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Title

Can functional magnetic resonance imaging studies help with the optimization of health messaging for lifestyle behaviour change? A systematic review

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Abstract

Unhealthy behaviours, including smoking, poor nutrition, excessive alcohol consumption, physical inactivity and sedentary lifestyles, are global risk factors for non-communicable diseases and premature death. Functional magnetic resonance imaging (fMRI) offers a unique approach to optimize health messages by examining how the brain responds to information relating to health. Our aim was to systematically review fMRI studies that have investigated variations in brain activation in response to health messages relating to (i) smoking; (ii) alcohol consumption; (iii) physical activity; (iv) diet; and (v) sedentary behaviour. The electronic databases used were Medline/PubMed, Web of Science (Core Collection), PsychINFO, SPORTDiscuss, Cochrane Library and Open Grey. Studies were included if they investigated subjects aged ≥10 years and were published before January 2017. Of the 13,836 studies identified in the database search, 18 studies (smoking k=15; diet k=2; physical activity/sedentary behavior k=1) were included in the review. The prefrontal cortex was activated in seven (47%) of the smoking-related studies and the physical activity study. Results suggest that activation of the ventromedial, dorsolateral and medial prefrontal cortex regions were predictive of subsequent behavior change following exposure to aversive anti-smoking stimuli. Studies investigating the neurological responses to anti-smoking material were most abundant. Of note, the prefrontal cortex and amygdala were most commonly activated in response to health messages across lifestyle behaviors. The review highlights an important disparity between research focusing on different lifestyle behaviors. Insights from smoking literature suggests fMRI may help to optimize health messaging in relation to other lifestyle behaviors.

Keywords

List of abbreviations

PSA – public service announcement

MRI – magnetic resonance imaging

fMRI – functional magnetic resonance imaging

NCD – non-communicable diseases

UK – United Kingdom

USA – United States of America

BOLD – blood oxygen level dependent

PRISMA – preferred reporting items for systematic reviews and meta-analyses

FDA – food and drug administration

Background

Non-communicable diseases (NCDs) such as cardiovascular disease, cancers and type 2 diabetes are reaching epidemic proportions; accounting for 60% of all deaths worldwide (1). The onset of more than two thirds of all new NCD cases is widely attributed to four specific modifiable risk factors; smoking, excessive alcohol consumption, poor nutritional intake and physical inactivity (2). The prevalence for each of these risk factors is staggering with one in five UK adults current cigarette smokers (3), over 85,000 alcohol-related deaths annually (4), a rising global body mass index (5) and only 5% of UK (6) and US (7) adults achieving national guidelines. This highlights that effective interventions to promote healthy lifestyles are needed. One approach that has been widely used is public health messaging which has the important advantage of reaching whole populations.

Promoting lower sugar intake, increased regular physical activity (e.g. "Change4Life"), smoking cessation (e.g. "Smoke Free") and minimizing excessive alcohol consumption (e.g. "Know your limits") are common aims of public health campaigns. In addition to these campaigns, point-of-decision prompts (e.g. take the stairs) and on-product packaging (e.g. "Smoking Kills") also presents persuasive micro-level messages which can also reach a wide

audience. In particular, pictures of tar-filled lungs and yellow teeth are now commonplace on cigarette packages (8). These prompts are attributed in part to the reductions in smoking prevalence (9; 10). However, ensuring campaigns and the information or images provided are impactful and evidence-based is crucial when implementing these behavior change approaches (11). Therefore, to help ensure public health campaigns and point-of-decision prompts are given the greatest chance to succeed in changing behavior, it is important to assess how people respond to them.

Lifestyle behaviors are influenced not only by conscious choices (e.g. choosing to active commute to work) but also by subconscious responses to the environment and stimuli (e.g. emotional responses to a television advertisement or billboard). In order for a decision to be made by the brain, self-related processing must occur which involves the evaluation of environmental stimuli with regards to its personal relevance. Given this, neuroimaging can provide valuable insight into subconscious responses to stimuli by examining regions of the brain and levels of brain activation when individuals view health-related messages. These insights may then be used to bolster the persuasiveness of health messages (12) and as a result, increase the likelihood of changing behavior (13). Previous research has highlighted that regions within the medial prefrontal cortex of the brain are associated with self-related processing (14) with people subsequently reducing time spent sitting when activations within the ventromedial prefrontal cortex were observed (15). Predicting behavior change based on neural activity through fMRI offers an interesting brain-behavior link (16); highlighting the importance of optimizing the content of health messages as they have a direct effect on how people's brains engage with the health message and whether they ultimately change their behavior. By producing and disseminating health messages that activate brain regions linked with successful behavior change, health campaigns may have greater population-level success and be more cost-effective (16; 17).

