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Research report

Beyond the N400: Complementary access to early neural correlates of novel metaphor comprehension using combined electrophysiological and haemodynamic measurements

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ABSTRACT

The simultaneous application of different neuroimaging methods combining high temporal and spatial resolution can uniquely contribute to current issues and open questions in the field of pragmatic language perception. In the present study, comprehension of novel metaphors was investigated using near-infrared spectroscopy (NIRS) combined with the simultaneous acquisition of electroencephalography (EEG)/event-related potentials (ERPs). For the first time, we investigated the effects of figurative language on early electrophysiological markers (P200, N400) and their functional relationship to cortical haemodynamic responses within the language network (Broca's area, Wernicke's area). To this end, 20 healthy subjects judged 120 sentences with respect to their meaningfulness, whereby phrases were either literal, metaphoric, or meaningless. Our results indicated a metaphor-specific P200 reduction and a linear increase of N400 amplitudes from literal over metaphoric to meaningless sentences. Moreover, there were metaphor related effects on haemodynamic responses accessed with NIRS, especially within the left lateral frontal cortex (Broca's area). Significant correlations between electrophysiological and haemodynamic responses indicated that P200 reductions during metaphor comprehension were associated with an increased recruitment of neural activity within left Wernicke's area, indicating a link between variations in neural activity and haemodynamic changes within Wernicke's area. This link may reflect processes related to interindividual differences regarding the ability to classify novel metaphors. The present study underlines the usefulness of simultaneous NIRS measurements in language paradigms – especially for investigating the functional significance of neurophysiological markers that have so far been rarely examined – as these measurements are easily and efficiently realizable and allow for a complementary examination of neural activity and associated metabolic changes in cortical areas.

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1. Introduction

Pragmatic types of language, such as metaphoric speech, are remarkably frequent in everyday language (Lakoff & Johnson, 1980; Pollio, Barlow, Fine, & Polio, 1977). Metaphors integrate semantic entities that are "normally" not related. The literal meaning of metaphors may or may not be plausible, but in either case needs to be suppressed (Giora, 2003; Glucksberg, 2003; Ortony, 1993). Scientific approaches which try to account for the particular cognitive operations underlying metaphor comprehension address the question how the brain distinguishes between metaphoric and literal meanings. Especially earlier research assumed that the literal meaning of metaphors is processed first, then rejected and replaced by the correct metaphoric interpretation (Ortony, 1993). This model would imply that metaphors essentially require additional cognitive processes relative to literal sentences. However, research on the processing speed indicates that, within a conclusive context, metaphoric expressions are processed with equal speed, a finding that is not compatible with the sequential model (see Glucksberg, 2003).

A number of studies addressed difficulties in metaphor comprehension in different clinical populations (Rapp & Wild, 2011; Thoma & Daum, 2006). This anomaly was confirmed in patients with schizophrenia (Kircher, Leube, Erb, Grodd, & Rapp, 2007; Mitchell & Crow, 2005; Rapp, 2009; Spitzer, 1997), autism (Giora, Gazal, Goldstein, Fein, & Stringaris, 2012; Gold & Faust, 2012), brain lesions (Rapp, 2012; Winner & Gardner, 1977), and recently extended to other neurodevelopmental disorders (e.g., Williams Syndrome, Annaz et al., 2009; Faust, 2012b) and dementias (Rapp & Wild, 2011). Compared with other language functions, metaphor comprehension evolves relatively late during development (Nippold, Hegel, Uhden, & Bustamante, 1998; Nippold, Martin, & Erskine, 1988) and this process is further delayed in neurodevelopmental disorders (Annaz et al., 2009).

