targeted to high-BMI adults with low physical activity levels) and 30 control messages unrelated to physical activity in a block design randomized across two runs (15 health messages and 15 control messages in each) presented using PsychoPy 2 (run1= 376 volumes, run2=344 volumes, 720 volumes total)[2]. See Supplementary Figure 2 for example health stimuli. The health messages varied across three themes: a) health risks (e.g., “you are more likely to die early if you stay sedentary”), b) reasons to be more active and less sedentary (e.g., “You can live longer to enjoy the things you love if you start to sit less.”), or c) advice on how to

[2] Refer to https://github.com/cnlab/PhysicalActivity2 for more details about the fMRI session.

increase physical activity and decrease sedentary behavior (e.g., “Make a habit of walking up and down the stairs whenever you can.”). In addition, the task included blocks with 30 parallel messages regarding other daily behaviors (e.g. “It's very dangerous and illegal not to wear your seatbelt”), which are not the focus of the current investigation. In each block, the textual message was paired with black and white pictograms and an audio repetition of the text to control for reading speed. Each block consisted of a health message (8s), relevance rating (4s), and every fifth block contained a block of rest (12s). Gobbledygook (SMOG) grade was used to control for reading levels across all messages. See Supplements A for details on scanning parameters and Supplements B for additional analyses with the control messages unrelated to physical activity.

Functional Connectivity

A summary of our preparation and analysis of the functional imaging data from the health messaging task is as follows: we preprocessed and denoised the blood oxygen level dependent (BOLD) time series, after which we created an association matrix representing the functional connectivity among regions of the default mode and salience brain systems for each participant. We then quantified default mode and salience integration for each association matrix. We provide additional detail below.

BOLD Time Series Extraction and Pre-processing

To examine brain integration in the default mode and salience systems while participants viewed health messages in the scanner, we first created brain network masks for the two specific systems of interest using a parcellation that assigns brain nodes *a priori* to the default mode and salience systems (Power *et al.,* 2011) (See Supplementary Figure 3). The default mode system comprised 58 nodes and the salience system comprised 18 nodes. We used these brain masks to extract fMRI time courses for each subject across the two health messages task runs. We concatenated the two runs, allowing us to estimate functional connectivity across 30 messages. Next, time series were warped to the MNI template.

Confound regression to remove signals of non-neural origin that were not of interest included standard confound signals (six motion parameters plus global signal, white matter, and cerebrospinal fluid) as well as the temporal derivative, quadratic term, and the temporal derivative of the quadratic term (36 parameters in total; Lydon-Staley et al., 2019). Given that residual effects of head motion may influence functional connectivity measures despite applying preprocessing steps to reduce the impact of motion (Satterthwaite et al., 2013), we also included the average framewise displacement across the two task runs as a covariate in the regression models. Data were bandpass filtered in the range 0.01-0.12 Hz, detrended, standardized and extracted from 8-mm radius spheres around the nodes (Ciric et al., 2017). Despiking was used to minimize the effect of outliers and high variance confounds were removed (Behzadi et al., 2007).

Brain Network Construction

From the extracted time series of nodes within the default mode and salience systems, we used a Pearson's correlation coefficient between pairs of nodal time series to estimate functional connectivity. For each participant, we collated all individual functional connectivity estimates and studied them as undirected and weighted matrices. All matrices were normalized via a Fisher r-to-z-transform and negative edge weights were retained. See Supplementary Figure 4 for average adjacency matrix across all participants.

Default Mode and Salience Integration

The default mode and salience system integration measure described the relative strength of the connectivity between the default mode and salience systems relative to the average connectivity observed within each system We calculated the relative integration index as follows:

$$\text{Relative default mode salience integration} = \overline{DMNSN_b} - \frac{(\overline{DMN_w} + \overline{SN_w})}{2},$$

where we use (*DMNw*) to refer to the default mode within-system connectivity strength, computed as the mean connectivity strength of edges between all node pairs within the default mode system. We use (*SNw*) to refer to the mean salience within-system connectivity strength, measured as the average connectivity strength of edges between all node pairs within the salience system. The line above each term refers to the average value. We computed the overall average within connectivity system strength by taking the average of the within connectivity strengths of each of the two systems *DMNw* and *SNw.* To calculate the connectivity strength between the two systems, we computed the mean connectivity strength of edges between all pairs of nodes that span the two systems noted as (*DMNSNb*). To obtain the relative integration vs. segregation between the default mode and salience systems we subtracted the average within connectivity strength across the two systems from the connectivity strength between the two systems. Similar to prior measures (Cohen & D'Esposito, 2016), the integration measure allowed to capture important individual variability in the relative strength of between default mode and salience network connectivity, while simultaneously accounting for individual differences in the strength of the within network connectivity. Higher relative integration scores capture increased connectivity strength between the default mode and the salience systems relative to the connectivity within each specialized system. In turn, lower integration scores capture decreased between system connectivity and higher within-system connectivity within the default mode and the salience systems.