Methods

The present review aims to systematically review studies that have used fMRI to examine brain activity in response to health messages pertaining to physical activity, sedentary behavior, dietary intake, smoking and alcohol consumption. The aims of the review were to (i) examine stimuli content and modality; (ii) identify activated brain regions in response to stimuli

presented and (iii) assess the capacity of fMRI results to predict behavior change. The protocol of this systematic review was developed in accordance with the PRISMA-P guidelines (18).

Search Strategy

An electronic search was conducted using Medline/Pubmed; PsychINFO; SPORTDiscus; Web of Science (Core Collection); Cochrane Library; and Open Grey. The reference lists of included records were manually screened for identifying additional relevant records. The electronic database search was conducted on the 10th January 2017. The search strategy was identical across databases but the affiliation field was adjusted for each database (see Electronic Supplementary Material, Table 1). The search strategy used for all databases was: ("functional magnetic resonance imaging" OR "functional MRI" OR fMRI OR "blood oxygen level dependent" OR BOLD OR neuroimaging) AND (smoke* OR smoking OR cigarette OR tobacco OR alcohol OR drink OR "sedentary lifestyle" OR sedentary behavio* OR sedentar* OR sitting OR "physical activity" OR "physical inactivity" OR "activities of daily living" OR fitness OR exercise OR food OR snack OR diet OR eat OR eating OR calorie OR caloric OR campaign OR message OR messaging OR communication OR "mass media" OR PSA OR "public service announcement" OR graphic OR warning OR label OR image OR video).

Selection criteria and study selection

To be included, identified records had to meet the following criteria: (i) published in English prior to January 2017; (ii) involved human participants aged ≥10 years; (iii) investigated physical activity, sedentary behavior, dietary intake, smoking and/or alcohol consumption; (iv) assessed health messages; and (v) studied subjects using fMRI. We excluded all systematic reviews and meta-analyses. Record screening and data extraction were conducted using DistillerSR Version 2.0 (Evidence Partners, Ottawa, Canada). After inspection for any duplicates, the titles and abstracts of all records were reviewed by one reviewer (MW). Where a decision to include or exclude was not attained based on the title/abstract, the full text was sourced. Full text records were examined by two reviewers (MW and MO). Conflicts were discussed and if consensus was not achieved, a third reviewer (DE) was included.

Recorded variables, data extraction and analysis

Data were extracted on standardized forms developed a priori by the lead author for the following variables: authors and year of publication; publication title, number of subjects included within analyses; number of subjects excluded from analyses; age; gender distribution;

subject handedness; lifestyle behavior investigated; fMRI task design; fMRI principle findings; presence of a follow up component and follow up principle findings (see Table 1 and Table 2). Further fMRI methodological variables were extracted (see Electronic Supplementary Material, Table 3 and Table 4).

Results

Full details of the search results, including reasons for exclusion are summarized in Figure 1. Total search results obtained from each database were recorded (see Electronic Supplementary Material, Table 2). Of 13,836 records identified by the electronic database searches, 13,420 records (97.0%) were excluded based on title and abstract sifting. Of the remaining 416 records, 400 were excluded during full-text sifting: 350 (87.5%) because they did not assess health messages, 20 (5.0%) due to inappropriate article type, 15 (3.8%) did not investigate fMRI and a lifestyle behavior of interest in this review, 9 (2.3%) had no visual stimuli, 2 (0.5%) did not provide sufficient detail, 2 (0.5%) studied subjects aged <10 years and 2 (0.5%) were duplicates. Reference lists of the 16 included records yielded 2 additional records for inclusion; resulting in the inclusion of 18 studies for this review.

