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Evaluation of multisensory stimuli—Dimensions of meaning and electrical brain activity

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ABSTRACT

The semantic differential technique is used to statistically define connotative dimensions of meaning. The brain depends on these dimensions to process words. Earlier studies demonstrated that stimuli of the different semantic classes led to differences in neuronal processing. We investigated the influence of connotative meaning on multisensory processing (food words strongly related to odor, taste, vision or somatosensory texture). A group of 795 subjects rated 197 food words on the basis of 11 pairs of adjectives with opposite meanings. Factor analysis revealed three dimensions (Evaluation, Potency and Texture). Words with high positive or negative scores, and low scores on the other dimensions, were used as stimuli in an ERP experiment. EEG was recorded in 40 healthy adults from 30 channels and averaged according to semantic stimulus class.

Component latency, global field power and topography were influenced by semantic meaning. These experiments determined that very early effects at 107 ms after stimulus presentation where latency and GFP were affected by stimulus class. When mapped topographically, different stimulus classes led to different scalp topography of evoked brain activity in sagittal direction already at an early state of processing (around 107 ms). The extent of lateralization of potential fields' centers of gravity was influenced by stimulus class around 304 ms.

In summary, semantic dimensions influence neuronal processing of words related to multisensory perception. Such effects suggest a rapid and complex way of processing multisensory stimuli.

1. Introduction

Sensory perception of the physical and chemical environment is a fundamental determinant for adaptive behavior. The human brain needs to integrate these multimodal stimuli to create a unified perception of the environment. Peripheral interactions have been defined as requiring common receptive structures, whereas central interactions occur independently of these receptive structures (Verhagen & Engelen, 2006). Brain areas as well as single neurons have been found to react in a multimodal way. It is known that individual experience influences these central multisensory interactions, but their overall regulation is only poorly understood. This paper addresses a possible approach to better understand the rules for central multisensory interactions mediated through language.

The meaning of a word is first of all a factual and objective acceptation that denotes its lexical meaning. In addition, words carry affective and subjective meaning in terms of an affective connotation. Also, sensory perception leads to affective connotations that depend mainly on memorized experiences. In this study, we analyzed the electrophysiological response to defined word stimuli to answer the question of whether connotative meaning is important for the processing of sensory perception in the brain.

Connotative associations of words can be explored by the semantic differential method. This method is used to identify different dimensions of connotative meaning in word processing. Words are rated on scales of adjectives with opposite meanings. By using a factor analysis, different dimensions of meaning are identified and quantified with each semantic dimension describing an affective connotation (Osgood, Suci, & Tannenbaum, 1957). Three dimensions have repeatedly been found: *evaluation* ("E") describes connotations reaching from good ("E+") to bad ("E−"), *potency* ("P") reflects associations between strong ("P+") and weak ("P−"), and *activity* ("A") differentiates active ("A+") and passive ("A−") connotations. Such semantic dimensions of word meaning are independent of language and culture (Skrandies & Chiu, 2003). Moreover, certain connotative associations are reflected by event-related potentials (ERPs) which are elicited by word perception (Skrandies, 1998). Various semantic dimensions cause measurable effects as early as 80 and 265 ms after stimulus presentation. Effects

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refer to the global field power, latency and topographical features of the electroencephalogram (EEG). Other studies described local changes of regional blood supply in the human brain as an effect of semantic dimensions (Suzuki, Gyoba, & Sakuta, 2005).

In consequence, affective and emotional connotations influence the elicited brain activity. A study measuring the response to olfactory stimuli by positron emission tomography (PET) suggests that a defined emotional judgment for the stimulus by itself activates certain areas of the brain (Royet et al., 2000). Therefore, the sensory modality was less determining than the emotional connotation of pleasure and displeasure. Analyzing EEGs, similar reactions to the perception of odor were investigated when presenting real odor stimuli (Kline, Blackhart, Wooward, Williams, & Schwartz, 2000) or words related to odor (Sutton & Davidson, 2000). Perceived favor and disfavor influenced topographical features of the EEG. Whether odors are primarily processed emotionally or cognitively influences the evaluation of the stimulus (Royet et al., 2001). Similarly processing taste depends, at least in part, on subjective preference. Rolls (2005) has illustrated that contentment with odor and flavor is represented in the orbitofrontal cortex.