Physical Activity Outcomes

We assessed three behavior change outcomes and their associations with relative default mode and salience system integration: changes in sedentary behavior, changes in light physical activity, and changes in moderate-to-vigorous activity. See Supplements A for more detail on physical activity calibration and previous work (Kang *et al.,* 2018). Consistent with prior work, we tested the association between individual differences in relative integration during health messaging and each of the three behavioral outcomes separately as these may have related yet distinct effects on health. For instance, being sedentary is a risk factor for poor health independent of physical activity (Hamilton *et al.,* 2008). Further, moderate-to-vigorous physical activity (MVPA) is independently linked to cardiorespiratory benefits (Knaeps *et al.,* 2016). Briefly, to obtain behavioral change scores, we first computed the average daily proportions of activity during the baseline and post intervention periods by dividing the durations of sedentary times, light moderate/vigorous, activity separately, by the total usable time that excludes sleep and non-wear time for each day tagged by three blind coders.

Next, the daily scores for sedentary times, light and moderate/vigorous activity were averaged across the ten-day baseline and one-month post-intervention periods. Finally, to obtain change scores for sedentary behavior, light physical activity, and moderate-to-vigorous activity, we subtracted the average baseline intervention proportion scores from post intervention proportion scores for each of the three outcomes. Consistent with Kang et al. (2018), we excluded days with fewer than 5 hours of accelerometer wear from further analyses (6,242 days of 7,092 tagged, or 88%, remained after applying this exclusion criteria and were included in subsequent analyses). We did not observe any substantive differences in results when retaining all days (See Supplements B).

Self-reports

In all three visits, participants also completed a modified version of a health-behavior change survey (Fishbein et al., 1992), which asked participants to report their attitudes, efficacy, and intentions towards changing their physical activity levels, among other measures. Attitudes were measured using 10 items presented on 7- point bipolar adjective scales. The instrumental component was captured by the following items that came after the stem “Increasing my physical activity on a daily basis would be”: wise-foolish, pleasant-unpleasant, correct-incorrect, easy-difficult, enjoyable-unenjoyable, good-bad, I like-I dislike, beneficial-harmful, fun-boring, healthy-harmful. The attitudinal scores were summed, with higher scores representing more positive attitudes about being physically active. Cronbach's α indicated acceptable scale reliability at each of the three visits: T1 = 0.81; T2 = 0.84; T3 = 0.83.

To measure efficacy, participants responded to one-item "I can be physically active at least 5 times per week for at least 30 minutes" on 7-point Likert Type scales ranging from 1 (extremely disagree) to 7 (extreme agree). To measure intentions, participants rated one-item "I intend to be physically active at least 5 times per week for at least 30 minutes" on 7-point Likert Type scales ranging from 1 (extremely disagree) to 7 (extreme agree). Additionally, participants reported on other self-reported items beyond the focus of the present report (Kang et al., 2018).

Analysis Plan

We performed regression analyses to test the association between default mode and salience system integration and changes in light, sedentary, and moderate-to-vigorous behavior, independently. In all models, we controlled for participant baseline activity levels prior to message exposure, condition (with control condition as the reference group), and in-scanner motion. In addition, we reexamined the association between default mode and salience integration and changes in light, sedentary, and moderate-to-vigorous behavior controlling for age, gender, ethnicity, years of education and differences in accelerometer wear time, and we observed no substantial results in our findings (See Supplementary Table 1). All analyses were performed in R (v3.0.1, www.r-project.org) using the R-studio interface (v0.98.1103).

Results

Descriptive Statistics

The brain and behavioral analyses included 150 participants (64% female) with a mean age of 33.17 years (*SD* =11.18). The self-identified race/ethnicity composition of the usable sample included: 43% Black, 37% white, 7% Asian, 5% Hispanic, and 8% other. The average BMI was 31.8 (*SD* = 5.8). Descriptive statistics and correlations associated with key study variables may be found in Supplementary Table 2.

Relative Default Mode and Salience System Integration and Behavior Change.

