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Role of Alpha Oscillations in Reweighting
Multiple Attributes During Choice

A Thesis Presented

by

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Of Claremont McKenna, Pitzer, and Scripps Colleges

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Abstract

In our everyday lives, we must often weigh the different attributes of items in order to select the item that best fits our current goals, allowing us to make optimal decisions. Construal Level Theory proposes a psychological mechanism for re-weighting attributes, utilizing selective attention as the process by which we implement self-control. It has been hypothesized that switching attention between attributes is facilitated by the suppression of cortical oscillations over posterior brain regions within the alpha (8-12 Hz) frequency range. To test this idea, we re-examined previously collected whole-brain electroencephalography (EEG) data from a dietary choice experiment in which participants made decisions naturally or with a weight loss incentive. Prior analysis found that although hungry subjects primarily relied on taste properties while responding naturally, they increased their behavioral and neural weighting of health when motivated to lose weight. Reanalyzing this data using time-frequency analyses, we compared alpha oscillations related to healthy versus unhealthy foods under natural and self-control conditions. We predicted that when participants exercised self-control we would see suppression of alpha oscillations over occipital sensors starting around 400 ms post-stimulus onset, for trials presenting healthy relative to unhealthy foods; no such suppression should appear during natural responding when ignoring health information. Consistent with our hypothesis, we found a significant decrease in alpha oscillations over occipital sensors between 440 and 800 ms post-stimulus onset for healthy compared to unhealthy items in the self-control condition. No such effect was seen for health information in natural choice, or for taste. Our findings extend previous research by linking alpha band suppression to the neural re-weighting of multiple attributes, suggesting a neuro-cognitive mechanism for self-control that uses selective attention to choose between multiple attributes.

Introduction

Throughout the course of everyday life, people are often presented with situations in which they must weigh multiple attributes of an object in an attempt to select the object that best fits their current goals. For example, when choosing whether or not to eat a piece of chocolate cake, a person could look at the distinct attributes of the cake: for example, how tasty it is versus how healthy it is. In this example, the chocolate cake would normally be deemed very tasty, but not very healthy. A choice to eat the chocolate cake would reflect the individual's increased weighting on the taste over the health of the food, whereas someone on a diet would most likely choose not to eat the chocolate cake. Individuals weight the importance of different attributes by mentally assigning values to specific attributes based on their current goals (Bettman et al., 1998).

So how are different attributes, such as health and taste, differentiated during the decision-making process? While the outcomes of dietary decisions are easy to observe, the underlying psychological mechanism that mediates multi-attribute decision-making is still not fully understood. One psychological model that suggests a possible mechanism for multi-attribute decision-making is Construal Level Theory (CLT) of psychological distance (Trope & Liberman, 2003; Liberman & Trope, 2008). CLT proposes that people use their perceived psychological distance to an object to create a mental representation of that object. Psychological distance is the cognitive concept of how far away an object is perceived to be in space, time, or probability of occurring.

The main concept of CLT is that people represent the world around them at different levels of construal (Liberman and Trope, 1998). Liberman and Trope (1998) propose that people use higher-level construals when attempting to represent more abstract or temporally

distant ideas or features. Higher-level construals are necessarily more abstract because people cannot know all possible future outcomes, and must be able to adjust their actions accordingly when new information becomes available. In contrast, people use lower-level construals when representing information that is temporally closer and more concrete (Trope & Liberman, 1998).

Returning to the example of chocolate cake, we can use the idea of construal to represent the attributes of taste and health. Taste is necessarily a lower-level construal because it is based on concrete features of food. People know almost immediately whether or not they find the taste of a familiar food pleasing, off-putting, or bland. Health is harder to mentally represent as it is not a salient feature of food, and must be determined by the potential to fulfill dietary needs. Additionally, choosing a healthy option often involves weighting long-term benefits over short-term gratification (Chapman and Elstein, 1995). Therefore, health can be considered a higher-level, more abstract construal. Consistent with this idea, recent evidence suggests that taste attributes affect food choices nearly 200 ms before health information, indicating that health information requires a longer and more complex recognition and valuation process (Sullivan et al., 2015).

Therefore, when choosing whether to eat a food, people may assign differing weights to attributes of tastiness and healthiness, depending on whether their current goal is sensory gratification or losing weight. At the cognitive level, this change in construal may be implemented through shifts in selective attention. Selective attention is the ability to actively focus on a chosen stimulus while simultaneously ignoring other irrelevant stimuli (Duncan, 1984; Moran & Desimone, 1985; Bollimunta et al., 2011; Payne et al., 2013; Payne & Sekuler, 2014). In the domain of dietary choice, changes in exogenously directed attention

have been associated with shifts in decision-making towards selecting healthier food options (Hare et al., 2011). When participants were explicitly instructed to consider the health attributes of different snack foods, they made healthier dietary choices, even though they were free to choose whichever foods they wanted (Hare et al., 2011).

In the same study, Hare and colleagues used functional magnetic resonance imaging (fMRI) to show that this increased responsiveness to the healthiness of foods was associated with changes in the neural correlates of value. This suggests that there is a mechanism for value modulation reliant upon attentional switching. In particular, their results join previous research in pointing to separable roles of two distinct regions within the prefrontal cortex, the ventromedial prefrontal cortex (vmPFC) and the dorsolateral prefrontal cortex (dlPFC), in value computation versus attention and self-control.

Neural Basis of Valuation and Self-Control

Given that people are capable of re-weighting different attributes of a stimulus depending on their current goals, one question is how this process is represented at the neural level. Previous research has identified an area within the frontal lobes, the prefrontal cortex (PFC), as playing important roles in both valuation and decision-making (Mitchell, 2011).