In fact, only a small part of the sensory cortex in primates is unimodal—most areas are influenced by more than one sensory modality (Kaas & Collins, 2004). Especially, within the orbitofrontal cortex different senses converge (De Araujo, Rolls, Kringelbach, McGlone, & Phillips, 2003; Kadohisa, Rolls, & Verhagen, 2005; Rolls, 2004, 2010). Intracranial recordings of activity of single neurons of macaques (Verhagen, Kadohisa, & Rolls, 2004) revealed neurons within the taste cortex that are also activated by oral texture sensations. For example, these neurons reacted to viscosity and fatty textures. Some neurons were influenced by the combination of taste, temperature and texture. Other cells reacted bimodally to taste and smell (Rolls & Baylis, 1994). Within the orbitofrontal cortex of macaques roughly one-third of neurons appear to react bimodally, and one-third react multimodally (Kadohisa et al., 2005). Consequently, different sensory perceptions are integrated. By measuring the oxygenation of hemoglobin in human brains, Kobayashi et al. (2004) came to similar conclusions about the integration of texture processing and taste perception. Even the imagination of taste alone yielded such results. Associations between texture perception and other senses as well as between odor perception and taste are probably learned through daily experience (De Araujo, Rolls, Kringelbach, McGlone, & Phillips, 2003; Delwiche, 2004; Rolls, 2004; Stevenson & Prescott, 1995). There is also a connection between vision and other sensory perceptions. When olfactory stimuli were rated edible or enjoyable, an increase of cerebral blood flow within the primary visual cortex was detected by PET (Royet et al.,2001). On the other hand, the identification of an aroma is inhibited when its color is changed artificially (Delwiche, 2004). The exclusive information about taste of food alone is not sufficient for its identification, but rather the convergence of taste, smell, and vision is essential (Kobayashi et al., 2004).

Multisensory interactions were detected at a very early stage of neuronal processing. For example, in an ERP study Giard and Peronnet (1999) found convergence of vision and auditory processing just 40 ms after stimulus presentation. Effects of compatible and incompatible olfactory and gustatory perceptions were explored in an ERP study (Skrandies & Reuther, 2008). Stimulus compatibility affected ERP components that occurred around 100 ms after stimulus presentation. Thus, decisions about the compatibility of sensory stimuli are made at a very early stage of processing. This implies that integration and evaluation of perceptions take place very early and affect sensory processing.

Consequently, affective connotations play an important role in regard to multisensory processing. We hypothesized that such connotations of sensory stimuli are crucial for central multisensory processing. Therefore, we investigated affective connotations of multisensory stimuli by using the semantic differential. In recent studies, odor and taste could be evaluated by semantic differential (Reik & Skrandies, 2006). We expected words related to food to lead to multisensory associations, because edible items themselves are characterized by a certain combination of odor, taste, look and texture. Especially words related to fruit lead to increased activation of the orbitofrontal cortex which is associated with processing of olfactory and gustatory sensations (Goldberg, Perfetti, & Schneider, 2006). In our study, food items were rated on a scale of different adjectives strongly related to different sensory modalities. Imagination of odor perception leads to activation of brain areas that were congruent with real odor perception (Djordjevic, Zatorre, Petrides, Boyle, & Jones-Gotman, 2004). Also, the imagination of taste and real taste perception led to neuronal activity in partially congruent areas (Kobayashi et al., 2004). Rolls (2010) found accordant patterns of somatosensory processing regardless of whether perception was real or imagined. In consequence, the imagination of a sense is comparable to the real perception.

As Verhagen and Engelen (2006) have shown, multimodal stimuli are of central importance in human food perception. The goal was to analyze the importance of meaning dimensions for multisensory processing in a large, representative group of adult subjects. As described above, dimensions of meaning are translated into electrophysiologically measurable events. This is not only true for common words, but also for descriptions of taste and odor (Skrandies & Reuther, 2008). Thus, we expected that semantic dimensions which describe affective connotations of food words in terms of imaginary multisensory experience would also show neurophysiologic correlates. The topographical recording of electrophysiological activity in healthy subjects allowed us to characterize the differential processing of multisensory perception in the brain with a high temporal resolution.

In the present paper, we investigated the processing of connotative meaning of food words presumably activating multisensory mental concepts in a group of 40 healthy adults in order to: (1) quantitatively and statistically define food items and (2) study the effects of stimulus class on event-related brain activity. These data are expected to extend our previous research in this field and will complement existing results from invasive animal studies and brain imaging studies on human subjects.

2. Method

2.1. Questionnaire

In order to determine the dimensions of connotative meaning which represent sensory modalities, 197 food words were rated by 795 healthy subjects (aged 18–54 years: mean 22 years; 666 females and 129 males) on 17 adjective scales. Participants had to rate every food item on 17 different 7-point scales of two adjectives of opposite meaning. Each pair of adjectives was related to taste, odor, texture perception, or vision, for example “spicy/mild”, “sweet/bitter” or “light/dark”. Principle component analysis followed by Varimax rotation was conducted to identify underlying factors that describe different semantic dimensions. The “eigenvalues = 1” rule was used, and this revealed five independent factors (*evaluation*, *activity*, *texture*, *potency*, and *visual dimension*). In order to reduce number of semantic dimensions, a confirmatory factor analysis was computed resulting in three independent dimensions: *evaluation* (“E”), *potency* (“P”) and *texture* (“T”).

Stimulus classes were defined by adjectives that had either high positive or negative factor loadings on the three factors. Loadings smaller than −0.7 defined negative “polarity”, whereas loadings higher than 0.7 defined positive “polarity”. This resulted