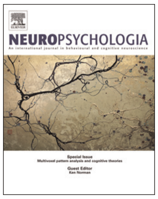
Neuropsychologia 69 (2015) 67–76

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia



The organization of words and environmental sounds in memory[☆]

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ARTICLE INFO

Article history:
Received 5 August 2014
Received in revised form
21 November 2014
Accepted 23 January 2015
Available online 24 January 2015

Keywords:
ERP
N400
Word
Environmental sound
Semantic memory

ABSTRACT

In the present study we used event-related potentials to compare the organization of linguistic and meaningful nonlinguistic sounds in memory. We examined N400 amplitudes as adults viewed pictures presented with words or environmental sounds that matched the picture (Match), that shared semantic features with the expected match (Near Violation), and that shared relatively few semantic features with the expected match (Far Violation). Words demonstrated incremental N400 amplitudes based on featural similarity from 300–700 ms, such that both Near and Far Violations exhibited significant N400 effects, however Far Violations exhibited greater N400 effects than Near Violations. For environmental sounds, Far Violations but not Near Violations elicited significant N400 effects, in both early (300–400 ms) and late (500–700 ms) time windows, though a graded pattern similar to that of words was seen in the mid-latency time window (400–500 ms). These results indicate that the organization of words and environmental sounds in memory is differentially influenced by featural similarity, with a consistently fine-grained graded structure for words but not sounds.

1. Introduction

Our ability to interpret the world around us crucially depends on how the brain organizes meaningful auditory information in memory. The organization of semantic memory for one form of meaningful information, linguistic items (e.g. words), has been well investigated, and is based on several factors. Among the most important is featural similarity (i.e. the perceived likeness between concepts), which aids in categorization (Kay, 1971; Murphy et al., 2012; Paczynski and Kuperberg, 2012; Rosch et al., 1976; Sajin and Connine, 2014). Far less is known about how the brain processes and organizes meaningful auditory information that is not linguistic (e.g. environmental sounds). The current paper examines whether semantic information is organized similarly in memory for words and environmental sounds, and specifically whether featural similarity is useful for the organization of environmental sounds in memory. Uncovering how the brain organizes meaning associated with diverse forms of referential auditory information is vital for understanding the relation between language and cognition.

1.1. *The processing of words and environmental sounds*

Words and environmental sounds share many spectral and temporal characteristics (Gygi, 2001; Shafiro and Gygi, 2004) and are modulated by contextual cues (Ballas and Howard, 1987), item familiarity (Ballas, 1993; Cycowicz and Friedman, 1998), and frequency of occurrence (Ballas, 1993; Cycowicz and Friedman, 1998). Like words, environmental sounds carry deep semantic associations with a corresponding referent (Ballas, 1993). Multiple lines of evidence suggest that words and environmental sounds are processed similarly. It has been shown with behavioral measures (accuracy, response time) that semantically congruent words or pictures can prime environmental sounds, and it has likewise been shown that environmental sounds can prime words or pictures (Ballas, 1993; Chen and Spence, 2011; Özcan and Egmond, 2009; Schneide et al., 2008; Stuart and Jones, 1995). Electrophysiological measures reveal a similar effect. N400 (described in detail below) priming effects (attenuated N400 amplitudes to semantically related compared to unrelated primes) have been found for word or picture targets primed by environmental sounds (Schön et al., 2010; Daltrozzo and Schön, 2009; Frey et al., 2014; Koelsch et al.,

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[☆] This research was supported by NIH Training Grant 5T32DC007361 to the first author, NIH No. HD068458 (to Dr. Friend), and NIH R01DC009272 and R01DC03681 (to Dr. Love) The content is solely the responsibility of the authors and does not necessarily represent the official views of the NICHD or the NIH.

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http://dx.doi.org/10.1016/j.neuropsychologia.2015.01.035
0028-3932/Published by Elsevier Ltd.

2004; Van Petten and Rheinfelder, 1995) and for environmental sound targets primed by words, pictures, or other environmental sounds (Aramak et al., 2010; Cummings et al., 2006, 2008; Cummings and Čeponienė, 2010; Daltrozzo and Schön, 2009; Orgs et al., 2008; Orgs et al., 2006; Plante et al., 2000; Schirmer et al., 2011; Schön et al., 2010; Van Petten and Rheinfelder, 1995). Indeed several studies of N400 priming effects using bimodal (visual/auditory) stimulus presentation have found similar scalp distributions for the N400 priming effects to words and environmental sounds across multiple ages (Cummings et al., 2006, 2008; Cummings and Čeponienė, 2010; Orgs et al., 2007) Finally, functional imaging results have shown activation to both word and environmental sound stimuli in areas commonly thought of as language specific: left inferior frontal and superior temporal regions (Binder et al., 2000; Leech and Saygin, 2011; Price et al., 2005; Thierry et al., 2003; Tranel et al., 2003) and similar neural networks being implicated in the semantic processing of speech and musical sounds (Koelsch, 2005; Koelsch et al., 2004; Steinbeis and Koelsch, 2008).

Despite these similarities, there are some important differences between words and environmental sounds. These differences exist on multiple dimensions since environmental sounds are non-linguistic. Whereas words have an arbitrary linkage to the items to which they refer, environmental sounds obtain meaning through the causal relation with the event or object that produces them (Ballas and Howard, 1987). Thus, the “lexicon” of environmental sounds is rather small, and tends to converge on a limited number of referents (Ballas, 1993).