The prefrontal cortex is located just behind and above the eyes in the most forward part of the frontal lobe. This region has numerous anatomical connections to other brain regions such as visual, auditory, somatosensory, and motor cortices (Miller & Cohen, 2001). These inter-regional connections allow the PFC to exercise cognitive control; integrating signals from different brain regions and producing goal-directed behavior (Miller & Cohen, 2001). The production of goal-directed behavior is necessary for action-maintenance, the

process by which people actively adjust their behaviors to match their current goals (Miller & Cohen, 2001).

Two specific regions of interest within the PFC are the ventromedial prefrontal cortex (vmPFC), responsible for encoding stimulus values, and the dorsolateral prefrontal cortex (dlPFC), associated with the implementation of cognitive control (McClure et al., 2004; Padoa-Schioppa & Assad, 2006; Hare et al., 2009; Fellows, 2011; Harris et al., 2013; Hare et al., 2014). Recent evidence suggests that the encoding of stimulus values can be modulated by cognitive control regions during the exercise of self-control, thus allowing for goal-directed decision-making.

Ventromedial Prefrontal Cortex

The vmPFC is located on the ventral (bottom) and medial (inner) part of the frontal cortex. This brain region is connected to, and has been functionally linked with sensory areas, such as visual and auditory cortices, medial temporal regions involved in memory, and with cognitive control regions within the prefrontal cortex. This linkage to numerous other brain regions allows the vmPFC to assign value to stimuli along multiple attributes, producing a unique stimulus value depending on sensory features, learned preferences, and current goals (McClure et al., 2004; Kable & Glimcher, 2007; Hare et al., 2008).

Evidence for the role of the vmPFC in subjective value computations comes from a growing literature associating the vmPFC with the encoding of stimulus values during decision-making (McClure et al., 2004; Fellows & Farah, 2005; Padoa-Schioppa & Assad, 2006; Kable & Glimcher, 2007; Plassmann et al., 2007; Hare et al., 2008). These studies cover a wide range of methodologies, including electrophysiological recordings from

monkeys, studies of patients with frontal lobe damage, and human neuroimaging experiments.

Monkey electrophysiology studies provide initial support for the idea that the vmPFC encodes independent subjective values for available options (Padoa-Schioppa, 2006; Kennerly et al., 2011; Luk and Wallis, 2013). In monkeys, the OFC has been found to encode values for potential outcomes during decision-making when monkeys chose between differing amounts of juice as their reward (Padoa-Schioppa & Assad, 2006; Kennerly et al., 2011). Luk and Wallis (2013) were able to confirm the results of Padoa-Schioppa and Assad (2006), finding that the OFC in monkeys is responsible for the valuation of stimuli during stimulus-guided decision-making.

By examining brain-damaged patients, researchers have found that damage to the vmPFC contributes to deficiencies in value-based decision-making in humans (Fellows & Farah, 2005; Fellows, 2007). Patients with lesions to the vmPFC demonstrate an impaired ability to perform value-based judgments (Fellows & Farah, 2005; Henri-Bhargava et al., 2012). Likewise, Camille et al. (2011) found that patients failed to show value-maximizing behavior in economic discrimination tasks when compared to healthy control subjects. These results suggest that people with damaged vmPFCs have difficulty constructing or “interpreting” the value of potential outcomes as well as the likelihood of that outcome occurring (Hsu et al., 2005).

Supporting the findings of monkey electrophysiology experiments and patient studies, neuroimaging research has demonstrated that the vmPFC plays an active role in the construction of stimulus values (Kable & Glimcher, 2007; Plassmann et al. 2007; Hare et al., 2008). Activity in the vmPFC reflects the perceived riskiness of monetary gambles (Tom et

al., 2007) and decreases with increased delay of rewards (Kable & Glimcher, 2007). It also correlates with people's stated willingness-to-pay for foods (Plassmann et al., 2007), charitable donations (Hare et al., 2010), and common consumer goods (Chib et al., 2009). These data suggest that the vmPFC plays an important role in integrating the subjective value of an option across individual stimulus attributes.

Consistent with this idea, experiments using event-related potentials (ERPs) and magnetoencephalography (MEG) have found evidence for the construction of stimulus values beginning approximately 400 ms after stimulus onset (Harris et al., 2011; Hunt et al., 2012). For example, Harris et al. (2011), using a dietary choice task, were able to localize the production of value signals to regions including the vmPFC. Posterior brain regions showed connectivity with the vmPFC, signifying that a larger neural network, beyond just the vmPFC, may be responsible for value computation (Harris et al., 2011). This finding suggests that different brain regions may feed stimulus information to the vmPFC, but that the vmPFC is ultimately responsible for the integration of information into a single overall value signal.

Dorsolateral Prefrontal Cortex

Located on the dorsal (upper) and lateral (outer) surface of the frontal lobes, the dlPFC, like the vmPFC, is interconnected with many other brain regions. Specifically, the dlPFC is linked with temporal and parietal cortices, and has been associated with value-based decision-making (Hare et al., 2009; Mitchell, 2011). While the vmPFC is responsible for the formation of stimulus value signals, activity in the dlPFC has been linked to the modulation of these value signals. This modulation suggests the dlPFC may play a role in a cognitive

control mechanism through which attentional processing may be regulated (Camus et al., 2009; Hare et al., 2009; Hare et al., 2014).

The role of the dlPFC can be separated into two distinct functions. The first is the modulation of attention and memory, redirecting attention away from irrelevant stimuli when they do not align with current goal values (Camus et al., 2009; Hare et al., 2011; Harris et al., 2013). The second is the facilitation and implementation of action regulation through self-control (McClure et al., 2004; Hare et al., 2009; Hare et al., 2014). These functions allow the dlPFC to contribute to cognitive regulation, both indirectly via sensory suppression and directly by modulating value signals in support of people's current goals (McClure et al., 2004; Hare et al., 2009; Harris et al., 2013; Hare et al., 2014).