PRISMA 2009 Flow Diagram
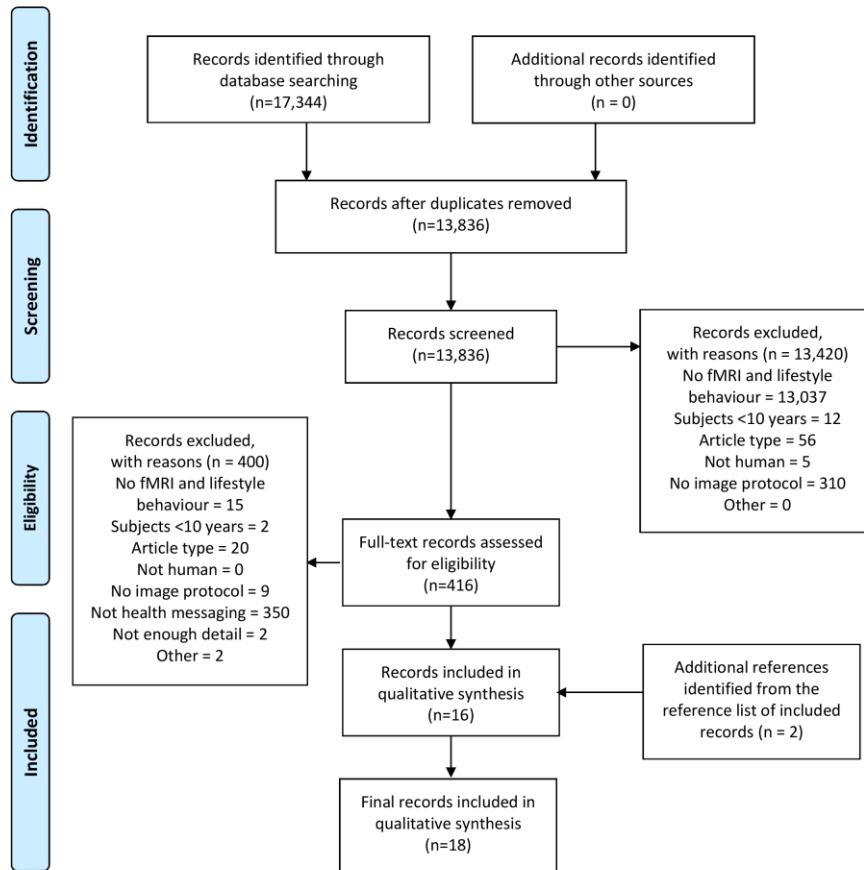
Figure 1: Selection procedure; based on the PRISMA flow diagram template from www.prisma-statement.org

Characteristics of included studies

Of the resulting 18 studies, studies investigated smoking (k=15), diet (k=2), physical activity and sedentary behavior (k=1) and no studies were included for alcohol consumption (see Table 1 and 2). All studies were published between January 2009 and November 2015 (inclusive). The sample sizes of the included studies ranged from having 24 to 91 participants. Included studies recruited participants between the ages of 13 and 69 years. Fourteen (77.8%) studies

recruited both males and females, 1 (5.6%) study recruited males only and 3 (16.7%) studies did not provide sufficient detail.

Of the 18 studies, ten (55.6%) were cross-sectional and eight (44.4%) were longitudinal in design. The eight longitudinal studies followed up participants one to four months following fMRI and were conducted via telephone, appointment or email to assess level of smoking abstinence (k=6), objectively measure sedentary behavior and physical activity (k=1) or intention to quit smoking (k=1).

Fourteen (77.8%) of studies were conducted in the USA, specifically Michigan (k=6), Pennsylvania (k= 6), California (k=1) and South Carolina (k=1). The remaining studies were conducted in Germany (k=2) and Canada (k=2). Further characteristics for each of the included studies are provided in Table 1.

Table 1: Study characteristics of the included studies.

Title	Sample Characteristics					Author, year
	N included within analyses	N excluded from analyses	Mean age (SD)	Gender	Handedness	
Physical Activity or Sedentary Behaviour						
Self-affirmation alters the brain's response to health messages and subsequent behaviour change	46	21	Affirmed 33.7 (13.5); control 30.1 (13.1)	27 F 19 M	45 R	Falk et al., 2015 (15)
Diet						
Nutrition labels influence value computation of food products in the ventromedial prefrontal cortex	25	10	23.3 (4.4)	14 F 11 M	Detail not provided	Enax et al., 2015 (19)
Relation of obesity to neural activation in response to food commercials	30	Detail not provided	15.2 (1.1)	17 F 13 M	Detail not provided	Gearhardt et al., 2014 (20)
Smoking						
Neural responses to elements of a web-based smoking cessation program	41	Detail not provided	38.3 (11.5)	10 F 31 M	41 R	Chau et al., 2009 (21)
Neural correlates of message tailoring and self-relatedness in smoking cessation programming	24	Detail not provided	40.0 (11.2)	12 F 12 M	24 R	Chau et al., 2009 (22)
Self-related neural response to tailored smoking-cessation messages predicts quitting	91	Detail not provided	37.5 (11.5)	44 F 47 M	91 R	Chau et al., 2011 (23)

Brain activity in self- and value-related regions in response to online antismoking messages predicts behaviour change	46	4	32.1 (12.6)	19 F 27 M	46 R	Cooper et al., 2015 (24)
Where there's smoke, there's fire: the brain reactivity of chronic smokers when exposed to the negative value of smoking	30	Detail not provided	31.9 (9.4)	15 F 15 M	29 R 1 L	Dinh-Williams et al., 2014 (25)
Executive-affective connectivity in smokers viewing anti-smoking images: an fMRI study	30	Detail not provided	31.8 (9.2)	15 F 15 M	28 R 1 L 1 A	Dinh-Williams et al., 2014 (26)
FDA cigarette warning labels lower craving and elicit frontoinsular activation in adolescent smokers	79	1	Detail not provided	Detail not provided	79 R	Do et al., 2015 (27)
Neural activity during health messaging predicts reductions in smoking above and beyond self-report	28	3	45.0 (10.1)	15 F 13 M	28 R	Falk et al., 2011 (16)
Functional brain imaging predicts public health campaign success	44	6	Detail not provided	Detail not provided	Detail not provided	Falk et al., 2016 (28)
Amygdala response to smoking-cessation messages mediates the effects of serotonin transporter gene variation on quitting.	82	Detail not provided	Quitters 36.4 (11.4); non-quitters 38.4 (12.3)	38 F 44 M	Detail not provided	Jasinska et al., 2012 (29)
Reduced prefrontal and temporal processing and recall of high 'sensation value' ads	15	3	Detail not provided	3 F 12 M	Detail not provided	Langleben et al., 2009 (30)