We performed three separate regression analyses to test associations between relative default mode and salience system integration and changes in sedentary behavior, light physical activity, and moderate-to-vigorous physical activity. The results of the first regression indicated that relative default mode and salience system integration, baseline sedentary behavior, motion, and condition explained ~10% of the variance of the change in sedentary behavior (R^2=.10, F(5,144) = 3.22, p <.01; Table 1). A parallel regression model explained ~8% of the variance in light physical activity (R^2 =.08, F(5,144) = 2.49, p = .03, Table 1) and ~9% of the variance in moderate-to-vigorous activity (R^2= .09, F(5,144) =2.74, p = .02, Table 1). Relative default mode and salience system integration accounted for ~3% of variance in the behavior change in the models.

Greater default mode and salience system integration was significantly associated with message consistent behavior change, as indicated by a decrease in sedentary behavior in the post intervention period (β = -.17, t(5,144)= -2.04, p = .04), and an increase in light physical activity (β = .18, t(5,144)= 2.14, p = .03). We observed no association between default mode and salience system integration and changes in moderate-to-vigorous activity (β = -.02, t(5,144)= -.19, p = .85. Together, these findings (Figure 1) suggest that individuals with more integrated default mode and salience systems, relative to the average within-system segregation, may be more receptive to persuasive messages and may subsequently engage in message consistent behavior changes by decreasing their sedentary behavior and increasing their light physical activity.

Additional Analyses. Additional analyses and robustness checks are included in the Supplements. These analyses include tests of the added value of considering the relative-integration between the default and salience systems versus considering the component connectivity variables. Findings indicated that the raw within component variables are not associated with behavior change outcomes. Additional analyses include control comparisons indicating that the observed associations between default mode system and the salience system are specific to the two systems of interest and to processing health messages versus messages unrelated to physical activity (though effects are in the same direction). Additional analyses also indicated that default mode and salience system integration was associated with behavior change measures above and beyond self-reported ratings of behavior change (See Supplements B).

Discussion

Substantial differences exist in how people process and respond to persuasive messages and how messages in turn impact their health-related behaviors. The current study examined how between-person differences in the relative integration between the default mode and salience systems at the time of persuasive health messaging exposure relates to future changes in health behavior. Participants viewed messages in the scanner highlighting risks associated with being inactive, and how and why to be active, and we assessed later changes in physical activity outside the lab environment. Individuals with stronger than average default mode and salience system integration were more receptive to the messages, demonstrating a greater likelihood of engaging in message-consistent behavior in the month following message exposure. We observed associations between system segregation and both decreased sedentary behavior and increased light physical activity. However, we did not observe any associations between system segregation and moderate-to-vigorous physical activity.

Our findings are consistent with theoretical models conceptualizing health message processing as a value-based decision making process (Falk & Scholz, 2018, Berkman et al., 2017, Berkman, 2018). When persuasive messages are delivered, the default mode system may integrate diverse inputs facilitated by the salience system, including attentional, salient, and affective responses, into a summary signal of the subjective value towards the health promoting stimuli (Haber and Knutson, 2010; Roy et al., 2012; Bartra et al., 2013). Consistent with this view, one common feature of the salience system, among many others, is that it is involved in salience detection and switching attention between salient external stimuli and internal cognitions, thus readying the individual for action in response to salient stimuli (Menon & Uddin, 2010; Sridharan et al., 2008). It is possible that increased integration between the salience and default mode system during message exposure, may reflect a greater propensity for attention to be captured by salient, affective stimuli and shifted towards deeper, internally-oriented processing of persuasive message content, an effect described in the cognitive psychology literature as processing stimuli more deeply (Craik & Lockhart, 1972). In the current study, activity in the salience system in response to the health messages may provide inputs to an individual's calculation of the value that may be gained by performing the health-related behavior (increasing physical activity). In turn, greater integration between the salience and default more systems may facilitate the aggregation of these inputs in the value computations, supported by the default mode system. This theoretical view is consistent with a recent study where Doré et al. (2019b) observed that salient inputs from health-promoting messages increased the perceived value of health messages. Similarly, our study suggests that more salient and stronger affective responses facilitated by salience system processing, may provide the default system with more favorable inputs into value computations, and thus lead to greater message consistent behavior change.