Further support for the role of dlPFC in self-control is presented by Hare et al. (2009), who examined brain activity in self-reported dieters during a dietary choice task. Self-control was demonstrated through subjects' decisions to not eat tasty foods that were unhealthy, instead selecting healthy, but less appealing foods. Dividing subjects on the basis of their self-control success, Hare et al. (2009) found that successful dieters showed greater activity in the dlPFC, and that this activity was negatively correlated with activity in the vmPFC; this suggests that the dlPFC is able to modulate the stimulus value signals produced by the vmPFC.

In a follow-up study, Hare and colleagues further demonstrated that this modulatory function of the dlPFC could be manipulated through external cues to shift attention (Hare et al., 2011). In their experiment they had two separate conditions where subjects were instructed to focus on different attributes of the food items: either health or taste. When subjects were cued to focus on the healthiness of the food, they showed an increased

weighting on health in their dietary choices, compared to their natural responses (Hare et al., 2011). As in their previous study, vmPFC value signals were modulated by the dlPFC, supporting this region's role in the modulation of stimulus values (Hare et al., 2011).

ERP Correlates of Self-Control

Although previous studies of valuation and self-control have identified the vmPFC and dlPFC in these processes, the timing and neural correlates of activity in these regions have not been as fully addressed. The main reason for this is the poor temporal resolution of standard functional neuroimaging techniques. One solution to this problem is to use the high temporal resolution of electroencephalography (EEG) to measure the timing of neural activity during decision-making and self-control tasks. In particular, event-related potentials (ERPs) reflect the neural activity related to specific cognitive events, such as the onset of a stimulus or preparation for a response, and can be time-locked to specific cues within an experiment.

Harris et al. (2013), like Hare et al. (2011), looked at the differences in ERP responses while subjects made multi-attribute dietary decisions. However, Harris and colleagues did not cue subject to attend to the taste or health of food items, instead allowing subjects to self-determine which attributes they would focus on during their choices. Subjects made dietary decisions naturally (natural condition, NC) and with a monetary incentive to lose weight (self-control condition, SCC). They found that during the natural condition subjects relied primarily on the taste attribute of the food to make their decisions. However, when a monetary incentive to lose weight was imposed, subjects changed their weighting of

the different stimulus values by increasing their attention to the health attribute of the food while deciding whether or not to eat the different food items (Harris et al., 2013).

This change in selective attention, and subsequent reweighting of attributes, was found to occur between 400 and 650 milliseconds (ms) post-stimulus onset. Furthermore, this representation of attribute reweighting was localized to the vmPFC (Harris et al., 2013). In order to look for other brain regions associated with the change in attribute weighting, Harris et al. (2013) performed a causal connectivity analysis, finding a causal connection from the dlPFC to the vmPFC within the 400 – 650 ms post-stimulus onset time window. This causal connection between the dlPFC and vmPFC indicates that the two brain regions work in a cooperative fashion to shift attention between attributes, depending on current goals.

Cortical Oscillations as a Neural Mechanism for Selective Attention

It has now been established that the vmPFC is responsible for the formation of stimulus values and that these values can be regulated by activity in the dlPFC. The regulatory action by the dlPFC allows people to exercise self-control by shifting their attention between stimulus attributes, such as the taste and health properties of food (Hare et al., 2011; Harris et al., 2013). However, while the consequences of selective attention and attribute reweighting have been observed, the underlying neural process is not as well understood. One possible neural mechanism that could be responsible for producing selective attention is cortical oscillations (Fries et al., 2001; Bauer et al., 2006). Cortical oscillations are patterns of neuronal firing, measured in hertz (Hz), which involve populations of neurons firing in conjunction with one another, also known as synchronized firing (Engel et al., 1991;

Fries et al., 2001; Bauer et al., 2006). The increases and decreases in synchronized oscillation are measured using power, or amount of energy at a specific oscillation frequency.

Fries and colleagues (2001) examined changes in cortical oscillations in visual area 4 (V4) of macaque monkeys while they were directed to attend to relevant stimuli and ignore irrelevant ones. In addition to increases in gamma (35-90 Hz) oscillations, they also found that increased attention reduced low-frequency oscillations (~10 Hz) within V4, the range of the so-called alpha band (8-12 Hz). One possible explanation for the decrease in low-frequency oscillations within V4 is that when an attend-stimulus is registered by a population of neurons, the synchronized firing of those neurons may in turn activate interneurons, which have an inhibitory effect on neurons receiving distracting inputs (Fries et al., 2001).

This finding of “alpha suppression” to attended stimuli has been replicated repeatedly using EEG (Bauer et al., 2006; Payne et al, 2013; for a review, see Payne & Sekuler, 2014). Bauer et al. (2006) had participants attend and ignore different tactile stimuli, finding that suppression in alpha oscillations was due to a selective increase in participant attention to relevant stimuli. The increase in attention to relevant stimuli was coupled with a decrease in attention to irrelevant stimuli (Bauer et al., 2006). They found this effect occurred over parieto-occipital sensors between 150-400 ms post-stimulus in the unattended condition and between 150-600 ms post-stimulus in the attend condition. The duration of alpha suppression was found to increase with increased attentional durations, providing evidence for the connection between selective attention and alpha suppression (Bauer et al., 2006). Similarly, Payne et al. (2013) compared alpha power when participants were cued to attend or ignore different stimuli. They found that alpha power became significantly decreased in the attend condition compared to the ignore condition beginning around 500 ms post-cue. Together,

these data support the idea that alpha suppression is important for people's ability to selectively attend to relevant stimuli.

Explaining Multi-Attribute Choice through Attentional Oscillations

Harris et al. (2013) found that when hungry subjects made dietary choices naturally they relied heavily on their valuation of the taste attribute of a food item, choosing to eat tasty instead of healthy foods. However, this behavior changed during the SCC when subjects were monetarily incentivized to lose weight. Subjects in the SCC selectively attended to the health attribute of the food items, forgoing tasty options in favor of the healthier foods. This change in selective attention is thought to reweight the value signals in the vmPFC, and is supported by the fact that subjects preferentially selected healthy foods in the SCC (Harris et al., 2013). This preferential selection of healthy foods was correlated to an increase in the ERP signal associated with healthy food items in the SCC versus the NC. However, it is also important to note that Harris et al. (2013) found no significant difference in weighting of ERP data for the taste attribute between the NC and SCC.

