# Examining the neural correlates of goal priming with the NeuroShop, a novel virtual reality fMRI paradigm

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## Abstract

**Objective**: Health goal priming has been shown to stimulate healthy food choices by activating an individual's weight-control goal. The present study combined fMRI with a novel virtual reality food choice task to elucidate the underlying neural mechanisms of health goal priming. Previous research has suggested that the ventromedial prefrontal cortex (vmPFC) and dorsolateral prefrontal cortex (dlPFC) play a role in the incorporation of health considerations into the food choice process. Responses may be more representative for those found in real life when assessed in an environment similar to the actual choice environment. Therefore, the first aim of the study was to explore if a novel virtual reality food choice task is sufficiently sensitive to detect basic valuation processes in food choice. The second aim was to examine whether increased activation in the dlPFC drives the effects of health goal priming.

**Methods**: Fifty-six female participants performed an fMRI food choice task embedded in a virtual supermarket environment. They chose between perceived healthy and unhealthy products in a health prime, hedonic prime, and non-food control condition, while activation in brain areas involved in self-control and valuation (vmPFC, dlPFC) was assessed.

**Results**: There were no differences in relative preference for perceived healthy products over unhealthy products between the conditions. There were also no main effects of prime condition on brain activation in the vmPFC and dPFC during food choice. Across conditions, activation in the vmPFC correlated with the tastiness of the chosen product during food choice.

**Conclusions:** Although the study does not provide support for health goal priming triggering neural self-control mechanisms, results did show that virtual reality has potential for a more realistic fMRI food choice paradigm.

**Keywords**: health goal priming, self-control, food choice, external cue, virtual reality supermarket

Neural mechanisms of Health Goal Priming

A growing number of people are overweight or obese (Ng et al., 2014), and this puts them at risk for a range of serious health consequences, like diabetes (Kahn, Hull, & Utzschneider, 2006) and high blood pressure (Kotsis et al., 2005). Although many people try to control their weight by dieting (Kruger, Galuska, Serdula, & Jones, 2004), persistent weight loss turns out to be difficult to achieve (Jeffery et al., 2000). The continuous exposure to tempting food cues in our environment is considered a cause of overeating (Cohen, 2008) since these cues act as primes that unconsciously trigger peoples' motivation to consume food (Levitsky & Pacanowski, 2012). Exposing people to cues for healthy eating has been suggested to be an effective strategy to counter these influences. The present experiment was designed to examine the neural mechanisms underlying such health primes, in order to establish whether they rely on well-evidenced self-control mechanisms in the brain.

Primes are environmental cues that can influence an individual’s thoughts, feelings, and behavior (Bargh & Chartrand, 2000). Health goal primes can be used as an intervention tool to cue personal health goals in the micro-environment in which food choices are made (Hollands et al., 2017; Papies, 2016; Sheeran, Gollwitzer, & Bargh, 2013). In health goal priming, an external cue, such as a flyer with diet-related words (Papies et al., 2014), activates an individual’s long-term goal of healthy eating and controlling one’s weight, which can then affect cognition and behaviour to be more in line with those long-term goals (Papies, 2016). Research in both laboratory and real-world settings has shown that health goal priming can stimulate healthier food choices (Boland, Connell, & Vallen, 2013; Brunner & Siegrist, 2012; Papies & Hamstra, 2010; Papies, Potjes, Keesman, Schwinghammer, & van Koningsbruggen, 2014; Papies & Veling, 2013; Van der Laan, Papies, Hooge, & Smeets, 2017), especially among participants with a strong dieting goal (for a meta-analysis, see Buckland, Er, Redpath,

& Beaulieu, 2018). To date, it is largely unknown through which neural mechanisms health goal priming influences choice.

Studies on the neural processes of self-control in food choice have shown that brain areas involved in inhibitory control show increased activation during successful self-control (Hare, Camerer, & Rangel, 2009; Lopez, Hofmann, Wagner, Kelly, & Todd, 2014; Van der Laan, de Ridder, Viergever, & Smeets, 2014). The interaction between the ventromedial and dorsolateral prefrontal cortex has an important role in successful self-control (e.g., Hare et al., 2009). Activation in the dorsolateral prefrontal cortex (dlPFC) was stronger when weight-concerned individuals successfully exercised self-control during food choice (i.e., when choosing less tasty healthy food over tasty but unhealthy foods). The authors also found that the dlPFC activity modulated activity in the ventromedial prefrontal cortex (vmPFC) (Hare et al., 2009), which is involved in the integration of different decision-related factors (O'Doherty, 2011), such as taste and healthiness in food choice. Hare and colleagues (2009) found that activity in the vmPFC reflected both health and taste considerations in successful self-controllers, but only reflected taste in non-successful self-controllers. Therefore, they proposed that in order to make healthy food choices, dlPFC activation is required to incorporate health considerations into the vmPFC goal value computation. Similarly, Hare, Malmaud, and Rangel (2011), examined the effect of an explicit attention cue on food choice and the underlying neural mechanisms in a group of non-dieting participants. Here, participants were explicitly instructed to consider the food's healthiness in their choice. This instruction increased activity in the dlPFC during food choice and resulted in healthier food choices. Again, healthy food choices resulted from modulation of the vmPFC activity by increased activation in the dlPFC. A recent study replicated this finding and showed that considering the healthiness of food increased the connectivity between the vmPFC and the dlPFC (Van Meer et al., 2017). Similarly, product cues associated with healthiness, such as organic labels, (Aguirre, 2007; Yiridoe, Bonti-Ankomah, & Martin, 2005), increase activity in the dlPFC during food choice (Linder et al., 2010; Lusk et al., 2015).