Further, the proposed theoretical framework builds on behavioral research proposing that attentional and affective responses are central components to the effects of persuasive communication (Dillard and Peck, 2000; Petty et al., 2003; Nabi, 2021). Individuals must first pay attention to a health message to process it (Chaiken et al., 1987) and more emotionally evocative responses to health messages may be more likely to elicit message effectiveness (Dunlop et al., 2008). However, attentional and affective responses to health messages alone may not be sufficient to translate into downstream, message-induced behavior change in the real world, if they do not also contribute positively to an integrative value response (Falk &

Scholz, 2018). As such, our data provide new insight into the underlying mechanisms of effective message-induced behavior change, suggesting that the neural integration of attentional and affective reactivity (supported by the salience system) with value computations (supported by the default mode system) at the moment when messages are delivered facilitate behavior change.

More specifically, our results highlight the value of considering the integration between the default mode and the salience systems to understand individual differences in effective message processing. Independently, the connectivity strength within the saliency system and within the default mode during message processing was not associated with behavior change. Instead, the relative integration between the two systems, provided important information for understanding behavior change that was not captured by examining within-system connectivity and between system connectivity separately. This finding lends further support for the role of integrative processes between brain systems in facilitating effective health information processing and downstream message effects (Cooper et al., 2018). Further, it highlights the value of expanding the focus from the role of a single brain system or set of regions to larger-scale connectivity in the brain to understand variability in complex health behavior change.

An additional finding of interest was that the relative integration between the default mode and the salience brain system during message processing was associated with changes in sedentary and light physical activity above and beyond participants' changes in self-ratings of physical activity-related attitudes, efficacy, and intentions over the intervention period. These findings add to a body of literature indicating the unique variance in health behaviors explained by fMRI approaches that is not captured by self-report methods (Falk et al., 2011; Knutson et al., 2007). The unique contribution to understanding behavior change available via fMRI may stem from the contribution of information that is not biased by social desirability effects (Booth-Kewley et al., 2007) or a lack of conscious access to factors implicated in health behavior change (Rebar et al., 2016).

The findings of this study should be interpreted in the light of the strengths and limitations of the current study design. First, the current sample purposefully recruited individuals with more than 200 minutes of weekly physical activity weekly and BMI greater than 25 to reach individuals at elevated risks from physical inactivity. Thus, findings may not generalize to nationally or world representative populations. Second, more work is needed to understand the underlying origin of individual differences in functional connectivity. One open question relates to the extent to which the observed differences in default mode system and salience system integration during message processing are associated with individual person-level traits, states, or message content features. Although integration of default mode and salience systems during health message exposure was significantly associated with behavior change and during control message exposure was not, the effects were directionally similar (See Supplements B), suggesting that more research is needed to determine the extent to which these effects are driven by person-level traits, message-induced responses, or their interaction.

Conclusion

The present study builds on findings suggesting that effective health message processing simultaneously relies on specialized connections within individual systems in addition to between-system cross talk in the brain in order to integrate salient and affective responses in response to external stimuli into value computations. Thus, examining individual differences in salience and default mode integration during exposure to health messages may provide insight into who is more or less likely to change their behavior in response to health promoting messages. This line of work helps advance the understanding of underlying persuasion and health behavior change processes in the brain and may further help to strengthen individual health messaging receptiveness by developing ways to increase default mode and salience integration.

References

Bartra, O., McGuire, J. T., & Kable, J. W. (2013). The valuation system: a coordinate-based meta-analysis of BOLD fMRI experiments examining neural correlates of subjective value. *Neuroimage*, 76, 412-427.

Bassett, D. S., & Sporns, O. (2017). Network neuroscience. *Nature Neuroscience, 20*(3), 353-364.

Bassett, D. S., Wymbs, N. F., Porter, M. A., Mucha, P. J., Carlson, J. M., & Grafton, S. T. (2011). Dynamic reconfiguration of human brain networks during learning. *Proceedings of the National Academy of Sciences, 108*(18), 7641-7646.

Behzadi, Y., Restom, K., Liau, J., & Liu, T. T. (2007). A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *Neuroimage*, *37*(1), 90-101.

Berkman, E. T. (2018). Value-based choice: An integrative, neuroscience-informed model of health goals. *Psychology & Health*, *33*(1), 40-57.

Berkman, E. T., Livingston, J. L., & Kahn, L. E. (2017). Finding the “self” in self-regulation: The identity-value model. *Psychological Inquiry, 28*(2-3), 77–98.

Bonnelle, V., Ham, T. E., Leech, R., Kinnunen, K. M., Mehta, M. A., Greenwood, R. J., & Sharp, D. J. (2012). Salience network integrity predicts default mode network function after traumatic brain injury. *Proceedings of the National Academy of Sciences, 109(*12), 4690-4695.