Study	N	SD	Age	Sex	Handedness	Reference
Neural biomarkers for assessing different types of imagery in pictorial health warning labels for cigarette packaging: a cross-sectional study	50	Detail not provided	27.6	24 F 26 M	Detail not provided	Newman-Norlund et al., 2014 (31)
Severity of dependence modulates smokers' neuronal cue reactivity and cigarette craving elicited by tobacco advertisement	43	5	Non-abstinent 31.0 (7); never-smokers 29.0 (5)	43 M	43 R	Vollstadt et al., 2011 (32)
Content matters: neuroimaging investigation of brain and behavioural impact of televised anti-tobacco public service announcements	63	8	High AS 29.0 (1.6); low AS 30.0 (1.9)	High AS 18 F 15 M; Low AS 14 F 16 M	Detail not provided	Wang et al., 2013 (33)
Emotional reaction facilitates the brain and behavioral impact of graphic cigarette warning labels in smokers	19	5	Detail not provided	Detail not provided	19 R	Wang et al., 2015 (34)

A, ambidextrous; AS, argument strength; F, female; L, left; M, male; N, number; R, right; SD, standard deviation

Main findings

Stimuli content and modality

 Identifying the content and modality of stimuli helps provide valuable understanding as to what forms of health messages are being assessed using functional MRI. Full details of the stimuli presented in the eighteen studies are presented in Table 2. Of the eighteen identified studies, nine studies used static images (k=8 smoking, k=1 diet), four studies used videos (k=3 smoking, k=1 diet) and five studies used text-based messages (k=4 smoking, k=1 physical activity/sedentary behaviour). Static messages included the presentation of images such as banner adverts (24) and warning labels found on cigarette packaging (27). Videos included food commercials (20) and public service announcements highlighting the importance of smoking cessation (30). Finally, text-based messages included the presentation of motivational messages that encouraged smoking cessation (21) or presented tailored, untailored and neutral statements (23).

Table 2: An overview of the fMRI task paradigm and the main findings of the included studies.

Author, year	fMRI task		fMRI task principle findings	Follow up	Follow up principle findings
	Stimuli modality	Content			
Physical activity or sedentary behaviour					
Falk et al., 2015 (15)	Visual	Promote activity and emphasize risks due to being sedentary (n=10); reasons not to be sedentary (n=10) or more active (n=10); tips for how to become more active (n=10) or less sedentary (n=10).	Affirmed participants showed greater activity within vmPFC during exposure to targeted health messages.	Accelerometry 1 month. 2 SMS messages per day: 1 value affirmation (either affirmation or control allocation) and 1 health message.	Activity within the vmPFC predicted sedentary behaviour in the subsequent month.
Diet					
Enax et al., 2015 (19)	Visual	Healthy TL (n=25); unhealthy TL (n=25); healthy GDA (n=25); unhealthy GDA (n=25)	TL unhealthy showed significantly increased activation in the left inf. front. gyrus/dlPFC.	No follow up	N/A
Gearhardt et al., 2014 (20)(20)	Visual (presence of audio unknown)	Food commercials (n=20); non-food commercials (n=20)	Food commercials exhibited greater activation in bilateral post. cerebellar lobe (declive), bil. middle occipital gyrus, right precentral gyrus, right inf. temporal gyrus, bil. inf. parietal lobe, left postcentral gyrus, right precuneus and right sup. parietal lobe.	No follow up	N/A

Smoking					
Chau et al., 2009 (21)	Visual (presence of audio unknown)	Personalization/feedback; motivational; instructional; control messages (targeted and neutral)	Personalization/feedback messages activated the mPFC and precuneus/post. cingulate.	Web-based tailored smoking-cessation program and a 10 week course of nicotine patches. Follow up at 4 months	Detail not provided
Chau et al., 2009 (22)	Audio-visual	High tailored messages; low tailored messages; generic statements	High-tailored messages produced greater activity in rmPFC and precuneus/post. cingulate regions.	No follow up	N/A
Chau et al., 2011 (23)	Audio-visual	Tailored messages (n=50); untailored messages (n=50); neutral messages (n=50).	The dmPFC, precuneus, and angular gyrus were preferentially engaged by tailored messages.	Web-based tailored smoking-cessation program. Follow up at 4 months.	Greater activation in the dmPFC during tailored messages significantly predicted the odds of quitting smoking. Greater activation in the precuneus was marginally correlated.
Cooper et al., 2015 (24)	Visual	Banner ads (n=23)	Detail not provided	Follow up at 40 days.	Behaviour change was significantly related to activity in both self- and value-related sub-regions of the mPFC (replicated previous findings).

