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Research Paper

A neural signature of food semantics is associated with body-mass index

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A R T I C L E I N F O

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A B S T R A C T

Visual recognition of objects may rely on different features depending on the category to which they belong. Recognizing natural objects, such as fruits and plants, weighs more on their perceptual attributes, whereas recognizing man-made objects, such as tools or vehicles, weighs more upon the functions and actions they enable. Edible objects are perceptually rich but also prepared for specific functions, therefore it is unclear how perceptual and functional attributes affect their recognition.

Two event-related potentials experiments investigated: (i) whether food categorization in the brain is differentially modulated by sensory and functional attributes, depending on whether the food is natural or transformed; (ii) whether these processes are modulated by participants' body mass index. In experiment 1, healthy normal-weight participants were presented with a sentence (prime) and a photograph of a food. Primes described either a sensory feature ('It tastes sweet') or a functional feature ('It is suitable for a wedding party') of the food, while photographs depicted either a natural (*e.g.*, cherry) or a transformed food (*e.g.*, pizza). Prime-feature pairs were either congruent or incongruent. This design aimed at modulating N400-like components elicited by semantic processing. In experiment 1, N400-like amplitude was significantly larger for transformed food than for natural food with sensory primes, and *vice versa* with functional primes. In experiment 2, underweight and obese women performed the same semantic task. We found that, while the N400-like component in obese participants was modulated by sensory-functional primes only for transformed food, the same modulation was found in underweight participants only for natural food. These findings suggest that the level of food transformation interacts with participants' body mass index in modulating food perception and the underlying brain processing.

1. Introduction

Given the essential role of food for survival, the brain is likely to be endowed with the ability to readily recognize edible items, and to extract information about their potential nutritional value (Foroni, Pergola, Argiris, & Rumiati, 2013; Killgore et al., 2003; Toepel, Knebel, Hudry, le Coutre, & Murray, 2009). Human food choices are guided by homeostatic needs, such as hunger; however, hedonic drives and non-nutritional food value (*e.g.*, health-related concerns) may override them (Berthoud, 2011; Kenny, 2011). To speed up food recognition and choice, humans greatly benefit from experience on which semantic knowledge is built up (Martin, 2009).

One important feature of food that affects human choices is its level of transformation (Foroni & Rumiati, 2017; Rumiati & Foroni, 2016). Compared to raw food, transformed food provides an energetic advantage for survival (Carmody, Weintraub, & Wrangham, 2011; Carmody & Wrangham, 2009, 2013; Wrangham & Conklin-Brittain, 2003; Zink & Lieberman, 2016). Empirical evidence in support of this view is provided by a mice study showing an increase in body mass when the animals were fed with cooked food as well as a preference for cooked food in fasted animals (Carmody et al., 2011). Great apes, too, tend to prefer cooked food over natural food (Warneken & Rosati, 2015; Wobber, Hare, & Wrangham, 2008). However, how this preference is wired in the human brain is yet to be understood.

Neuropsychologists observed in brain-damaged patients selective object recognition deficits for living things, such as animals and plants,

Abbreviations: BMI, body mass index; DSH, domain specific hypothesis; ERP, event-related potential; SFT, sensory-functional theory

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or non-living things such as tools, vehicles or furniture (for a review, see Capitani, Laiacona, Mahon, & Caramazza, 2003). These patterns of pathological and intact recognition of living and non-living things led neuropsychologists to propose the sensory-functional theory (SFT) according to which the semantic memory is organized in putative modality-specific semantic subsystems (Warrington & McCarthy, 1983, 1987; Warrington & Shallice, 1984). One subsystem represents sensory properties of objects (*e.g.*, color, texture or taste), while the other subsystem codes their functional properties (*e.g.*, prototypical use and the functions that they entail). In line with the SFT, recognition of living things is expected to depend more on perceptual attributes, and recognition of non-living things to predominantly rely on the information concerning their functions and the actions they enable; thus damage to the former subsystem will give rise to a deficit in recognizing living things while damage to the latter subsystem will give rise to a deficit in recognizing nonliving things. However, not all category-specific semantic deficits showed by brain-damaged patients seem to comply with the SFT (Capitani et al., 2003). Caramazza and collaborators proposed and later refined the Domain Specific Hypothesis (DSH) to account for all the observed patterns (Caramazza & Shelton, 1998; Mahon & Caramazza, 2011). According to this proposal, the organization of the semantic memory has been shaped by the evolutionary pressure in categories that are more salient for survival such as animals, plants, vegetables, and conspecifics.

The application of such theories to food recognition is not straightforward. According to the SFT, for instance, one would expect different recognition mechanisms for sensory and functional aspects of food as different foods are characterized more by sensory attributes and others by specific functions or actions they require in order to be prepared, as in the case of natural food versus transformed food. According to the DSH, instead, foods should be represented in a unique category, shaped by evolutionary pressure. There should not be a principled distinction in recognition processes of natural food and transformed food.