From a neurobiological perspective, an elaborate investigation of the functional and structural bases of pragmatic language comprehension is associated with a number of methodological and technical challenges. Due to its fast temporal processing and its representation and integration among complex, widespread neural networks, the perception of language and its neurobiological correlates should preferably be examined by means of imaging methods that offer both good temporal and spatial resolution. Because most non-invasive neuroimaging techniques exhibit either high temporal [e.g., electroencephalography (EEG), magnetencephalography (MEG)] or spatial resolution [e.g., functional magnet resonance imaging (fMRI), positron emission tomography (PET)], a combination of methods can strongly enhance measurement validity. The simultaneous application of EEG and near-infrared spectroscopy (NIRS) is not only economic and offers very good ecological validity, it is also particularly useful for language studies (Dieler, Tupak, & Fallgatter, 2012; Horovitz & Gore, 2004; Wallois, Mahmoudzadeh, Patil, & Grebe, 2012), as there is no irritating noise possibly interfering with language perception (as compared to fMRI), there is no need for the injection of radioactive agents (as compared to PET), both techniques exhibit higher temporal resolution compared to fMRI, PET and Single Photon Emission Computed Tomography (SPECT), and the absence of side effects makes this specific combination of methods particularly suitable for studies with children (i.e., for language development studies). Moreover, EEG–NIRS combinations are not tainted with technical interferences as both methods rely on different aspects of brain activation: Whereas EEG assesses neural responses directly based on electrical activity, NIRS gathers local haemodynamic responses based on the distinct optical properties of oxygenated and deoxygenated haemoglobin in order to indirectly measure activation changes in the brain. Hence, EEG–NIRS combined measurements allow for a complementary examination of neural as well as haemodynamic aspects of brain activation. We, therefore, applied simultaneous EEG–NIRS measurements to systematically assess both electrophysiological markers (i.e., event-related potentials – ERPs) – focussing also on early processes beyond the classically reported N400 component (see also below) – and haemodynamic correlates of activation within the language perception network, in order to gain new insights into the functional meaning and complex interplay of different aspects of novel metaphor comprehension. Although, up to now, no studies have used NIRS to investigate cortical haemodynamic responses specifically related to metaphoric language, the method has been repeatedly applied in various language perception studies in infants and adults and has been proven to be a useful and reliable tool in determining the neural basis of language comprehension during several task types (see Dieler et al., 2012, for an overview). Distinct frontal, temporal, and temporo-parietal activation patterns could be identified using NIRS in studies during auditory (Homae, Watanabe, Nakano, & Taga, 2007; Noguchi, Takeuchi, & Sakai, 2002; Saito et al., 2007; Sato, Sogabe, & Mazuka, 2007; Sato, Takeuchi, & Sakai, 1999), audiovisual (Bortfeld, Wruck, & Boas, 2007), and visual (Fallgatter, Mueller, & Strik, 1998; Hofmann et al., 2008; Liu, Borrett, Cheng, Gasparro, & Kwan, 2008) language presentation.

Examining the functional correlates of nonliteral language processing in particular, a wide range of imaging studies has been conducted using fMRI. At least 15 brain lesion studies (Lundgren, Brownell, Cayer-Meade, Milione, & Kearns, 2011; see Rapp, 2012) and at least 20 functional magnetic resonance imaging (fMRI) studies (Prat, Mason, & Just, 2012; Rapp, Mutschler, & Erb, 2012; Shibata et al., 2012) addressed the functional division of language associated brain structures and the role of the hemispheres during metaphor comprehension. fMRI based research suggests that left and – to a smaller degree – right inferior frontal and middle temporal brain structures and the parahippocampal gyrus may play a key role for metaphor comprehension. While some studies support the idea that right hemispheric areas are crucial for metaphor comprehension (Anaki, Faust, & Kravetz, 1998; Faust, 2012a, 2012b), a recent review and meta-analysis of the fMRI evidence suggests a predominantly left lateralized fronto-temporal network that is crucial for metaphor comprehension (Rapp et al., 2012). The left anterior inferior frontal gyrus is part of this network and could possibly be a functional correlate of the process of mapping semantic domains of the "source" and "target" during metaphor