Dinh-Williams et al., 2014 (25)	Visual	Aversive smoking-related (n=25); aversive non-smoking related (n=25); appetitive smoking-related (n=25); neutral (n=25).	Aversive smoking-related elicited activations in the visual association cortex and ext. visual system, the temporal and parietal lobes, limbic system, lat. orbitofrontal cortex, inf. front. gyrus and mPFC.	No follow up	N/A
Dinh-Williams et al., 2014 (26)	Visual	Aversive smoking-related (n=25); aversive IAPS control (n=25); neutral IAPS control (n=25)	Aversive smoking-related elicited significantly greater activations in regions of the occipital, temporal and parietal lobes, amygdala, lat. orbitofrontal cortex, inf. front. gyrus and mPFC.	No follow up	N/A
Do et al., 2015 (27)	Visual	FDA warning labels (n=9); non-graphic labels (control) (n=9)	Smokers' demonstrated blunted recruitment of insula and dlPFC relative to non-smokers.	No follow up	N/A
Falk et al., 2011 (16)	Visual (presence of audio unknown)	TV commercials relevant to smokers who were trying to quit (n=16).	Detail not provided	Follow up at 1 month.	Neural activity in the mPFC significantly predicted behaviour change. The med. precuneus/post. cingulate and a region involved in motor planning supplementary motor area were also highly associated.
Falk et al., 2016 (28)	Visual	Anti-smoking images with a tag-line Negative images (n=10) Neutral images (n=10)	Detail not provided	Population-level email campaign (n=400,000).	Activity within MPFC sub-region predicted population-level campaign responses

		Personal/control images (n=10)		Presented either anti-smoking or neutral image with a tagline to stop smoking. Measured intention to quit via option to obtain free nicotine patches	Self-related neural processing predicted outcomes in response to graphic warning labels, but not in response to compositionally similar neutral images.
Jasinska et al., 2012 (29)	Audio-visual	Tailored messages (n=50); untailored messages (n=50); neutral messages (n=50).	Detail not provided	Web-based tailored smoking-cessation program and a 10 week course of nicotine patches. Follow up at 4 months.	The mean amygdala response was a significant predictor of subsequent post-intervention quitting outcome.
Langleben et al., 2009 (30)(30)	Audio-visual	Anti-smoking PSAs (n=8); neutral videos (n=8)	PSAs were associated with higher activity in the inf. and mPFC, the occipital cortex (fusiform and lingual gyri) and the temporal cortex (hippocampus and parahippocampus).	No follow up	N/A
Newman-Norlund et al., 2014 (31)	Visual	Graphic health warning label (n=19); suffering health warning label (n=19); symbolic health warning label (n=19)	Stimuli elicited a significant neural response in the amygdala, insula and visual association cortex, front. gyrus, temporal gyrus, parietal lobe (inf.), suppl. motor area, parahippocampal gyrus and thalamus.	No follow up	N/A

Vollstadt et al., 2011 (32)	Visual	Smoking-related (n=45); control (n=45)	Moderately dependent smokers' brain activity elicited by tobacco advertisement was higher in the amygdala, hippocampus, putamen and thalamus.	No follow up	N/A
Wang et al., 2013 (33)	Audio-visual	Anti-smoking PSAs High AS/high MSV (n=8); high AS/low MSV (n=8); low AS/high MSV (n=8); low AS/low MSV (n=8)	The interaction of AS and MSV was observed in the bil. inf. parietal lobule, left inf. front. gyrus, left fusiform gyrus, the right dmPFC, and the precuneus.	Follow up at 1 month.	Activation in the dmPFC predicted the urine cotinine levels.
Wang et al., 2015 (34)	Visual	High FDA graphic warning label (n=12); low FDA graphic warning label (n=12); control (n=12)	Graphic warning labels evoked greater activation in the bil. occipitoparietal cortex, including visual and fusiform areas, cuneus and precuneus, bil. temporal and inf. front. cortices, amygdala, hippocampus and parahippocampus.	No follow up	N/A

AS, argument strength; bil., bilateral; dmPFC dorsomedial prefrontal cortex; FDA, Food and Drug Administration; ext., extended; front., frontal; GDA, guideline daily amount; IAPS, International Affective Picture System inf., inferior; lat., lateral; med., medial; mPFC, medial prefrontal cortex; mid., middle; MSV, message sensation value; post., posterior; PSAs, public service announcements; rmPFC, rostral medial prefrontal cortex; sup., superior; suppl., supplementary; TL, traffic light; vmPFC ventromedial prefrontal cortex

Brain activations

The most common brain regions activated in the studies are presented in Table 3 with only listed regions identified in at least two studies highlighted.