To date, there has been little investigation in either healthy or brain damaged individuals on how these different food properties are represented in the brain (Rumiati, Foroni, Pergola, Rossi, & Silveri, 2016). The present investigation aimed to fill this gap. In addition, based on the evidence that body mass index (BMI) may modulate some aspects of cognition, we hypothesized that this variable would also play a role in food recognition processes (Cournot et al., 2006). Thus, in the present event-related potentials (ERP) study, we investigated the neural underpinnings of sensory and functional information associated with food in normal, obese, and underweight individuals. Specifically, we hypothesized that a differential neural activity would underlie food processing depending on the type of food (natural vs transformed) and on the type of attributes associated with food (sensory vs functional). Like a man-made tool, transformed food is purposefully prepared for consumption in particular contexts. We reasoned that since transformed food is the product of human work, it may be processed by the brain more like a tool than like a living item (see Foroni & Rumiati, 2017; Rumiati & Foroni, 2016 for reviews). In particular, the SFT predicts that transformed food should rely more strongly on functional than on sensory attributes. *Vice versa,* processing natural food pictures is predicted to rely more on sensory attributes, as is the case of other natural entities, such as animals and plants. Based on the DSH one might instead predict no differences in processing natural and transformed foods or, at least, no differences in processing the sensory properties of these different kinds of food (as sensory properties are shared by both natural and transformed foods, Rumiati & Foroni, 2016).

We exploited the N400 component that reflects the neural computations involved in accessing conceptual incongruence/congruence in a sequence of stimuli (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980a, 1980b). This paradigm allowed us to investigate which specific neural and cognitive components of food recognition are modulated by food type and sensory-functional attributes. Participants saw a sentence that described either a sensory attribute (*e.g.*, 'It tastes sweet') or a functional attribute defined as the context in which the food is eaten (*e.g.*, 'It is suitable for a wedding meal'), followed by a photograph depicting either a natural or a transformed food (pineapple or pizza, respectively). Image-sentence pairs could be congruent ('It tastes sweet' with pineapple) or incongruent ('It tastes salty' with pineapple). Based on the paradigm, which mixed verbal primes with pictorial stimuli (see Hamm, Johnson, & Kirk, 2002 for comparison), we expected to observe the modulation of a N400-like potential and investigated multiple electrode sites because we had no a priori hypotheses with respect to topographies.

Two experiments were performed. In experiment 1, conducted with normal weight participants, we expected that natural food paired with functional sentences, and transformed food paired with sensory sentences, would trigger greater incongruence, and thus, elicit larger N400-like amplitudes (indexed as incongruent–congruent difference waves). Such a result would be consistent with the SFT and not with the DSH. In experiment 2, two groups of underweight and obese participants performed exactly the same task as in experiment 1. If individuals with different BMI categorize food differently, the underlying brain activity should differ by food type. For instance, overweight and obese individuals show attentional bias towards food cues compared with non-food cues, as assessed by behavioral and electrophysiological indices (Hume et al., 2015; reviewed by Hendrikse et al., 2015; Wolz, Fagundo, Treasure, & Fernandez-Aranda, 2015). Moreover, underweight individuals seem to rely on functional categorization of food more than normal-weight controls (Urdapilleta, Mirabel-Sarron, Meunier, & Richard, 2005). Therefore, we expected to observe a group difference between underweight and obese participants in the neural signature identified in experiment 1 with normal-weight participants.

2. Materials and methods

2.1. Experiment 1: normal-weight participants

In experiment 1 normal-weight participants performed a semantic memory task while EEG was recorded, with the aim to identify the neural signature of food perception and categorization by investigating N400-like components.

2.1.1. Materials and methods

2.1.1.1. Participants. Eighteen healthy, right-handed (assessed with the Edinburgh Handedness Inventory; Oldfield, 1971), native Italian-speakers performed the experiment. Participants were recruited via a dedicated social-networking site and were monetarily compensated (25 €) for their participation. Exclusion criteria for participation included: a) daltonism, achromatism; b) history of psychiatric or neurological disorders or substance abuse; c) medical conditions currently under pharmacological treatment that may affect cognitive performance (*e.g.*, psychotropic drugs, histamine antagonists, *etc*…); d) a Body Mass Index (BMI) outside normal range (BMI normal range: 18.5–24.99; (Keys, Fidanza, Karvonen, Kimura, & Taylor, 1972); e) self-reported food restrictions such as vegetarianism or avoidance of specific foods because of religion, allergy, medical conditions, self-reported symptoms of eating disorders, and so on. Participants' BMI was used as an indicator of human body fat (Keys et al., 1972), and was computed based on participants' self-reported height and weight. Sixteen participants were included in the final analysis (seven females; mean age = 22.6 years, SD = 2.2, range: 19–27), after having excluded two participants for excessive artifacts in the ERP analysis. The average BMI of the final sample was 21.8 (SD = 1.4, range = 19.2–24.0).

2.1.1.2. Demographic screening. Upon arrival, participants first signed a written consent form and then completed two questionnaires to confirm right-hand laterality and to assess their current state with respect to energy homeostasis. This assessment included five questions pertaining