Although these studies have shown that product cues and explicit health instructions can influence food choice and neural processes underlying choice, the effect of more implicit cues, such as health goal primes, is unknown. Goal primes can influence an individual's momentary mindset such that food attributes related to longer term goals are taken into account, without explicit instructions or conscious awareness (Fishbach, Friedman, & Kruglanksi, 2003; Papies et al., 2014; Papies, 2016). Because goal primes can be delivered as words or images and can be integrated into menus, advertisements, or shop displays, making health goal priming a potentially scalable intervention strategy, even in complex daily-life environments such as supermarkets (Hollands et al., 2017; Papies, Potjes, Keesman, Schwinghammer, & van Koningsbruggen, 2014). Therefore, the present study examined the effect of a health goal prime on the neural responses to food choices in a supermarket setting.

For health goal priming and many other intervention approaches, responses may be more representative for those found in real life when the effects are assessed in an environment similar to the actual choice environment (e.g., Best, Barsalou, & Papies, 2018). Therefore, the first aim of the current study was to explore if a novel virtual reality food choice task is sufficiently sensitive to detect basic valuation processes in food choice. Previous neuroimaging studies on food choice have been performed in laboratory settings with highly controlled and simplified choice paradigms. A need for more realistic food choice contexts for food-related fMRI research has been echoed in a recent good-practice paper (Smeets et al., 2019). Several situational factors that influence (health) goals and preferences are either absent (i.e., in-store cues) or present (i.e., medical equipment such as an MRI scanner) and may hamper the translation of fMRI findings to real life contexts. Considering that interventions should ultimately affect behaviour in the complex setting of daily life, the food choices in the present study were made in a virtual supermarket with realistic goal primes (i.e., advertisement posters). Though virtual reality has become a common research tool (Hoenink et al., 2020, Blom et al., 2021; Smit et al., 2021, Van Herpen et al., 2016) in non-neuroimaging studies, its use in fMRI research is still scarce and to the authors' knowledge no fMRI food choice tasks have been employed yet. Virtual reality induces feelings of presence (Witmer & Singer 1998) in the virtual environment (i.e., the supermarket) such that awareness of the actual physical situation (i.e., lying in an MRI scanner) is reduced. Research has shown that shopping behavior in virtual supermarkets is comparable to shopping behavior in a regular supermarket (Waterlander, Jiang, Steenhuis, & Mhurchu, 2015) and that food (compared to nonfood) stimuli elicit similar psychological responses in VR compared to real life (Van der Waal et al., 2021). However, a downside of virtual reality is that it may results in more noise and excessive visual input, thereby reducing the sensitivity for picking up effects of interest. For these reasons we here explored the potential of the NeuroShop, a novel virtual reality fMRI food choice paradigm. The NeuroShop could be regarded as a valid instrument if it enables detection of basic neural food valuation responses that are robustly found in previous studies employing standardized food choice tasks. To this end, we assessed if we could detect two previously established basic food valuation responses (e.g., Van Meer et al., 2017, Hare et al., 2011), namely 1) an association between the tastiness of the chosen product and vmPFC activation during choice, and 2) an association between the perceived healthiness of the chosen product and dlPFC activation during choice.

The second aim of this study was to assess the effect of a health goal prime on the neural activation during food choice in a realistic virtual food choice environment. We expected that the health goal prime would result in increased activation in the dlPFC during food choice, since increased activation in the dlPFC is seen in food choices after explicit health cues (Hare et al., 2011). In line with this, the first hypothesis was that food choices after a health goal prime would elicit stronger activation in dlPFC than food choices after a neutral or hedonic prime. The study also examined the effect of a health goal prime on preferences for healthy versus unhealthy products, compared with a hedonic prime and a non-food control prime. We expected that health goal primes would stimulate healthy food choices, in line with previous behavioral studies on health goal priming (e.g., Boland et al., 2013; Papies, 2016; Papies & Hamstra, 2010; Papies et al., 2014; Papies & Veling, 2013; Van der Laan et al., 2017). Therefore, our second hypothesis was that exposure to a health goal prime would result in more healthy food choices than a neutral or hedonic prime.

# Method

## Participants

The study sample consisted of 56 females (age in years: *M* = 22.4, *SD* = 4.0, BMI in kg/m²: *M* = 22.4, *SD* = 2.6). Participants were recruited through university subject pools and posters at the University of Amsterdam, VU Amsterdam, and Utrecht University for a study on the brain responses to visual food cues. Interested participants were sent a link to complete an online questionnaire on demographic information, dietary restraint (*M* = 2.6, *SD* = 0.7) as measured by the Dutch Eating behavior Questionnaire (Van Strien et al., 1986), and exclusion criteria. All participants were healthy, right-handed, and had normal or corrected-to-normal vision. Exclusion criteria were: neurological and eating disorders, gastro-intestinal disorders, diabetes, vegetarian or vegan diets, food allergies, medically prescribed diets, or a contraindication for Magnetic Resonance Imaging (MRI), such as pregnancy, claustrophobia, and irremovable metal in or on the body. Smokers or individuals using psychotropic medication were also excluded. Only women were included in the study because they have different neural responses to food cues compared to men (Chao et al., 2017). The study was approved by the Ethics Committee of the University of Amsterdam and participants' informed consent was obtained before the start of the study. Participants received €30 in gift cards as a compensation for their participation.

**Design**

The experiment had a within-subject design with three conditions: a health goal prime condition, hedonic prime condition, and non-food control condition. The hedonic prime condition served as an additional control condition, to increase the contrast with the health goal prime. While undergoing fMRI, participants performed a virtual supermarket food choice task (i.e., NeuroShop Choice Task) in which they chose between perceived healthy (PH) and perceived unhealthy (PU) food products.