The lack of change in the ERP weighting for the taste attribute of food between conditions indicates that subjects did not suppress taste information; rather they selectively focused their attention on the health attribute of food when making decisions in the SCC (Harris et al., 2013). Based on this finding, it is thought that depending on the condition, subjects can exercise self-control by changing their weighting of different stimulus attributes in order to make dietary choices that are consistent with their current goals.

Given that subjects can reweight different attributes to fit their current goals by selectively attending to them, one question is how this is accomplished at the neural level

during multi-attribute choice. As described above, changes in selective attention have been linked to the suppression of cortical oscillations within the alpha band, shown by decreases in alpha power over occipital sensors (Payne et al., 2013). The suppression of cortical oscillations within the alpha band is thought to be associated with increased attention to goal-specific stimuli. If this is the correct mechanism by which stimulus values of attributes are reweighted, it would follow that increased alpha suppression should be seen in trials that necessitate the use of self-control.

Predictions

We predicted that changes would be observed within the alpha band during trials that required the use of self-control, as increased attention to stimuli has been shown to produce a decrease in alpha power. Because of the increased weighting given to health in this experiment, we predicted that there would be greater attention to health attributes during self-control. This increased attention to health would correspond to a decrease in alpha power during trials in which a food previously rated healthy was presented, compared to when the presented food had previously been rated unhealthy. Specifically, we only expected to see a decrease in alpha power for health during self-control, because during natural choice subjects relied heavily on their taste rating to make decisions. Because subjects focused their attention on different attributes during different conditions, we expected to see an interaction of session (natural vs. self-control) and attribute (taste vs. health). Consistent with Harris et al. (2013), we predicted that the effects of alpha suppression would begin around 400 to 650 ms post-stimulus, as this temporally correlates with the valuation modulation found in the vmPFC (Harris et al., 2013).

Methods

Experimental Procedure

The present study consists of a re-analysis of an EEG experiment previously conducted by Harris et al. (2013). In this experiment, EEG and behavioral data were collected from participants while they performed a dietary decision-making task in two separate experimental sessions: the natural condition (NC) and the self-control condition (SCC).

Both sessions were broken up into three individual blocks. The first block was performed prior to collecting EEG data. Subjects were asked to rate 200 appetitive snack foods for both tastiness and healthiness using a four-point scale (1 = Strong-No, 2 = Weak-No, 3 = Weak-Yes, 4 = Strong-Yes). To control for hunger, participants were asked to fast for 2 hours before the experiment. Harris et al. (2013) had subjects complete a self-reported hunger assessment, and excluded any participants whose ratings suggested that they were not hungry at the time of the experiment.

In the second part of the experiment, EEG recordings were made while subjects performed a dietary choice task. Subjects were shown each of the 200 previously rated food items one at a time and were asked to decide whether or not they wanted to eat the food. Once again, subjects used the four-point scale in their responses. The purpose of this scaled response was to allow for measurements of both choice (yes/no) and strength of their choice (strong/weak) (Harris et al., 2013). During this second block, subjects were asked to make dietary decisions in three experimental runs, each time being presented with all 200 food items, for a total of 600 trials.

After subjects finished the decision-making phase, a food item was chosen at random from the 200 food items. If the subject had responded with a Strong- or Weak-Yes to the food item in at least two of the three experimental runs then subject was required to eat some of the food. If the subject had responded with two or more Strong- or Weak-No responses to the food, then he or she did not eat the food. Regardless of whether the subjects did or did not eat the selected food item, they were required to stay in the lab for thirty minutes after the conclusion of the experiment (Harris et al., 2013). Subjects were told before making their decisions that they would have to stay for an additional thirty minutes after the experiment, in order to encourage them to record accurate responses.

Despite having the same procedure, the two sessions differed in what instructions were given to participants. In the NC condition, which was conducted first, subjects were instructed to choose naturally. Harris et al. (2013) encouraged participants to make decisions as they would in everyday situations, evaluating food items normally. In contrast, during the SCC condition subjects were financially incentivized to lose weight, which would be measured in a re-weighing session 7-9 days later. The purpose of the financial incentive was to encourage participants to exercise self-control by selecting healthier food items that would help them achieve their weight loss goals.

EEG Data Acquisition and Processing

The EEG data were collected using a HydroCel Geodesic Sensor Net (Electrical Geodesics) with 128 channels and AgCl plated electrodes. A sampling rate of 500 Hz was used with a built-in 200 Hz low-pass Bessel filter and a hardware high-pass filter of 0.1 Hz. Impedances were kept under 50 k Ω , and were adjusted, if necessary, in the 10 minute breaks

between experimental runs. For the present study, preprocessing was performed offline using the EEGLAB toolbox (Delorme & Makeig, 2004) for Matlab (MathWorks, Andover, MA). Epochs of 3000 ms were extracted time-locked to stimulus onset (1000 ms pre-, 2000 ms post-).

Experimental artifacts were identified and extracted using independent component analysis (ICA), implemented via second-order blind identification (SOBI; Belouchrani et al., 1997; Tang et al., 2005). Artifact components are not task-related and generally reflect sensory noise created by eye blinks, eye movements, muscle activity, or electrical noise produced by the EEG equipment. The purpose of removing artifacts from the data is to obtain “artifact correct brain signals” by using only nonartifactual components (Jung et al., 2000).