Static health messages

Significantly more activation in the temporal and parietal lobes, lateral orbitofrontal cortex, inferior frontal gyrus and medial prefrontal cortex were consistently observed across two studies assessing aversive smoking versus control images (25; 26). Another study observed activations in other regions (e.g. amygdala and hippocampus) in response to tobacco advertisement images (32). Of the three studies investigating graphic warning labels, two studies identified significant neural responses in the amygdala (31; 34). The two remaining smoking-related studies (24; 28) focused on the predictive capacity of neural activation therefore the results are not highlighted in this section. Only one study (19) examined neural activation toward static health messages restricting the opportunity for comparison. No studies were identified for physical activity or sedentary behaviour.

Video health messages

Of the three studies investigating smoking-related health messages presented by video, one study (28) focused only on the predictive capacity of brain activation on subsequent behaviour. The other two studies examined neural activation in response to anti-smoking public service announcements but compared these stimuli with neutral videos (30) or varying videos with varying levels of "message sensation value" and "argument strength" (33). This was reflected in the findings which highlighted no common brain regions between them. In addition, only one study (20) investigated diet health messages delivered by video. No studies were identified for physical activity or sedentary behaviour.

Text-based health messages

Three of the four studies identified regions within the prefrontal cortex and precuneus as preferentially engaged in response to tailored/personalized text-based messages. These regions included the rostral medial prefrontal cortex (22), medial prefrontal cortex (21) and the dorso-medial prefrontal cortex (23). The fourth study (29) instead focused on the predictive capacity of brain activation on subsequent behaviour. In contrast, only one study (15) investigated this form of health message for physical activity/sedentary behaviour. No studies were identified for text-based health messages relating to diet.

Table 3: An overview of the most commonly identified brain regions (minimum two studies report the brain region).

	Physical activity or sedentary behaviour	Diet		Smoking										
	Falk et al., 2015 (15)	Enax et al., 2015 (19)	Gearhardt et al., 2014	Chau et al., 2009 (21)	Chau et al., 2009 (22)	Chau et al., 2011 (23)	Dinh-Williams et al., 2014 (25)	Dinh-Williams et al., 2014 (26)	Do et al., 2015 (27)	Langleben et al., 2009 (30)	Newman-Norlund et al., 2014	Vollstadt et al., 2011 (32)	Wang et al., 2013 (33)	Wang et al., 2015 (34)
Inferior frontal gyrus		✓	✓				✓	✓			✓	✓	✓	✓
Precuneus	✓		✓	✓	✓	✓				✓			✓	✓
Amygdala							✓	✓	✓		✓			✓
Fusiform							✓				✓	✓	✓	✓
Inferior parietal lobe			✓				✓					✓	✓	
Middle temporal gyrus	✓						✓				✓			✓
Precentral gyrus			✓								✓	✓		✓

Lingual gyrus										✓	✓			✓
Medial prefrontal cortex				✓	✓			✓						
Middle frontal gyrus										✓	✓	✓		
Parra-hippocampal gyrus										✓	✓			✓
Posterior cingulate	✓			✓	✓									
Superior frontal gyrus	✓						✓					✓		
Caudate									✓	✓				
Cerebellum									✓					✓
Dorsolateral prefrontal cortex		✓							✓					
Dorsomedial prefrontal cortex						✓							✓	
Hippocampus											✓			✓
Inferior occipital							✓							✓
Insula									✓		✓			
Middle occipital gyrus			✓				✓							
Putamen									✓					✓
Superior temporal gyrus												✓		✓

Predictive capacity of fMRI for behavior change

Full details of the studies including a follow up component are presented in Table 2. In total, eight studies assessed the predictive capacity of functional MRI (k=7 smoking, k=1 physical activity/sedentary behaviour). Of the seven studies focused on smoking, six studies identified the following brain regions as predictive of smoking abstinence: the dorsomedial prefrontal cortex (k=2), medial prefrontal cortex (k=2), amygdala (k=1) and the supplementary motor area (k=1). The physical activity/sedentary behaviour study (15) identified the ventromedial prefrontal cortex as predictive of subsequent time spent sedentary.