**Procedure**

The study consisted of one session with a duration of approximately 100 minutes at the Spinoza Centre for NeuroImaging. Participants were asked not to eat or drink at least two hours before the session and to preferably have eaten a small meal 2.5 hours before the session. Upon arrival at the lab, participants completed a questionnaire on their current hunger level (e.g., "*How hungry are you at this moment?*", from 1 - *Not hungry at all* to 9 - *Very hungry; M* = 4.1, *SD* = 1.8). They also rated the tastiness of the food products used in the study (1 - *Not tasty at all* to 9 - *Very tasty*) on a computer. Next, participants entered the scanner. Participants first navigated through in the NeuroShop environment using a MRI compatible joystick, while the T1 MRI scan was being made. During the functional MRI, scan participants made food choices in the NeuroShop choice task, in which they were shown health goal prime advertisements, hedonic goal prime advertisements, and non-food advertisements. The NeuroShop environment and the NeuroShop choice task were presented on a screen at end of the bore of the MRI scanner, which participants could view through a mirror on the head coil. After the scan session, participants rated the healthiness of the study stimuli (1 - *Not healthy at all* to 9 - *Very healthy*). Lastly, participants completed the Igroup Presence Questionnaire (Schubert et al., 2001) that assessed how embedded they had been in the virtual supermarket (*M* = 3.14, *SD* = 0.50; α = .76). Further, participants were asked what they thought the aim of the study was. At the end of the experiment, participants were thanked, reimbursed, and debriefed.

**NeuroShop fMRI paradigm**

The NeuroShop fMRI paradigm consists of two applications, namely an environment that participants can freely navigate through and a standardized fMRI task. The NeuroShop environment has been evolved further into the VirtuMart virtual supermarket which has been used in non-neuroimaging food choice research and is evaluated by users as easy to understand and navigate through (Blom et al., 2021, Smit et al., 2021, Hoenink et al., 2020; Hoenink et al., 2021). The NeuroShop fMRI paradigm entails a computer-generated world displayed on a single screen that is experienced from a first-person perspective. In line with the definitions of Slater (2009), this implementation can be defined as non-immersive virtual reality (as opposed to ‘immersive VR’ which is displayed on a stereoscopic display or supports other sensorimotor contingencies).

**NeuroShop environment.** Participants navigated through the NeuroShop environment with an MRI compatible joystick for six minutes during the T1 MRI scan. Participants were instructed to walk around freely and explore the NeuroShop environment, which resembled a well-known Dutch supermarket and was designed with the 3D modeling software Blender by the first author (Figure 1). The purpose of this was to help participants become embedded in the supermarket environment and involved in the act of grocery shopping. All of the study’s food stimuli were displayed in 3D. The reported level of presence during the virtual shopping experience, based on the Igroup Presence Questionnaire (Schubert et al., 2001) was 3.14 (scale ranging from 1 to 5; higher is stronger presence). This can be regarded as a moderate level of presence and thus comparable to the reported levels of presence in other virtual supermarkets (Waterlander et al., 2015; Van Herpen et al, 2016).