Consequently, there is also some empirical support for the notion that distinct mechanisms underlie the processing of each sound type. Behavioral evidence suggests that environmental sound recognition is more susceptible to interference from semantically related competitors (e.g. cow and horse) than word recognition is (Saygin et al., 2005). Additionally, there is evidence from dichotic listening studies that environmental sounds are processed more efficiently in the right hemisphere, whereas words are processed more efficiently in the left hemisphere (Knox and Kimura, 1970; Kimura, 2011). While seemingly at odds with the dichotic listening research, ERP studies (using uni-modal auditory presentation) have found words and environmental sounds exhibit different scalp distributions for N400 priming effects: words showing a larger effect over the right hemisphere, whereas environmental sounds show a larger effect over the left hemisphere (Van Petten and Rheinfelder, 1995; but see above). We note here that the scalp topography of an ERP component does not correspond in any straightforward way to the location of its underlying neural generators, but reflects the summed activity of all generators, which vary in location, strength, and orientation with respect to the scalp. Therefore a right-sided asymmetry at the scalp does not implicate right-hemisphere generation, and results from dichotic listening tasks and ERP scalp topography are not necessarily at odds.

To further bolster the idea that words and environmental sounds indeed call upon different processing routines, and hence different neural networks, functional imaging research has revealed differential intra- and inter- hemispheric activation patterns for words (left angular gyrus, and left anterior and posterior temporal areas) and for environmental sounds (left superior and middle temporal gyri and right superior temporal cortex) (Noppeney et al., 2008; Thierry et al., 2003; Humphries et al., 2001). Finally, using electrophysiological and hemodynamic measures concurrently, Renvall et al. (2012) found that adding background noise affected the recognizability, timing, and location of cortical responses differently for each sound class.

1.2. The effect of featural similarity on N400 responses

All stimuli with referential meaning, whether auditory, visual, orthographic, or pictorial, elicit an N400 component, which is a negative voltage deflection peaking approximately 400 ms poststimulus onset (Kutas and Federmeier 2011; Kutas and Hillyard, 1980; Kutas and Hillyard, 1983). The prototypical (visual) N400 semantic incongruity effect – the relative amplitude of the waveform compared to another experimental condition (e.g. unprimed target minus primed target) – is typically maximal over right parietal, posterior temporal, and occipital sites. However auditory N400s tend to begin earlier, last longer, and have a somewhat more frontal and less right-biased scalp distribution than visual N400s (Holcomb and Neville,1990; and reviewed in Kutas and Van Petten, 1994). It has been shown that N400 amplitude (to visual or auditory stimuli) is sensitive to category membership. For instance, following a series of prime words from the same taxonomic category (e.g. flower), N400 amplitudes are larger for target words that belonged to a different category (e.g. apple) than target words belonging to the primed category (e.g. tulip) (Polich, 1985; review in Kutas and Van Petten, 1988).

N400 amplitude for words is not only sensitive to gross category membership (member vs. non-member) but is also incrementally sensitive to differences in featural similarity (i.e. the perceived likeness between concepts as measured by the degree of overlap in their semantic features) (Federmeier and Kutas, 1999, 2002; Federmeier et al., 2002; Ibáñez et al., 2006; Torkildsen et al., 2006). We know that the brain often represents feature information in a structured fashion such that neurons responding to similar features are physically close to one another (Hubel and Wiesel, 1972; Tanaka, 1996). If we characterize neural representations of words as a collection of features, then two words that share many features will show similarities in their underlying neural activity (Amuntz and Zilles, 2012; Federmeier et al., 1999). Indeed an incremental or graded effect in N400 amplitude for words based on featural similarity was first found by investigating the effects of sentential context on semantic memory organization (Federmeier and Kutas 1999; Federmeier et al., 2002). Federmeir and colleagues defined feature likeness in terms of taxonomic semantic categories (e.g. bears and pandas are within the same taxonomic category and therefore share more features than do bears and zebras). Participants were visually presented with sentences that ended in three types of words: expected exemplars (e.g. panda), unexpected exemplars from the same category (e.g. bear), and unexpected exemplars from a different category (e.g. zebra). Both within- and between-category violations exhibited significant N400 effects; however between-category violations (e.g. ‘zebra’ instead of ‘panda’) exhibited greater N400 amplitudes than within-category violations (e.g. ‘bear’ instead of ‘zebra’) (Federmeier and Kutas, 1999). What's more, the graded effect in N400 amplitudes based on featural similarity has been replicated in visual-auditory priming paradigms across the lifespan (Federmeier et al., 2002; Ibáñez et al., 2006; Torkildson et al., 2006).

Active listening paradigms (i.e. paradigms in which participants are given a concurrent behavioral task to maintain attention), like those mentioned just above, are not mandatory for eliciting the N400 priming effect; the effect has been repeatedly found during attentional blink tasks in which a visual stimuli is not detected due to rapid presentation (Luck et al., 1996; Maki et al., 1997; Vogel et al., 1998), and has even been found for participants who were presented with stimuli while asleep (Ibáñez et al., 2006). Thus active listening does not appear necessary to elicit N400 priming effects, and effects found with passive listening paradigms appear to be comparable to those found during active listening paradigms.

Together these works demonstrate that featural similarities between concepts in the world influence the neural organization