Discussion

Summary

The present review identified 18 studies; 15 relating to health messages about smoking, two relating to health messages about diet and one on health messages about physical activity and sedentary behavior. Areas of the prefrontal cortex and amygdala were most commonly activated with increased activation of the ventromedial prefrontal cortex predicting subsequent behavior change (e.g. smoking cessation). The vast majority of the evidence on the utility of fMRI to facilitate behavior change currently relates to smoking and there were a lack of RCTs; limiting findings to correlations rather than causal interpretation. More fMRI studies on health messages relating to physical activity, sedentary behavior, dietary intake and alcohol consumption are needed that incorporate an RCT design.

Stimuli content and modality

The present review highlighted that a range of anti-smoking materials were investigating both pictorial and video stimuli such as FDA warning labels (27; 34) and public services announcements (PSAs) (30), respectively. Studies that compared neural responses to tailored and untailored messages observed activations in the dorsomedial prefrontal cortex and precuneus/posterior cingulate (e.g. 22; 23). Other studies demonstrated that aversive smoking stimuli, compared with neutral images, elicited greater activations in the amygdala (25; 26); often associated with emotion regulation (35). With a range of anti-smoking materials currently advertised, it must be acknowledged that people will respond and engage differently with them. For instance, Do and Galvan (27) identified that current smokers had a blunted response in the dorsolateral prefrontal cortex and insula relative to non-smokers to cigarette warning labels.

This suggests that the health messages were not causing the same neural response in the smokers as in the non-smokers and so perhaps multiple versions of health messages should be produced to target all people. For example, specific messaging materials could be developed to highlight the benefits of not starting a behavior (proactive approach) and other materials to highlight the benefits of stopping a behavior (reactive approach). Presenting pictures of people living with obesity, having limited mobility or other health issues such as diabetic foot on chairs and inside escalators (including sites that are likely to attract active individuals e.g. gyms and parks) could be a comparable approach to promote physical activity across the whole population (i.e. active and inactive).

As demonstrated in the present review, point-of-decision prompts such as pictures on cigarette packaging or traffic light coding systems found on food items are widely used in anti-tobacco and food industry communications, respectively, to deter purchasing. Other methods, such as billboard advertisements and videos (e.g. PSAs) enable similar but wider messages to reach the wider public and are often accompanied by graphic health messages; suggested to elicit stronger emotional responses than text-based messages alone (36). As previously mentioned, for physical activity and sedentary behavior, point-of-decision prompts are placed at specific locations where people are forced to make a behavioral decision as to whether be active or sedentary, respectively. For instance, prompts that encourage people to take the stairs rather than the escalator have shown short-term promise (37). However, it is currently unknown whether these highlighted health messages activate brain regions associated with 'the self'; previously suggested to motivate people to adjust behavior (38). Efforts to change behaviour generally result in short-term successes and a subsequent relapse or complete failure (39). These failures are often aligned to the difficulty experienced when changing a habit and so rely on the use of cues and triggers to support the habit formation process (40). Therefore, more research using fMRI needs to be conducted to focus on alternative point-of-decision prompts that relate to promoting physical activity, minimizing sedentary behavior and improving dietary intake. Overall, this will likely help inform the distribution of effective health messages across the different lifestyle behaviors in various locations to encourage positive behaviors.

Activated brain regions

The present review identified that the ventromedial prefrontal cortex, medial prefrontal cortex, and dorsomedial prefrontal cortex were activated in response to anti-smoking health messages that were aversive or tailored. No studies explicitly stated whether the tailored messages were

aversive or not. The medial prefrontal cortex is a well-established area of the brain associated with self-related processing (14); suggesting that individuals are self-reflecting whilst shown stimuli and are therefore potentially more likely to be engaging with the stimulus compared with an individual who does not have activation in that region. However, as with all fMRI research, caution is advised when interpreting findings; mainly attributed to the notion of reverse inference which suggests that brain activation infers the engagement of a specific cognitive process (41). In comparison, tailored health messages activated regions of the prefrontal cortex, precuneus and posterior cingulate regions which are associated with retrieving episodic autobiographical memories (42) as well as reflecting on one's own traits (43) and personal intentions (44). The present review identified nine additional studies to those highlighted in a recent neuroimaging review (13) which focused on wider health communication; including studies focusing on narcotic substance use, safe sex and sun safety. These studies investigated the perceived value of health messages and how greater neural activity was observed in certain populations (e.g. high risk cannabis users) (13).

Presenting caloric information activated the inferior frontal gyrus/dorsolateral prefrontal cortex region (19); a region implicated in self-control (45; 46). The importance of this brain region is implicated in various domains of self-control, including compliance toward social norms (47) and controlling impulses in inter-temporal choice (48). The ventromedial prefrontal cortex is implicated in simple-choice value computation (19). These findings suggest that health messages resonate with the individual and encourage them to self-reflect but it does not confirm that those individuals subsequently change their behavior following exposure to the health message. Other studies, not eligible to be included in the present review, have begun to examine neural responses to pictures of individuals being physically active or sedentary (49; 50) and whether presenting people with these pictures could help change behavior. For instance, if an individual viewed a picture of someone else jogging, what brain regions are activated and does exposure result in changes to levels of physical activity? Recent advances, such as the release of a new parcellation (mapping) tool identifying 97 further sub-regions within the cerebral cortex (51), will help to further elucidate knowledge around the specific functions aligned with regions of interest which will help confirm findings obtained via studies using fMRI.