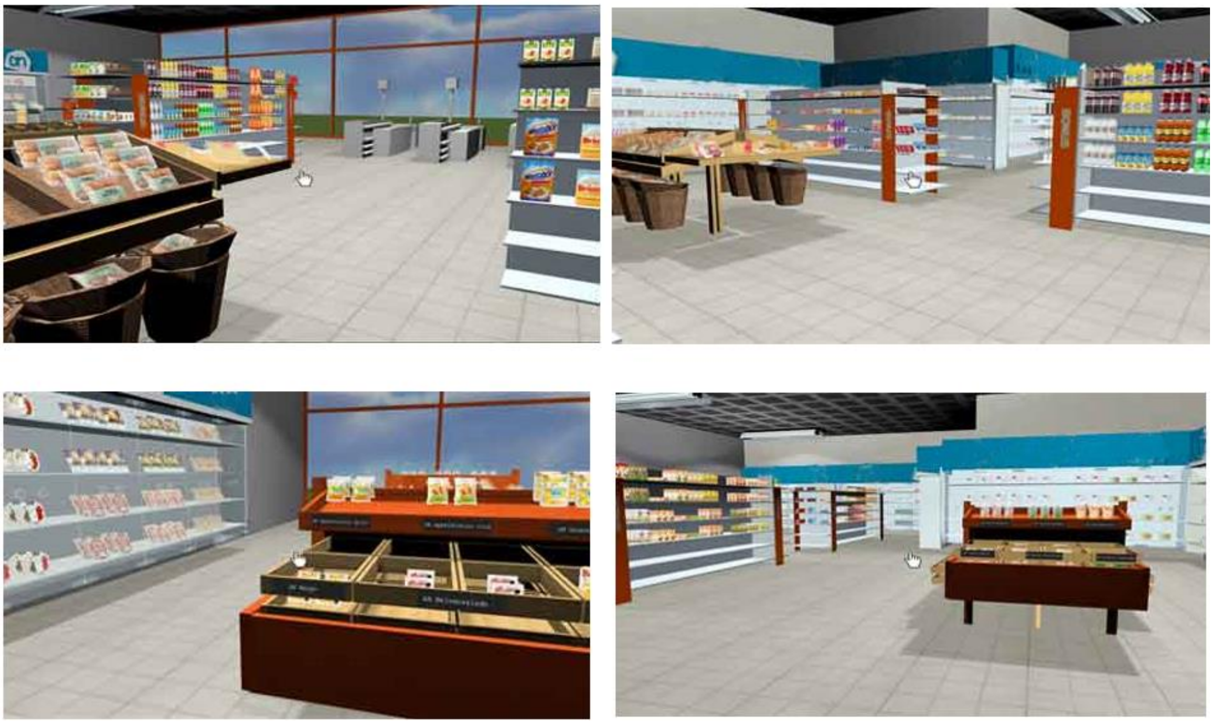

*Figure 1.* Screenshots of the NeuroShop environment

**NeuroShop choice task.** When the NeuroShop choice task started, participants first practiced the choice procedure with six choice screens containing non-food products. Participants were subsequently presented with 120 different choice screens that each displayed two products: one PH (perceived healthy) product and one PU (perceived unhealthy) product from the same category (e.g., meat, desserts, bread). These were the study stimuli that participants had also rated on tastiness. Participants were instructed to choose the product that they preferred, just as they would normally do when grocery shopping. They were instructed that they would be presented with several advertisements and movie clips of the NeuroShop environment to make the task resemble a regular supermarket visit as closely as possible. The movie clips depicted showed the process of navigating from one shelf to another in the NeuroShop. The purpose of showing the movie clips in the choice task was to keep embedding in the supermarket environment high. Participants indicated their product preference using an MRI compatible button box with four buttons, using their right index, middle, ring, and pinky fingers to indicate whether they had a "Strong preference for the top product", "Slight preference for the top product", "Slight preference for the bottom product", or "Strong preference for the bottom product" respectively. For half of the participants, the order of the response options was reversed. These responses were recoded such that for all participants, they reflect the relative preference for a PH product over a PU product: 1 = Strong preference for the PU product, 2 = Weak preference for the PU product, 3 = Weak preference for the PH product, 4 = Strong preference for the PH product.

The PH and PU product pairs on each choice screen were matched on tastiness for each participant, using the tastiness ratings for the products from each participant. Specifically, the products in each category were ranked from least to most tasty using a given participant's ratings. Next, products with equal ranks from paired categories were combined (e.g., the tastiest PH dessert was paired with the tastiest PU dessert for that participant). As a result, every participant was presented with choice screens that displayed products similar in tastiness. This was done to minimize the differences in pre-existing preferences between the products and thereby maximize the potential to detect health goal priming effects.

The task consisted of 12 blocks of 10 choice screens in random order. Four blocks were preceded by a health goal prime advertisement, four blocks by a hedonic goal prime advertisement, and four by a non-food advertisement, which means that each condition consisted of 40 choice screens. The conditions were randomly alternated throughout the task. The total duration of the task was approximately 24 minutes.

**Trial structure.** The trial structure is depicted in Figure 2. The first trial of each block started with the presentation of a 6000ms movie clip of the NeuroShop environment, followed by a fixation cross for 1s. Then, one of the primes appeared for 8s and a fixation cross for 4s.

Next, a choice screen was presented that displayed the food products on two shelves with three of each of the two products in a row (e.g., three PH products on the top shelf), to make the shelf look similar to those in a real supermarket. Participants had 4s to indicate their choice and once they pressed the button, the choice screen disappeared. The selected choice was briefly displayed on screen (0.5s), followed by a fixation cross with a random interval of 8-10s. The order of the choice screens was randomized, and the location (top or bottom) of the PU and PH products on the shelves was counterbalanced.

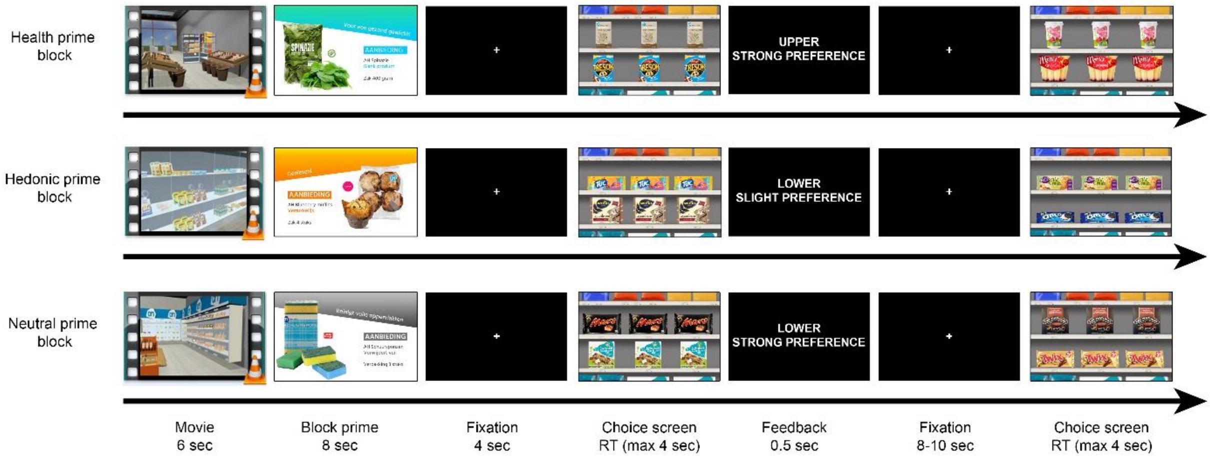


*Figure 2.* Trial structure of the NeuroShop food choice task.

**Stimuli**. The images of the products used in the NeuroShop fMRI paradigm were taken from the website of a major Dutch supermarket. All food products are commercially available in Dutch supermarkets. The selection of products contained well-known brands, as well as store-brand products. These were products from 20 product categories (e.g., desserts, bread, snacks (e.g., snack fruit) in which matched sets of PH and PU products were made. As a result, each PH product set contained six products matched with six products from a PU category. The PH products had a mean energy content of 206.3 kcal/100g (*SD* = 160.2) and the PU products had a mean energy content of 366.0 kcal/100g (*SD* = 177.2). Confirming the a priori categorisation of PH and PU products, PH products (*M* = 6.0, *SD* = 0.7) were rated as significantly higher on perceived healthiness than PU products (*M* = 2.9, *SD* = 0.7, t(55)

=36.6, $p < 0.001$). As intended, there were no significant differences in reported tastiness between the PH (*M* = 5.4, *SD* = 1.0) and PU products (*M* = 5.5, *SD* = 1.0, $t(55) = -0.7$, $p = 0.49$).