EEG Time-Frequency Analysis

The present analysis was designed to test whether power in the alpha band (8-12 Hz) decreased with the presentation of healthy versus unhealthy foods during dietary self-control. Therefore, we performed time-frequency analyses comparing alpha power for healthy versus unhealthy, as well as tasty versus untasty, in both the NC and SCC sessions. Frequency analysis was performed using the FieldTrip toolbox (Oostenveld et al. 2011) for Matlab, implemented via custom scripts written by Lieuw (2014).

The custom analysis written by Lieuw (2014) was designed to examine the changes in alpha power while subjects made decisions in the SCC condition. These scripts were adjusted to examine the changes in alpha power in both the SCC and NC for both taste and health. For ease of comparison, trials in which subjects answered with Strong- or Weak-No were combined into “Unhealthy” and Strong- or Weak-Yes were combined into “Healthy.” The

same combination method was applied to the taste ratings, and this was repeated in both the NC and SCC. The preprocessed data was then converted to the FieldTrip format using the `eeglab2fieldtrip` function in Matlab.

Time-frequency analysis was performed using a Morlet wavelet. The width of the wavelet was set to 7 as this allowed for the best combination of temporal and frequency resolution. In the resulting power spectrum, we focused for visualization purposes on frequencies roughly around the alpha band, from 4 to 20 Hz. This allowed for comparison between the alpha band and surrounding frequencies; however, note that all statistics were performed only on the alpha range (8-12 Hz). The time-frequency analysis was performed over a time window of -1 to 2 seconds in sliding steps of 0.004 seconds. The data was log-transformed to normalize the distributions of frequencies.

Statistical analysis focused on the alpha band (8-12 Hz); although initial analysis looked across the whole scalp, we also examined a set of “sensors of interest” (SOI) pre-defined as covering the occipital region. A dependent-samples two-tailed t-test with a threshold of $p = 0.05$ ($p = 0.025$ for each tail) was used to look for statistically significant changes in alpha power. Statistics were corrected for multiple comparisons using a cluster-based statistical test involving a Monte-Carlo permutation test with 500 permutations. The cluster correction bases significance on whether or not there are adjacent sensors that also demonstrate statistical significance, in order to reduce the likelihood of Type I errors (false positives) at single sensors.

Results

The original analysis by Harris et al. (2013) found that subjects re-weighted the taste and health attributes of food items in response to changes in their personal goals, a behavior that was matched by changes in the neural value signal localized to the vmPFC between 400 and 650 ms post-stimulus onset. Here we hypothesized, based in part on other data (Hare et al., 2011), that subjects achieved this neural re-weighting by selectively shifting more attention to health attributes during the SCC.

We further hypothesized that this shift in selective attention during the SCC would produce a decrease in alpha power over posterior (occipital and parietal) sensors. This decrease in alpha power has previously been found in selective attention experiments (Klimesch, 2012; Payne et al., 2013; Payne & Sekuler, 2014). We expected to see this effect within the same time window that Harris et al. (2013) found value modulation to occur (400 to 650 ms post-stimulus onset). Specifically, we predicted that this effect would only be seen in the SCC when comparing healthy foods versus unhealthy foods. When comparing healthy versus unhealthy in the NC, we expected to see no significant changes in alpha power. We also performed the same test for tasty versus untasty items. However, because previous behavioral and ERP data indicates that participants use taste information similarly in both sessions (Harris et al., 2013), we did not expect significant differences in the response to tasty versus untasty for NC compared to SCC sessions.

To test these hypotheses we used a two-tailed dependent samples *t*-test comparing alpha power between healthy versus unhealthy food trials within the time window of 0 to 800 ms post-stimulus onset. For this analysis only the frequencies between 8 and 12 Hz were analyzed for significant differences. Figures 1A and 1B are topographical layouts showing

time-frequency representations of power for all 128 sensors within the fixed-time window of -200 and 1000 ms post-stimulus onset. All 128 sensors are depicted in a scalp map at their correct location, looking down at the top of the head with the nose toward at the top and the ears on either side. Figure 1A depicts changes in alpha power for Healthy versus Unhealthy trials in the NC. In comparison, Figure 1B depicts changes in alpha power for Healthy versus Unhealthy trial in the SCC. In Figure 1B, large decreases in alpha power can be observed over posterior sensors, shown by the blue regions in the individual time-frequency plots.

Figure 1C depicts a time-frequency plot from the most posterior of the 128 sensors for Healthy versus Unhealthy trials in the SCC. Looking at the alpha band (8-12 Hz), denoted by the black box, we see the predicted decrease in alpha power when subjects viewed healthy foods relative to unhealthy foods (dark blue). The decrease in alpha power for Healthy versus Unhealthy trials in the SCC was found to be significant between 0 and 800 ms post-stimulus onset.

To further test the role of alpha suppression between Healthy versus Unhealthy in the SCC, we analyzed power changes in the alpha band over all 128 sensors. We found significant decreases in alpha power, $p < 0.05$, across the entire time window; 0 to 800 ms post-stimulus onset. Figure 2 depicts differences at 500 ms post-stimulus onset: the two statistical maps show the changes in alpha power at this time during the NC (Figure 2A) and SCC (Figure 2B). During the NC, decreases in alpha power are localized to frontal and midbrain sensors, and were not found to be statistically significant to a level of $p = 0.05$. In contrast, decreases in alpha power during the SCC were statistically significant ($p < 0.05$, cluster-corrected Monte Carlo permutation test). As predicted from previous results, this significant decrease in alpha power in the SCC was found largely over occipital sensors.

To illustrate the differences between taste and health attributes in the NC and SCC, another statistical comparison was run. Figure 3A shows a statistical map of changes in alpha power at 500 ms post-stimulus onset for Tasty versus Untasty trials for the SCC versus NC. The cluster-corrected Monte Carlo permutation test found no significant changes in alpha power (Figure 3A). Figure 3B shows changes in alpha power at 500 ms post-stimulus onset for Healthy versus Unhealthy trials for the SCC versus the NC. The white markers indicate sensors found to demonstrate cluster-corrected significant decreases in alpha power (cluster-corrected $p < 0.05$). Although this figure shows significant differences at 500 ms post-stimulus onset, significant decreases in alpha power occurred over occipital sensors during the time range from approximately 440 to 800 ms post-stimulus onset.