Booth-Kewley, S., Larson, G. E., & Miyoshi, D. K. (2007). Social desirability effects on computerized and paper-and-pencil questionnaires. *Computers in Human Behavior*, *23*(1), 463-477.

Chaiken, S. (1987). The heuristic model of persuasion. In Zanna, P., Olson M.J., & Herman C. P., (Ed.1), *Social influence: the Ontario symposium (Vol. 5)* (pp. 3-39). Lawrence Erlbaum Associates, Inc.

Chua, H. F., Ho, S. S., Jasinska, A. J., Polk, T. A., Welsh, R. C., Liberzon, I., & Strecher, V. J.

(2011). Self-related neural response to tailored smoking-cessation messages predicts quitting. *Nature Neuroscience, 14*(4), 426-427.

Ciric, R., Wolf, D. H., Power, J. D., Roalf, D. R., Baum, G. L., Ruparel, K., ... & Satterthwaite, T. D. (2017). Benchmarking of participant-level confound regression strategies for the control of motion artifact in studies of functional connectivity. Neuroimage, *154*, 174-187.

Cohen, J. R., & D'Esposito, M. (2016). The segregation and integration of distinct brain networks and their relationship to cognition. *Journal of Neuroscience*, *36*(48), 12083-12094.

Cooper, N., Bassett, D. S., & Falk, E. B. (2017). Coherent activity between brain regions that code for value is linked to the malleability of human behavior. *Scientific Reports*, *7*(1), 1-10.

Cooper, N., Garcia, J. O., Tompson, S. H., O'Donnell, M. B., Falk, E. B., & Vettel, J. M. (2018). Time-evolving dynamics in brain networks forecast responses to health messaging. *Network Neuroscience*, *3*(1), 138-156.

Cooper, N., Tompson, S., O'Donnell, M. B., & Emily, B. F. (2015). Brain activity in self-and value-related regions in response to online antismoking messages predicts behavior change. *Journal of Media Psychology*, *27*(3), 93-109.

Craik, F. I., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*(6), 671-684.

Dillard, J. P., & Peck, E. (2000). Affect and persuasion: Emotional responses to public service announcements. *Communication Research*, *27*(4), 461-495.

Dion, M., Sumner, J., & Mitchell, S. (2018). Gendered Citation Patterns across political science and social science Methodology fields. *Political Analysis*, *26*(3), 312-327.

Doré, B. P., Cooper, N., Scholz, C., O'Donnell, M. B., & Falk, E. B. (2019). Cognitive regulation of ventromedial prefrontal activity evokes lasting change in the perceived self-relevance of persuasive messaging. *Human Brain Mapping*, *40*(9), 2571-2580.

Doré, B. P., Tompson, S. H., O'Donnell, M. B., An, L. C., Strecher, V., & Falk, E. B. (2019). Neural mechanisms of emotion regulation moderate the predictive value of affective and value-related brain responses to persuasive messages. *Journal of Neuroscience*, *39*(7), 1293-1300.

Dunlop, S., Wakefield, M., & Kashima, Y. (2008). Can you feel it? Negative emotion, risk, and narrative in health communication. *Media Psychology*, *11*(1), 52-75.

Falk, E., & Scholz, C. (2018). Persuasion, influence, and value: Perspectives from communication and social neuroscience. *Annual Review of Psychology*, *69*, 329-356.

Falk, E. B., Berkman, E. T., Mann, T., Harrison, B., & Lieberman, M. D. (2010). Predicting persuasion-induced behavior change from the brain. *Journal of Neuroscience*, *30*(25), 8421-8424.

Falk, E. B., Berkman, E. T., Whalen, D., & Lieberman, M. D. (2011). Neural activity during health messaging predicts reductions in smoking above and beyond self-report. *Health Psychology*, *30*(2), 177.

Falk, E. B., O'Donnell, M. B., Cascio, C. N., Tinney, F., Kang, Y., Lieberman, M. D., ... & Strecher, V. J. (2015). Self-affirmation alters the brain's response to health messages and subsequent behavior change. *Proceedings of the National Academy of Sciences*, *112*(7), 1977-1982.

Fishbein, M., Bandura, A., Triandis, H. C., Kanfer, F. H., Becker, M. H., & Middlestadt, S. E. (1992). Factors influencing behavior and behavior change. (Report prepared for National Institute of the Mental Health). Bethesda, MD: National Institute of Mental Health.