**Priming manipulation.** Twelve different advertisements were used for the priming manipulation, four for each condition. Example posters are depicted in Figure 3. The advertisements resembled those regularly used in supermarkets. Priming was accomplished through images, colours, words, and labels (Forwood et al., 2015).

Specifically, the health goal prime advertisements displayed a healthy product (e.g., spinach), the hedonic prime advertisements displayed an indulgent product (e.g., chocolate), and the non-food control advertisements displayed a non-food product that could be bought in a supermarket (e.g., clothespins), each on a white background. None of the foods used in the choice task were shown in the advertisements. Furthermore, one corner of the advertisements was coloured. The corners in the health goal prime advertisements had a blue to green gradient (associated with healthiness; Gelici-Zeko, Luters, Ten Klooster, & Weijzen, 2013; Van der Laan, De Ridder, Viergever, & Smeets, 2012), the hedonic goal prime advertisements had an orange to yellow gradient, and the non-food advertisements had a dark grey to light grey gradient. Some of the words in the advertisements varied according to prime condition, showing health-related words in the health goal prime condition (e.g., "healthy", "low in calories" (based on Papies & Hamstra, 2010; Papies et al., 2014), hedonic words in the hedonic prime condition (e.g., "enjoy", "delicious"), and food-unrelated words in the non-food control condition (e.g., "strong wood", "cleans the dishes"). One of these prime words was printed in bold and in a colour that corresponded to a colour from the gradient (i.e., blue, orange, or grey). Lastly, on each advertisement contained a label that varied according to condition, suggesting that it was a healthy choice (health goal prime condition), a limited offer (hedonic prime condition) or a “good buy” (control condition).


*Figure 3.* Examples of a health goal prime advertisement, a hedonic goal prime advertisement and a control prime advertisement[1].

**Behavioral data analysis**

The statistical program R was used for all statistical analyses (R Development Core Team, 2007). The relative preference for a PH product over a PU product was measured by preference ratings given during the fMRI task and analyzed with a one-way repeated

[1] Dutch language is used in the text of the stimuli. A prime or control word is presented in the top banner. 'Laag in calorieën' = 'Low in calories'; 'Gezellig samen snacken' = 'Snacking together', 'Houten wasknijpers' = 'Wooden clothespins'; 'gezond' = 'healthy'; 'Genieten' = 'Enjoy', 'Stevig hout' = 'Firm wood'. Other Dutch words employed in the stimuli are the names of the products and the word 'Aanbieding' = 'Discount'.

measures ANOVA that assessed the effect of Prime condition on the relative preference for PH products over PU products.

**fMRI data analysis**

**Image acquisition and preprocessing.** The fMRI data was acquired with a 3 Tesla scanner (Philips Achieva, Philips Health-care, Best, Netherlands) with a 32 channel head coil. A T1-weighted structural scan was acquired for each participant (TR = 8.2ms, TE = 3.9ms, flip angle = 8°, slices = 220, voxel size = 1x1x1 mm, total scan duration = 363s). A $T_2^*$-weighted echoplanar imaging (EPI) sequence was used for the functional scans (TR = 2000 ms, TE = 28 ms, flip angle = 76°, slices = 36, voxel size = 3x3x3 mm, volumes = 715, interleaved acquisition, field of view = 240 x 240 mm).

The preprocessing and analysis of the data was done with Statistical Parametric Software (SPM 12; Wellcome Department of Imaging Neuroscience, Institute of Neurology, London, UK) ran with MATLAB R2016A (The Mathworks Inc, Natick, MA). The default settings for preprocessing were used, unless stated otherwise. The functional data were corrected for differences in slice-timing. To correct for movement, the functional images were realigned to the first functional scan. Data from one participant was not included in the analyses because of excessive head movement. The functional data were coregistered to the structural scan and the structural and functional data were normalized to Montreal Neurological Institute standard space. Further, an isotropic Gaussian kernel of 6 mm full width at half maximum was applied to smooth the data. To remove slow drifts in the signal or other low frequency noise, the data were high-pass filtered with a cut-off of 128s.

**Participant level analysis.** For each participant, a boxcar function was fitted to the time series. These boxcar functions were convolved with the canonical hemodynamic response function. We fitted two models, one to assess the effects of the prime conditions, and one to explore the sensitivity of the virtual NeuroShop paradigm. In model 1, the following conditions were modeled in a General Linear Model (GLM) for each participant: the movies, the prime screens, the choice screens after a health prime, the choice screens after a hedonic prime, the choice screens after a non-food prime, and the feedback screens. The six motion parameters that were calculated during the realignment were added as regressors. To examine the effect of Prime Condition on brain activity during food choice a contrast image was calculated for each participant in which the mean brain response during choice screens after a hedonic prime was subtracted from that of choice screens after a health prime. Additionally, a contrast image was calculated in which the mean brain response during choice screens after a control prime was subtracted from that after a health prime. In model 2, the same conditions as in model 1 were modeled in a GLM for each participant. In addition, two parametric regressors were added to each choice screen, namely the rated healthiness (first parametric regressor) and rated tastiness (second parametric regressor) of the product chosen in that particular choice trial. The parametric regressors were based on the health and taste ratings the participant provided for the stimuli. To examine the relation between brain activity and the healthiness of the chosen product during food choice a contrast image was calculated for the parametric regressor of health ratings. To examine the relation between brain activity and the tastiness of the chosen product during food choice a contrast image was calculated for the parametric regressor of taste ratings.