To demonstrate that significant changes in alpha power were only found for Healthy versus Unhealthy in the SCC we looked at the average channel plot across all occipital sensors for Tasty versus Untasty trials and Healthy versus Unhealthy trials in both the NC and SCC. Figure 4 depicts the average channel plot taken across all occipital sensors. The channel plots are shown for the time window, -200 to 1000 ms, and from 4 to 20 Hz. Looking across all four channel plots, only the Healthy versus Unhealthy trials in the SCC shows a decrease in the alpha band power within the statistically analyzed time window (black boxes) of 0 to 800 ms post-stimulus onset (Figure 4). Furthermore, examining the interaction of Healthy versus Unhealthy trials in the SCC versus NC sessions shows the earliest significant interaction effect starting at 440 ms post-stimulus onset, within the predicted time window of 400 to 650 ms, and continuing to 800 ms post-stimulus onset, the end of the statistically analyzed range (Fig. 4).

Discussion

Every day we are faced with choices that require us to weigh the different attributes of items with the intention of selecting the item that best fits our current goals. In order to do this we selectively switch our attention between the different attributes, weighting each one. Specifically, when making dietary decisions, people may assign different weights to the attributes of taste and health, dependent upon their current goal. If their current goal is sensory satisfaction, they will focus on and weight the value of the taste attribute higher. However, if their current goal is weight loss, they will focus on the healthiness of the food. This ability to selectively reweight different attributes during multi-attribute choice allows people to exercise self-control when making goal-directed decisions.

For the present study we re-analyzed EEG data collected during a self-control dietary decision-making experiment (Harris et al., 2013) in order to determine the neural mechanism by which people shift their attention and reweight multiple attributes. The original analysis found that subjects were able to change the neural weighting of the health attribute for food items. This re-weighting occurred during the time window associated with the integration of different value signals in the vmPFC.

A fundamental concept explaining the mechanism behind multi-attribute decision-making is Construal Level Theory (Trope & Liberman, 2003). CLT posits that people are able to switch their attention between different levels of construal to better match their current goals. This this type of switch in construal has been linked to subjects' ability to selectively shift attention to different stimulus attributes (Hare et al., 2011). Therefore, we hypothesized that the increased weighting on health under a weight loss incentive would be associated with greater attention to healthiness.

Based on previous EEG literature (Payne et al., 2013), we looked for neural markers of this attentional shift through decreases in power within the alpha band (8-12 Hz). These changes in alpha power associated with selective attention have been shown to occur over occipital sensors (Klimesch, 2012; Payne et al., 2013; Payne & Sekuler, 2014). Consistent with this idea, we observed a significant decrease in alpha power during the SCC for trials where subjects were shown healthy foods relative to trials where they were shown unhealthy foods. Observed decreases in alpha power were found over occipital electrodes, consistent with an attentional enhancement of visual processing (Payne & Sekuler, 2014).

Lieuw (2014) previously found increases in alpha suppression during trials where subjects exercised self-control (Healthy versus Unhealthy in the SCC), but she did not examine trials where subjects did not exercise self-control. It is important to note that this experiment did not find alpha suppression over occipital sensors in trials where subjects did not have current goals that were consistent with exercising self-control (Figure 4). This supports the idea that increases in selective attention are associated with the suppression of power within the alpha band (Payne & Sekuler, 2014), and that this suppression can be flexibly deployed depending on current goals or task demands.

The interaction between alpha power for healthy versus unhealthy items in self-control and natural conditions was significant from 440 to 800 ms post-stimulus onset, is consistent with previous research that has shown re-weighting of attributes occurs approximately 400-650 ms post-stimulus onset (Harris et al., 2013). This agrees with our prediction that we would see an increase in selective attention for healthier food items during the window of value computation. Decreases in alpha power were not observed for Healthy versus Unhealthy trials in the NC, nor for Tasty versus Untasty in either the SCC or NC. This

result builds upon and supports previous research that found decreases in alpha power during trials requiring self-control (Lieuw, 2014).

Previous studies (Payne et al., 2013; Payne & Sekuler, 2014) have used external cues to instruct subjects to either ignore or attend to different stimuli presented in the experiment. This experiment is fundamentally different because subjects were not instructed as to what stimuli to attend to or ignore. Instead, subjects had to change the value assigned to different attributes in the same stimuli, based on their current goals, in order to make decisions. Nonetheless, we found the same neural mechanism deployed when shifting attention between different aspects of the same item as has been previously reported for different items or spatial locations. These results are also among the first to link attentional suppression and multi-attribute decision-making by providing new insight into one neural mechanism through which selective attention can mediate multi-attribute choices. Nevertheless, further research could serve to increase our understanding of the results.

Specifically, analyses performed within other frequency bands could help further our understanding of communication between brain regions. Frequencies within the theta band (4-7 Hz) have been associated with short-term memory tasks (Vertes, 2005) and spatial learning (Buzsáki, 2005). Changes in theta may help to understand whether changes in subject responses when making dietary choices contain a learning component. If there is a change in familiarity with the task, subjects may be able to use less cognitive energy when making decisions, leading to decreases in power within the theta band. Another frequency band of interest is the gamma band (~32-100 Hz). Although this is a large frequency band, previous studies have been able to link activity in the gamma band to increases in selective attention (Fries et al., 2001; Siegel et al., 2008; Gregoriou et al., 2009). Fries et al. (2001)

specifically found simultaneous increases in gamma power and decreases in alpha power during selective attention. This combination may serve as further evidence for a cognitive control mechanism based on selective attention.