Predictive capacity of fMRI for behavior change

The present review identified that the brain regions that were identified as predictive (by association) of smoking cessation were the dorsomedial prefrontal cortex, amygdala, the

supplementary motor area and the medial prefrontal cortex; associated with self-related processing (14). The other lifestyle behavior study that conducted a follow up focused on changes in physical activity and sedentary behavior. Interestingly, Falk and colleagues (15) identified a different brain region as predictive of subsequent reductions in time spent sitting with activations observed in the ventromedial prefrontal cortex. Unfortunately, findings from the present review confirm that all studies that investigated the predictive capacity of fMRI for behavior change conducted prospective, longitudinal studies and so report correlational data which cannot be causal. In addition, there appeared to be inconsistent findings such that there was not a single brain region that was activated across all of the health message stimuli due to the variety of health messages presented.

Falk and colleagues also assessed the role of self-affirmation; in particular, how exposing individuals to their core values (e.g. friends and family, money and religion) prior to the task demonstrated that the stimuli was more self-relevant and valuable (15). The link between neural activity and behavior change via self-processing is supported (17) with findings suggesting that individuals more engrossed in anti-smoking advertisements report an increased benefit (i.e. are less likely to smoke or more likely to stop smoking) (52) and that self-relevant messages are likely more effective than generic messages (53; 54). Findings from Kaye and colleagues (13) confirmed that activation in the medial prefrontal cortex accounted for additional variance beyond that of self-report measures. Unfortunately, as highlighted by the present review, there is currently limited or a lack of evidence for changes in physical activity, sedentary behavior, diet and alcohol following health message exposure. Future studies should consider implementing an RCT within their longitudinal studies to help increase the amount of research that assesses behavior change across the different lifestyle behaviors.

Future considerations

With an increase in the application of digital technologies within healthcare systems for use in patients with chronic conditions, it is an important time to ensure that the health messages provided by these devices are effective (55). Presenting health messages via digital platforms such as wearable devices to promote standing and walking or via smartphone applications to help monitor food, cigarette and alcohol consumption, given their omnipresence, could be very effective and not too dissimilar to the handheld health message platform of a packet of cigarettes or food packaging. Overall, future fMRI studies should aim to evaluate brain responses to different forms of health messages across the different lifestyle behaviors and

incorporate longitudinal but controlled study designs to optimize the interpretation and consistency of study findings.

Literature Methodology

Of the 13 (72.2%) studies that stated their recruitment strategy, the majority presented advertisements in the community or via the internet; thus recruiting self-selected and non-randomized individuals. In addition, only 2 studies recruited adolescents despite the onset of an unhealthy lifestyle often beginning in the early-to-mid adolescent years. Also, most studies were conducted in either Michigan or Pennsylvania in the USA (k= 16); potentially attributable to the general limitations of fMRI (e.g. restricted access and cost). In addition, 9 studies either failed to report participant handedness or recruited a mixture of left, right and ambidextrous handed participants. The importance of reporting handedness is due to its clear link to cerebral dominance for activities such as language processing (56). Future research would benefit from standardizing, and precisely measuring, the time between tobacco, food and alcohol consumption and exercise before the onset of the fMRI task.

Limitations of the current literature

The present review acknowledges the following limitations. Firstly, there were only 18 studies identified by the electronic database search and reference lists and there was a lack of causational studies; therefore, it is difficult to draw any conclusions. Secondly, only 8 studies examined behavior change with 7 (87.5%) of these conducted in relation to smoking cessation. In addition, there was a lack of studies identified for physical activity, sedentary behavior, diet and alcohol. Studies published outside of the databases searched were not considered for inclusion. Future research is required to examine the utility of functional MRI to examine health messaging relating to these lifestyle behaviors.

Conclusions

The current review identifies an important disparity between the abundance of research across the different lifestyle behaviors. Collating findings from multiple lifestyle behaviors could prove useful in order to begin producing more persuasive messages for population behavior change; however, there is currently a deficiency of studies across the lifestyle behaviors to investigate this at this stage. Regardless of this, the review highlights that the prefrontal cortex and amygdala were most commonly activated in response to health messages and that the

ventromedial prefrontal cortex was predictive (by association) of subsequent behavior change. Future studies should focus on the assessment of point-of-decision prompts, PSAs and tailored messages (e.g. feedback notifications) across all lifestyle behaviors.

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