**Group level analysis.** To establish the main effect of the health goal prime, the model 1 contrast images from every participant of choice screens after health prime vs. hedonic prime and choice screens after health prime vs. non-food prime were subjected to one-sample t-tests. The same was done for the contrast images of the parametric regressors from model 2.

The right dlPFC, the left dlPFC and the bilateral vmPFC were a priori Regions Of Interest (ROIs) because of their role in self-control (vmPFC) and the incorporation of health considerations in food choice (dlPFC; Hare et al., 2009; Hare et al., 2011). The dlPFC and vmPFC definitions of Gozzi and colleagues (2009), were employed. The three masks were generated using the AAL-atlas (Tzourio-Mazoyer et al., 2002) of the WFU-pickatlas toolbox (Maldijan, Laurienti, Kraft, & Burdette, 2003). First, the whole-brain correlation T-map threshold was set at $P < 0.001$ ($T > 3.25$), $k > 0$. Second, small volume correction was applied by using a statistical threshold of p<0.05 Family Wise Error (FWE) corrected (cluster level) over the respective ROI volume to correct for multiple comparisons.

# Results

## Behavioral results

**Validation of paradigm** We performed an exploratory set of analyses to assess how choice behaviors and ratings relate to hunger and dietary restraint. There was a weak negative correlation (r = -.28, t(54) = -2.17, p = .03) between hunger level and relative preference for PH products. This means that the higher the hunger level the higher the relative preference for PU products. This is in line with previous research showing that people have a preference for unhealthy / high energy foods when in a hungry state. Hunger was not meaningfully correlated with tastiness or healthiness ratings (tastiness ratings: r = .22, t(54)=1.69, p=.10; healthiness ratings: r = .12, t(54)=.88, p=.38).

There was no significant correlation between dietary restraint and relative preference for PH products (r = .14, t(54) = 1.06, p = .29). Also no significant correlation was found between dietary restraint and mean tastiness or healthiness ratings (tastiness ratings: r =.09, t(54)=.63, p=.53; healthiness ratings: r = -.07, t(54)=-.54, p=.59).

**Effects of goal prime conditions** Overall, participants showed no preference for PH or PU products, with a mean score of 2.5 (*SD* = 0.4) on a 1-4 scale. . This equals to an average of 49.2% of PH choices and 50.8% PU choices. A one-way repeated measures ANOVA with Prime Condition as factor (health prime, hedonic prime, and non-food prime) showed that the relative preference for PH products did not differ significantly between the three prime conditions, $F(2,110) = 0.08$, $p = .923$, which does not support Hypothesis 2. Additional exploratory analyses can be found in the supplementary materials.

**fMRI results**

**Validation of paradigm: Relation between brain activation taste and health ratings in the virtual NeuroShop paradigm (model 2)** The parametric modulator healthiness of the chosen product was not (positively or negatively) related to brain activation in any of the ROIs. The parametric modulator tastiness of the chosen product during choice screens was positively related with brain activation in the bilateral vmPFC ROI ($Z = 3.78$, MNI(-3 ,47, -4), cluster-level $P_{\text{FWE-corrected}} = 0.012$, cluster extent = 31 voxels) (see Figure 4). No clusters of brain activation relating to tastiness were found in the other ROIs. Also, no negative relations with parametric regressor tastiness were found in any of the ROIs.

**Effects of goal prime conditions (model 1)** Comparing activation during choice screens after health primes vs. hedonic primes and health primes vs. non-food primes did not reveal clusters in the ROIs that were significantly more activated as a result of the health goal primes. This does not support Hypothesis 1.

The hypotheses of the current study concern only the vmPFC and dlPFC and the contrasts of interest above. For completeness and to enable future meta-analysis, we also report whole brain results at a statistical threshold of $p < 0.001$ uncorrected and a cluster extent $k \geq 10$ voxels, in the Supplemental Results.

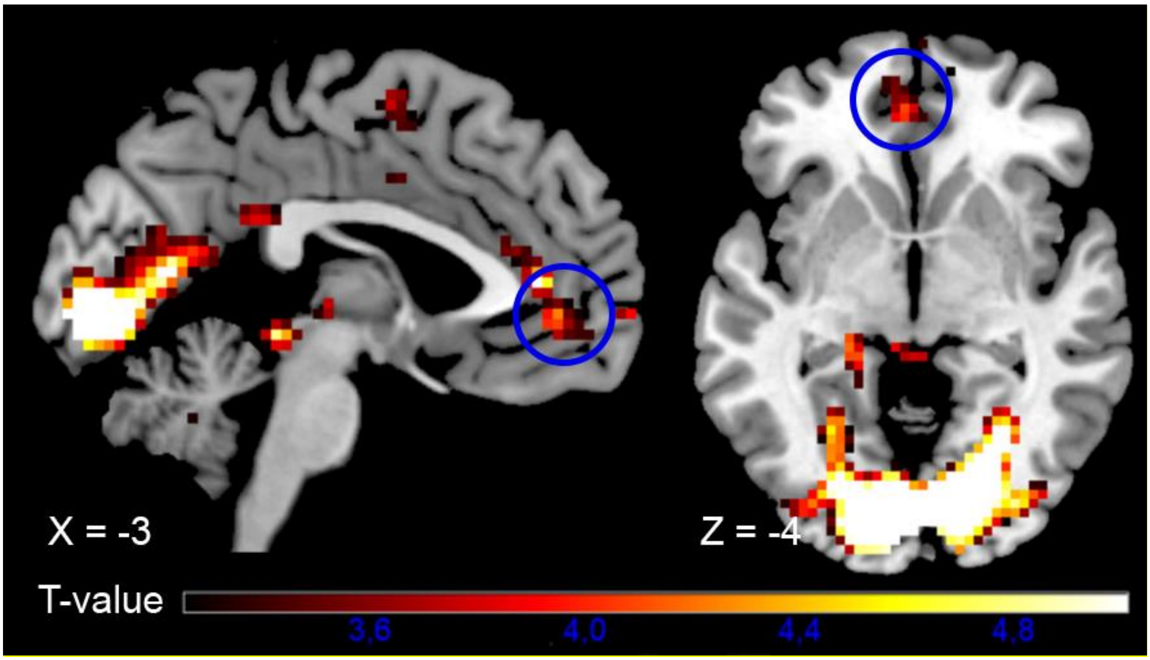


*Figure 4.* The parametric modulator tastiness of the chosen product during choice screens was positively related with brain activation in the bilateral vmPFC ROI. Cluster in vmPFC is circled in blue. For visualization purposes, fMRI results are thresholded at $T > 3.25$.