Fisher, J. T., Hopp, F. R., & Weber, R. (2020). A Practical Introduction to Network Neuroscience for Communication Researchers. *Communication Methods and Measures*, 1-20.

Gallen, C. L., & D'Esposito, M. (2019). Brain modularity: a biomarker of intervention-related plasticity. *Trends in Cognitive Sciences*, *23*(4), 293-304.

Guilbert, J. J. (2003). The world health report 2002–reducing risks, promoting healthy life. *Education for Health*, *16*(2), 230-230.

Haber, S. N., & Knutson, B. (2010). The reward circuit: linking primate anatomy and human imaging. *Neuropsychopharmacology*, *35*(1), 4-26.

Hamilton, M. T., Healy, G. N., Dunstan, D. W., Zderic, T. W., & Owen, N. (2008). Too little exercise and too much sitting: inactivity physiology and the need for new recommendations on sedentary behavior. *Current Cardiovascular Risk Reports*, 2(4), 292-298.

Huskey, R., Mangus, J. M., Turner, B. O., & Weber, R. (2017). The persuasion network is modulated by drug-use risk and predicts anti-drug message effectiveness. *Social Cognitive and Affective Neuroscience*, *12*(12), 1902-1915.

Jilka, S. R., Scott, G., Ham, T., Pickering, A., Bonnelle, V., Braga, R. M., ... & Sharp, D. J. (2014). Damage to the salience network and interactions with the default mode network. *Journal of Neuroscience*, *34*(33), 10798-10807.

Kable, J. W., & Glimcher, P. W. (2009). The neurobiology of decision: consensus and controversy. *Neuron*, *63*(6), 733-745. https://doi.org/10.1016/j.neuron.2009.09.003

Kang, Y., Cooper, N., Pandey, P., Scholz, C., O'Donnell, M. B., Lieberman, M. D., ... & Falk, E. B. (2018). Effects of self-transcendence on neural responses to persuasive messages and health behavior change. *Proceedings of the National Academy of Sciences*, *115*(40), 9974-9979.

Knaeps, S., Lefevre, J., Wijtzes, A., Charlier, R., Mertens, E., & Bourgois, J. G. (2016). Independent associations between sedentary time, moderate-to-vigorous physical activity, cardiorespiratory fitness and cardio-metabolic health: a cross-sectional study. *PloS one*, *11*(7), e0160166.

Knutson, B., Rick, S., Wimmer, G. E., Prelec, D., & Loewenstein, G. (2007). Neural predictors of purchases. *Neuron*, *53*(1), 147-156.

Lydon-Staley, D. M., Ciric, R., Satterthwaite, T. D., & Bassett, D. S. (2019). Evaluation of confound regression strategies for the mitigation of micromovement artifact in studies of dynamic resting-state functional connectivity and multilayer network modularity. *Network Neuroscience*, *3*(2), 427-454.

Maddison, R., Mhurchu, C. N., Jiang, Y., Vander Hoorn, S., Rodgers, A., Lawes, C. M., & Rush, E. (2007). International physical activity questionnaire (IPAQ) and New Zealand physical activity questionnaire (NZPAQ): a doubly labelled water validation. *International Journal of Behavioral Nutrition and Physical Activity*, *4*(1), 1-9.

Menon, V., & Uddin, L. Q. (2010). Saliency, switching, attention and control: a network model of insula function. *Brain Structure and Function*, *214*(5-6), 655-667.

Nabi, R. L. (2021). Theories of affective impact. In Thompson, T.L. & Scholz, P.J., *Health Communication Theory*, (pp.157). Wiley-Blackwell.

Pandey, P., Kang, Y, Cooper, N, O'Donnell, M, B., & Falk., E. B. (2021). Social networks and neural receptivity to persuasive health messages. [Manuscript submitted for publication]. Annenberg School for Communication, University of Pennsylvania.

Orbell, S., Perugini, M., & Rakow, T. (2004). Individual differences in sensitivity to health communications: consideration of future consequences. *Health Psychology, 23*(4), 388.

Petty, R. E., Fabrigar, L. R., & Wegener, D. T. (2003). Emotional factors in attitudes and persuasion. In R. J. Davidson, K. R. Scherer, & H. H. Goldsmith (Eds.), Series in affective science. *Handbook of affective sciences* (pp. 752–772). Oxford University Press.

Power, J. D., Cohen, A. L., Nelson, S. M., Wig, G. S., Barnes, K. A., Church, J. A., ... & Petersen, S. E. (2011). Functional network organization of the human brain. *Neuron*, *72*(4), 665-678.