The results from our experiment help to illuminate a neurocognitive process used by people on a daily basis in order to make decisions. When people make decisions, they often must exercise self-control in order to match their current goals and choices. Future research will help to further our understanding of self-control and the underlying neurocognitive mechanisms. This in turn may help us to better understand how people develop eating disorders as well as suboptimal decision-making related to lack of self-control.

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Figures

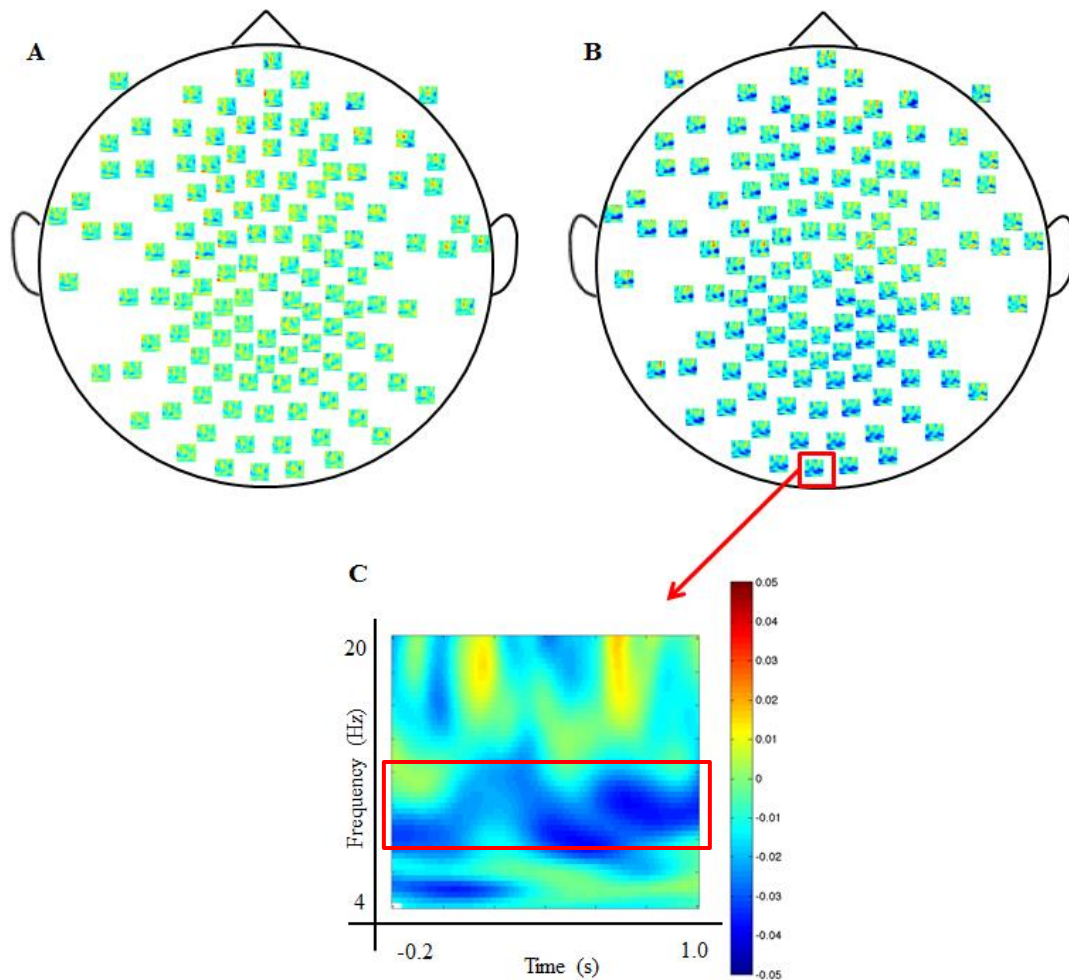


Figure 1. Topographical plot of time-frequency (TFRs) showing changes in power at individual sensors in healthy versus unhealthy trials. **A**, Scalp electrode map of all 128 sensors' TFRs in the NC. **B**, Scalp electrode map of all 128 sensors' TFRs in the SCC. **C**, Each of the 128 plots was measured from -200 to 1000 ms, for frequencies between 4 to 20 Hz. Red represents an increase in alpha power, blue represents a decrease in alpha power. The red box approximates the alpha band (8-12 Hz).

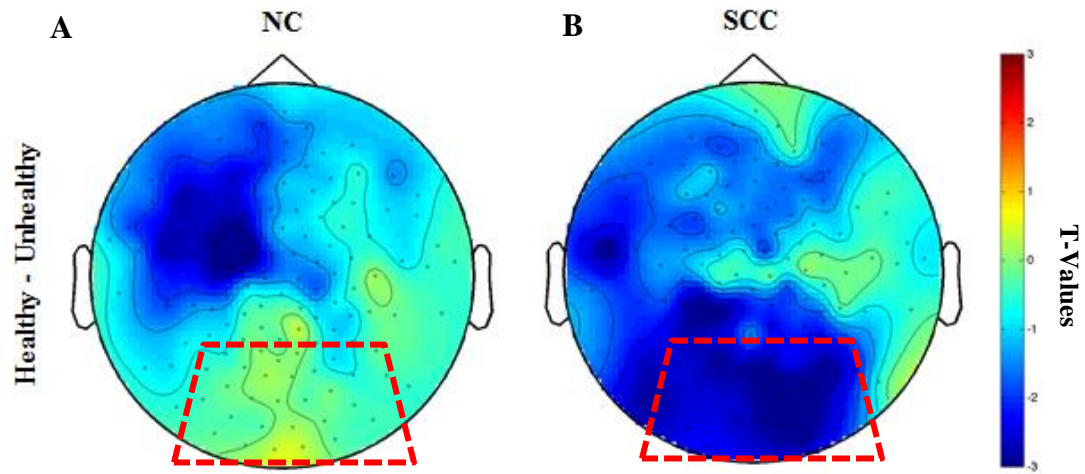


Figure 2. Statistical map showing change in alpha power from Healthy to Unhealthy trails for both NC and SCC conditions. Red represents an increase in alpha power; blue represents a decrease in alpha power. The red boxes indicate the occipital sensors that were used for statistical analyses.