# Discussion

## Validation of VR fMRI paradigm

The first aim of this study was to explore the potential of virtual reality to be employed in food-related neuroimaging. Virtual reality gives the opportunity to create an ecologically valid choice context in the lab and for this reason it is already commonly employed in behavioral research (Hoenink et al., 2020, 2021; Blom et al., 2021, Smit et al., 2020, Van Herpen et al., 2016). The potential of virtual reality was particularly coined for fMRI research as it may help to suppress the actual situation (lying in an MRI scanner) in favor of the virtual situation (the virtual supermarket; Smeets et al., 2019). Therefore, we here designed a paradigm in which participants first had the opportunity to explore the virtual environment freely (during the T1 scan), to become embedded in the environment. Next, they performed the standardized choice task, which still was interspersed with movies from the virtual supermarket, to restore the embedding. The reported level of presence in the virtual environment was moderate and thus in line with non-neuroimaging studies employing virtual reality (Waterlander et al., 2015; Van Herpen et al, 2016).

As a first exploration of the potential of virtual reality for studying food-related neuroimaging we investigated if the tastiness and healthiness ratings of products relate to the same areas as was found in previous fMRI studies not employing virtual reality. Studies employing traditional fMRI food choice tasks correlate health and taste ratings to brain activation to assess the role of these attributes in food choice (e.g., Hare et al., 2009, 2011; Van Meer et al., 2017). Indeed, in line with earlier (non-virtual reality) studies (and meta-analyses) showing that the value or taste of the stimulus under consideration is reflected in the signal in the vmPFC (Bartra, McGuire and Kable, 2013, Van Meer et al., 2017), we also here found that the tastiness of the chosen stimulus related positively to activation in the vmPFC.

No relation between brain activation in ROIs and healthiness ratings was found in the present study. It should be noted that the correlation of healthiness ratings with dlPFC in previous studies has been reported specifically in a condition in which subjects were explicitly instructed to ‘choose naturally’. In the current study, we did not use such instructions which may explain why we did not find this effect.

Our exploratory analyses of the task behavior revealed that hunger had a (weak) negative correlation with the relative preference for PH products. This is in line with previous research showing that people have a preference for unhealthy / high energy foods when in a hungry state. In sum, the novel virtual NeuroShop fMRI paradigm can be used to detect basic vmPFC valuation processes but further research is needed to assess if it is also sufficiently sensitive to pick up dlPFC and intervention-induced effects on choice.

**Goal priming**

The second aim of the present study was to examine the neural correlates of health goal priming effects on food choice. The behavioral results of the study showed that in the whole sample, participants had no preference for perceived healthy products or unhealthy products, and this was not influenced by the health goal prime. There was also no direct support for the hypothesis that increased activation in the dlPFC would be observed during food choices after a health goal prime compared to food choices after a hedonic or non-food prime.

**Behavioural goal priming findings** Contrary to our second hypothesis, the health goal prime did not result in significantly healthier food choices. This finding contrasts with previous studies that have shown that health goal primes can stimulate healthy food choices and activate an individuals' health goal (e.g., Van der Laan et al., 2017; Papies, 2016; see Buckland et al., 2018, for a meta-analysis). Moreover, a recent meta-analysis of priming effects across domains (Weingarten et al., 2016) showed that goal priming effects are robust and show little evidence for a publication bias.

Not finding an effect of the health goal primes was unexpected given previous experiments showing that health goal primes increased healthy choices. The food choice task was designed to be as sensitive as possible to detect small differences in preference for perceived healthy products. That is, every choice pair was matched on tastiness for each participant to avoid large differences in tastiness which may overrule subtle priming effects. The task also used a multi-item response scale (instead of a binary choice) to detect subtle differences in preference. Moreover, study design, primes (colors, words), and task were based on previous health goal priming studies that showed priming effects on behaviour Papies et al., 2014), and presented the primes just before the decision moment, as in previous studies. It is therefore unclear why no behavioral priming effects were found here.

One possible explanation might lie in the products used. Some health goal priming studies only assessed effects on certain food products, such as snacks, that tend to be unhealthy and provide discretionary calories (e.g., Anschutz et al., 2008; Papies et al., 2014; Versluis & Papies, 2016). The present study used a range of different products, including essential grocery items (e.g., snacks, breakfast products, dinner products, drinks; see also Van der Laan and colleagues 2017). Future research should examine whether health goal priming has a differential effect on different food categories, such as snacks and breakfast products.

It is also possible that the within-subjects design of the current study resulted in carryover-effects. That is, the effect of the short-term goal of enjoying tasty food might not have been completely worn off by the time the long-term goal of weight control was activated, and vice versa. However, previous research with primed lexical decision tasks has successfully used a within-subjects design (Kroese, Adriaanse, Evers, & De Ridder, 2011). Furthermore, Hare and colleagues (2011) also used a within-subjects design with health, taste, and natural blocks consisting of 10 trials, and they found that healthier food choices were made after an explicit health cue.  The explicit health instructions, however, might have made it easier for participants to switch between blocks than with our cues, which were more implicit. Even though the majority of the health goal priming studies have been performed with a between-subjects design, (e.g., Boland et al., 2013; Papies, et al., 2014; Papies & Veling, 2013; Van der Laan et al., 2017), it does not seem likely that the within-participants design can fully explain the current null findings, since within-subjects designs have been successfully used in earlier studies.