Ramsay, I. S., Yzer, M. C., Luciana, M., Vohs, K. D., & MacDonald III, A. W. (2013). Affective and executive network processing associated with persuasive antidrug messages. *Journal of Cognitive Neuroscience*, *25*(7), 1136-1147.

Rebar, A. L., Dimmock, J. A., Jackson, B., Rhodes, R. E., Kates, A., Starling, J., & Vandelanotte, C. (2016). A systematic review of the effects of non-conscious regulatory processes in physical activity. *Health Psychology Review*, *10*(4), 395-407.

Riddle Jr, P. J., Newman-Norlund, R. D., Baer, J., & Thrasher, J. F. (2016). Neural response to pictorial health warning labels can predict smoking behavioral change. *Social Cognitive and Affective Neuroscience*, *11*(11), 1802-1811.

Roberts, S. O., Bareket-Shavit, C., Dollins, F. A., Goldie, P. D., & Mortenson, E. (2020). Racial inequality in psychological research: Trends of the past and recommendations for the future. *Perspectives on Psychological Science*, *15*(6), 1295-1309.

Roy, M., Shohamy, D., & Wager, T. D. (2012). Ventromedial prefrontal-subcortical systems and the generation of affective meaning. *Trends in Cognitive Sciences*, *16*(3), 147-156.

Satterthwaite, T. D., Elliott, M. A., Gerraty, R. T., Ruparel, K., Loughead, J., Calkins, M. E., ... & Wolf, D. H. (2013). An improved framework for confound regression and filtering for control of motion artifact in the preprocessing of resting-state functional connectivity data. *Neuroimage*, *64*, 240-256.

Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., ... & Greicius, M. D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *Journal of Neuroscience*, *27*(9), 2349-2356.

Sheeran, P., Maki, A., Montanaro, E., Avishai-Yitshak, A., Bryan, A., Klein, W. M., ... & Rothman, A. J. (2016). The impact of changing attitudes, norms, and self-efficacy on health-related intentions and behavior: A meta-analysis. *Health Psychology*, *35*(11), 1178.

Shine, J. M., Bissett, P. G., Bell, P. T., Koyejo, O., Balsters, J. H., Gorgolewski, K. J., ... &

Poldrack, R. A. (2016). The dynamics of functional brain networks: integrated network states during cognitive task performance. *Neuron*, *92*(2), 544-554.

Sridharan, D., Levitin, D. J., & Menon, V. (2008). A critical role for the right fronto-insular cortex in switching between central-executive and default-mode networks. *Proceedings of the National Academy of Sciences*, *105*(34), 12569-12574.

Uddin, L. Q. (2015). Salience processing and insular cortical function and dysfunction. *Nature Reviews Neuroscience*, *16*(1), 55-61.

Uddin, L. Q., Yeo, B. T., & Spreng, R. N. (2019). Towards a universal taxonomy of macro-scale functional human brain networks. *Brain Topography*, *32*(6), 926-942.

Vezich, I. S., Katzman, P. L., Ames, D. L., Falk, E. B., & Lieberman, M. D. (2017). Modulating the neural bases of persuasion: why/how, gain/loss, and users/non-users. *Social Cognitive and Affective Neuroscience*, *12*(2), 283-297.