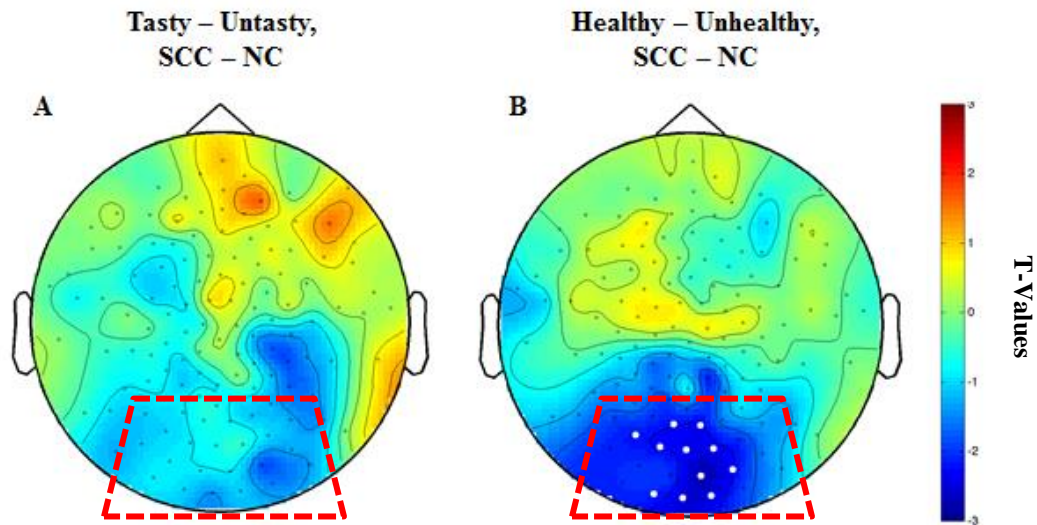


Figure 3. Statistical map showing change in alpha power. **A**, Tasty to Untasty and SCC to NC. **B**, Healthy to Unhealthy and SCC to NC. Significant sensors are colored white and measured at 500 ms post-stimulus onset. These sensors are significant to a cluster-corrected level of $p < 0.005$. The red boxes indicate the occipital sensors that were used for statistical analyses.

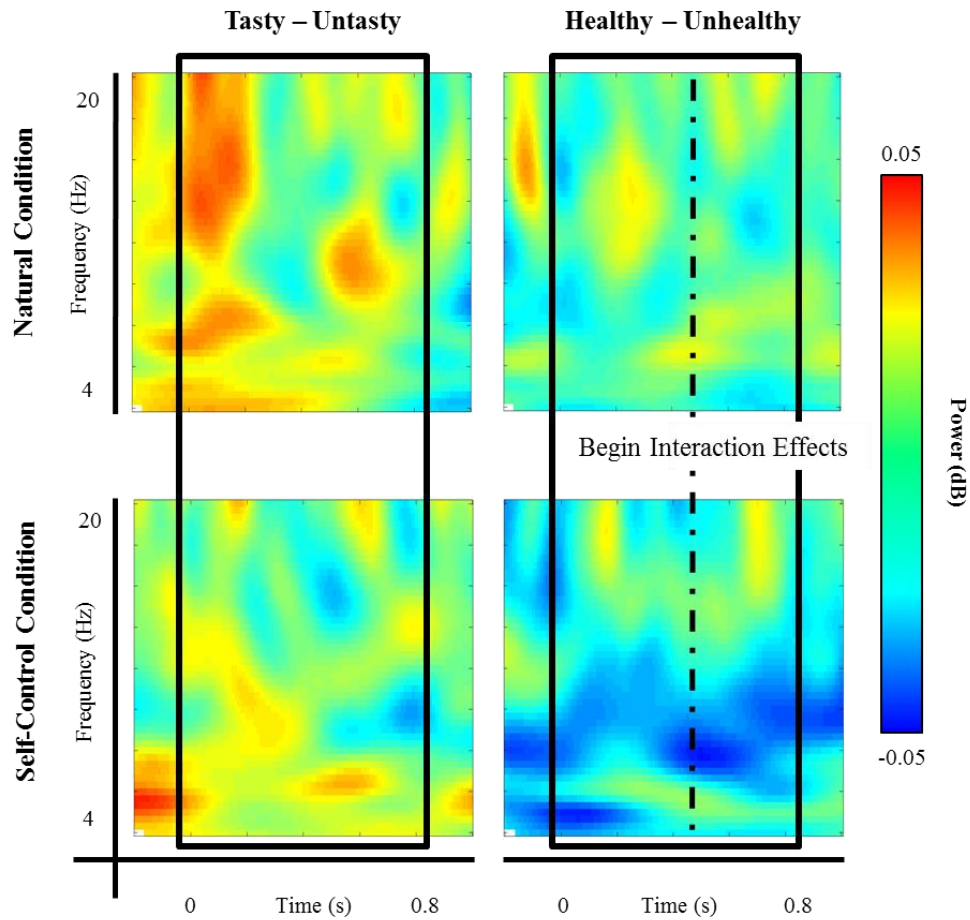


Figure 4. Channel plots of the average signal taken across all occipital sensors, measuring changes in alpha power for Tasty vs. Untasty (Left), Healthy vs. Unhealthy (Right), NC (Top), and SCC (Bottom) from -200 to 1000 ms, for frequencies between 4 to 20 Hz. Red represents an increase in alpha power, blue represents a decrease in alpha power. Black boxes designate the time window in which statistical analyses were run (0-800 ms post-stimulus). Dotted line indicates start of interaction effects between SCC and NC for Healthy vs. Unhealthy trials.