Another possible explanation for the absence of a behavioral main effect of the priming condition is statistical power. Previous behavioral health goal priming studies have typically had sample sizes of 100 participants or more (e.g., Anschutz et al., 2008; Boland et al., 2013; Papies & Hamstra, 2010), compared to 56 participants in our fMRI study.

Furthermore, several studies have reported that the effect size of health goal priming is small (e.g., Buckland et al., 2018; Papies et al., 2014; Versluis & Papies, 2016; Weingarten et al., 2016), it is possible that the sample of the present study was too small to detect a behavioral effect of the goal prime. The meta-analysis by Buckland and colleagues (2018) even suggests that the main effect of goal prime is negligible, and that a health goal priming effect only really emerges among participants with a strong health and weight control goal. Indeed, it has been argued that goal priming effects rely on existing motivational structures and will therefore only be effective among participants who strongly value the primed goal (Papies, 2016). Since the present experiment was not powered to detect such an interaction with existing goals, it cannot be ruled out that priming effects occurred among motivated participants. Importantly, the aim of the present study was not to replicate the behavioral effect of health goal priming, but to examine the neural correlates of health goal priming in food choice. For these reasons, the goal primes could possibly still have had an effect on the neural correlates, though the effect was not strong enough to produce a behavioral effect. With the small sizes inherent to neuroimaging research, null findings for behavioral effects are more often observed because brain activation is more proximal to the causal mechanistic process than is behavior.

**Neuroimaging goal priming findings** In line with the behavioral null findings, also no differences in vmPFC and dlPFC activation were found between the conditions. The absence of the expected behavioral effect may have resulted in finding no differences in the neuroimaging measures as well. Thus, the current results do not support but do also not rule out the hypothesis that dlPFC activation would be stronger during food choices after a health goal prime compared to food choices after a hedonic or non-food prime. The dlPFC is known for its role in cognitive control and inhibition (Menon, Adleman, White, Glover, & Reiss, 2001; Ridderinkhof, Van den Wildenberg, Segalowitz, & Carter, 2004), and is important for top-down attentional processes as well (MacDonald, Cohen, Stenger, & Carter, 2000; Miller & Cohen, 2001). These attentional and inhibitory control processes are needed to select responses or actions congruent with a long-term goal, while it competes with tempting alternatives satisfying short-term goals (Ridderinkhof et al., 2004), which is often the case in food choices.

Previous research with more explicit health cues has indeed shown that increased dlPFC activity is associated with self-control in food choice (Hare et al., 2009). Furthermore, Linder and colleagues (2010) found increased activity in the dlPFC in response to food products with an organic label, which is often perceived to signal healthiness, compared to a conventional label. A label on the product shelf is more distinct than a prime advertisement shown a few moments prior to the moment of choice. Though the null finding in the present study may have resulted from the lack of a behavioral effect, an alternative explanation could be that health goal primes, which are more implicit than the explicit cues used in the studies mentioned above, trigger no or weaker responses in the dlPFC.

**Strengths and limitations**

The present study has some important strengths. First of all, because of the highly realistic virtual environment, it assessed neural responses during food choices under much more realistic conditions than fMRI-paradigm in previous studies on food choice (Hare et al., 2009; Hare et al., 2011). Participants first navigated through the virtual supermarket to become embedded in the supermarket environment, and regularly saw movie clips of the supermarket during the choice task. Furthermore, the food choices in the present study are more comparable to choices made in daily life, since the largest part of the household budget for food is spent in the supermarket. The food categories were also matched in order to ensure comparable food choices in each trial (e.g., a choice between two snacks, or a choice between two desserts).

A limitation of the present study is that it did not control for the possible role of brands and shopping habits in participants' choices. It is possible that participants simply chose the product they usually buy and are most familiar with. However, the task was optimized to detect subtle effects of the primes since every product pair was matched on tastiness. Another limitation is that some of the participants, who were primarily students, might have chosen for the product they thought was the cheapest. The task specifically did not include price information to limit the influence of price on food choice, but since the store brand is usually the cheaper option, some participants might have based their choice on this information. Moreover, a broad range of products and brands from varying price ranges were included in the task in order to make the choice situations comparable to those in a real supermarket.

Eating behavior is heavily affected by social norms, or by what is perceived as appropriate behaviour in a given context. Therefore, as with all studies prompting participants with behavior that could be valued as socially (un)desirable, social desirability could have affected participants' behaviour. Specifically, their choices may have been affected by motivations to display desirable behaviours and give a positive impression of themselves. In this study, this would mean a general bias towards healthier choices. However, no such pattern was detected, which speaks against the presence of strong social desirability effects. In addition, it seems unlikely that the specific correlation of vmPFC activation during food choice with tastiness can be explained by social desirability.

To conclude, the present study is the first that examined the neural correlates of health goal priming in food choice with a novel virtual reality fMRI paradigm. The results do not support or rule out the role of regions involved in self-control (vmPFC, dlPFC) in the driving mechanism behind health goal priming. Nevertheless, the study did show that virtual reality can be employed in food-related fMRI research.

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**Data and code availability statement**

The author is willing to share data and code upon request.

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**Conflict of interest statement**

The authors declare no conflicts of interest.

**Ethics statement**

The study was approved by the Ethics Committee of the University of Amsterdam and participants' informed consent was obtained before the start of the study.

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