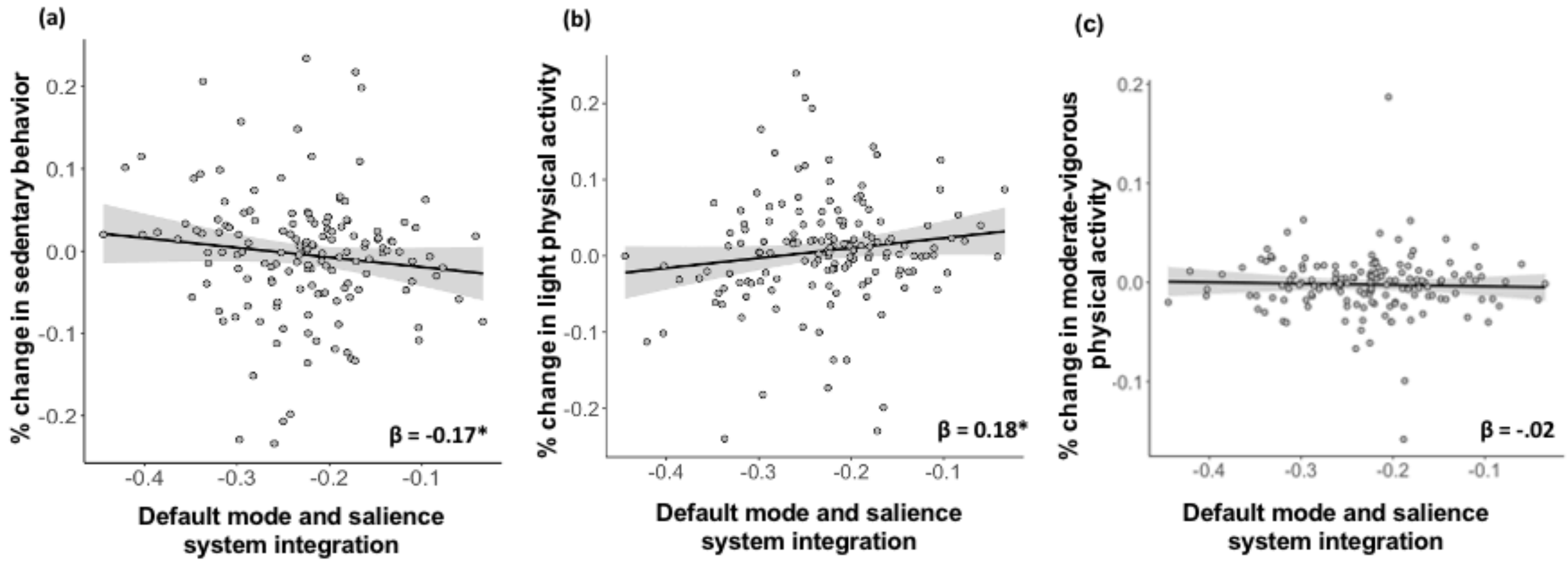
Wakefield, M. A., Loken, B., & Hornik, R. C. (2010). Use of mass media campaigns to change health behaviour. *The Lancet*, *376*(9748), 1261-1271.

Wang, A. L., Ruparel, K., Loughead, J. W., Strasser, A. A., Blady, S. J., Lynch, K. G., ... & Langleben, D. D. (2013). Content matters: neuroimaging investigation of brain and behavioral impact of televised anti-tobacco public service announcements. *Journal of Neuroscience*, *33*(17), 7420-7427.

Weber, R., Mangus, J. M., & Huskey, R. (2015). Brain imaging in communication research: A practical guide to understanding and evaluating fMRI studies. *Communication Methods and Measures*, *9*(1-2), 5-29.

Zhang, J., Andreano, J. M., Dickerson, B. C., Touroutoglou, A., & Barrett, L. F. (2020). Stronger functional connectivity in the default mode and salience networks is associated with youthful memory in superaging. *Cerebral Cortex*, *30*(1), 72-84.

Figure 1. Relationship between default mode and salience system integration during health messaging and future behavior change.



(*A*) Relative integration versus future sedentary behavior. (*B*) Relative integration versus future light physical activity. (*C*) Relative integration versus moderate-to-vigorous activity. On the x-axis, more positive integration scores correspond to greater integration between the default mode and the salience systems relative to the average within-system segregation.

Notes:**p*<0.05; β = standardized coefficient.

Table 1. ***Results for regression analysis testing association between default mode and salience integration and changes in sedentary behavior, light physical activity and moderate-vigorous physical activity***

	% change in sedentary behavior			% change in light physical activity			% change in moderate-vigorous activity		
	B	(S.E)	β	B	(S.E)	β	B	(S.E)	β
Intercept	-.02	(.03)	.00	.13**	(.04)	.00	.00	(.01)	00
Default mode and salience. Integration	-.17*	(.08)	-.17	17*	(.08)	.18	-.01	(.03)	-.02
Baseline sedentary/active (%)	-.14**	(.05)	-.23	-.11*	(.05)	-.19	-.09*	(.04)	-.18
In-scanner head motion	.16	(.11)	.12	-.13	(.11)	-.10	-.04	(.05)	-.08
Affirmation condition (ref. control)	-.01	(.01)	-.07	.00	(.01)	-.03	.01*	(.01)	.23
Compassion condition (ref. control)	-.03	(.02)	-.13	.02	(02)	.08	.01	(.01)	.12
Adjusted R^2		.07**			05*			.06*	
R^2		.10**			.08*			.09*	

Note. *$p \leq .05$, **$p \leq .01$, ***$p \leq .001$. B = unstandardized coefficient. SE = standard error. β = standardized coefficient. Ref. = reference category