NeuroImage 147 (2017) 812–824

Contents lists available at ScienceDirect

NeuroImage

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

Integration demands modulate effective connectivity in a fronto-temporal network for contextual sentence integration

Gesa Hartwigsen [a,b,*], Ilona Henseler [c], Anika Stockert [b], Max Wawrzyniak [b], Christin Wendt [b], Julian Klingbeil [b], Annette Baumgaertner [d], Dorothee Saur [b]

[a] Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences Leipzig, Germany
[b] Language & Aphasia Laboratory, Department of Neurology, University of Leipzig, Germany
[c] Department of Neurology, Max Planck Institute for Human Cognitive and Brain Sciences Leipzig, Germany
[d] Department of Speech Language Pathology, Hochschule Fresenius Hamburg, Germany

ARTICLE INFO

Article history:
Received 18 April 2016
Accepted 15 August 2016
Available online 16 August 2016

Keywords:
Inferior frontal gyrus
Dynamic causal modeling
Temporal cortex
Priming
Semantic processing
Language

ABSTRACT

Previous neuroimaging studies demonstrated that a network of left-hemispheric frontal and temporal brain regions contributes to the integration of contextual information into a sentence. However, it remains unclear how these cortical areas influence and drive each other during contextual integration. The present study used dynamic causal modeling (DCM) to investigate task-related changes in the effective connectivity within this network. We found increased neural activity in left anterior inferior frontal gyrus (aIFG), posterior superior temporal sulcus/middle temporal gyrus (pSTS/MTG) and anterior superior temporal sulcus/MTG (aSTS/MTG) that probably reflected increased integration demands and restructuring attempts during the processing of unexpected or semantically anomalous relative to expected endings. DCM analyses of this network revealed that unexpected endings increased the inhibitory influence of left aSTS/MTG on pSTS/MTG during contextual integration. In contrast, during the processing of semantically anomalous endings, left aIFG increased its inhibitory drive on pSTS/MTG. Probabilistic fiber tracking showed that effective connectivity between these areas is mediated by distinct ventral and dorsal white matter association tracts.

Together, these results suggest that increasing integration demands require an inhibition of the left pSTS/MTG, which presumably reflects the inhibition of the dominant expected sentence ending. These results are important for a better understanding of the neural implementation of sentence comprehension on a large-scale network level and might influence future studies of language in post-stroke aphasia after focal lesions.

Introduction

Rapid and accurate integration of contextual information into the overall meaning of a sentence is crucial for successful and efficient language comprehension in human everyday conversation. Numerous previous studies demonstrated that the integration of a final key word into a sentence is influenced by the preceding context (e.g., Hagoort, 2005; Hagoort and Indefrey, 2014; Rogalsky and Hickok, 2009; Obleser and Kotz, 2010, Zhu et al., 2013). Specifically, when accumulating words into a sentence, expectancies are generated with respect to the characteristics of the subsequent words (e.g. Kutas and Hillyard, 1980).

In everyday conversation, such expectancies are often violated, for instance in jokes, ironical statements, or when subdominant meanings of ambiguous words are processed. It was argued that situations that violate an expectation may partly affect lexical access and thus require additional integration processes to link a word to the previously established mental model (Franzmeier et al., 2012). Consequently, a word that corresponds well to a built-up expectation (e.g., "The housekeeper wipes the *floor*") is easier to integrate into a sentence than an unexpected ending (e.g., "The housekeeper wipes the *eyes*") (see Baumgaertner et al., 2002). Several electroencephalography studies demonstrated that the N400 component might represent an electrophysiological correlate of the integration demands of words into a given context (see Lau et al., 2008). Hence, higher integration demands such as unexpected sentence endings or semantic anomalies typically result in increased N400 amplitudes as well as increased response latencies when subjects are required to listen to or make decisions on these stimuli (e.g. DeLong et al., 2014; Federmeier et al., 2007; Kutas and Federmeier, 2000; Kutas and Hillyard, 1980). This

* Corresponding author at: Max Planck Institute for Human Cognitive and Brain Sciences Leipzig, Department of Neuropsychology, Research Group Leader "Modulation of Language Networks", Stephanstr. 1a, D-04103 Leipzig, Germany.
E-mail address: hartwigsen@cbs.mpg.de (G. Hartwigsen).

http://dx.doi.org/10.1016/j.neuroimage.2016.08.026
1053-8119/

indicates that deviance from sentential congruence increases integration difficulties. While these semantic integration effects are well characterized at the behavioral and event related potential level, the functional neuroanatomy of the underlying processes is less clear.

One of the few previous neuroimaging studies on contextual integration demonstrated that integration demands modulate task-specific neural activity in left-hemispheric fronto-temporal regions associated with semantic processing (Baumgaertner et al., 2002). In that study, healthy participants performed a lexical decision task on visually presented German sentences with varying integration demands, including highly expected endings ("the pilot flies the *plane*"), unexpected endings ("the pilot flies the *kite*"), semantically anomalous endings ("the pilot flies the *book*") or pseudoword endings ("the pilot flies the *foop*"). The priming effect of the sentential context led to prolonged response latencies with increasing integration demands. This was reflected in increased task-related activity in the left posterior middle temporal gyrus (pMTG) and, albeit to a lesser degree, in the left anterior inferior frontal gyrus (aIFG) for unexpected but semantically legal relative to expected endings, which in turn might indicate the successful reconciliation of semantic information with unexpected sentence endings. This is congruent with other studies which associated the left pMTG with tasks evoking semantic knowledge representations (e.g., Price et al., 1997). It also converges with the notion that a region encompassing pMTG and neighbouring superior temporal sulcus (STS) represents the best candidate for the storage of lexico-semantic information (see Lau et al., 2008).

Semantically incongruent (i.e., anomalous) relative to expected endings led to increased neural activity in left aIFG in the Baumgaertner et al. (2002) study. This supports the previously assigned role of the aIFG in the semantic executive system (e.g. Poldrack et al., 1999) and might particularly reflect increasing demands on semantic retrieval in the context of semantically conflicting situations (see Lau et al., 2008; Price, 2010).

Moreover, transcranial magnetic stimulation (TMS) studies demonstrated the functional relevance of both left pMTG and aIFG for lexical retrieval and selection during semantic processing with increased executive demands (Whitney et al., 2011b, 2012). In these studies, participants were required to determine which word was semantically related to a cue in the presence of two distractor items, with the target being strongly or weakly related to the cue (e.g., strong relation: salt-pepper, distractors: machine, land; weak relation: salt-grain, distractors: radio, adult). TMS over either aIFG or pMTG selectively impaired semantic decisions with high semantic control demands (i.e., weak relations), while decisions based on strong automatic associations were not affected. These results provide evidence for a key role of both regions in the executive semantic network supporting selection and controlled retrieval.

Recent neuroimaging studies suggest that the anterior part of the MTG at the border to the superior temporal sulcus (aSTS/MTG) also contributes to the processing of semantically legal sentences with low- compared to high-predictable endings (e.g. "he caught the fish in his *net*" vs. "the old man thinks about the *net*"; Obleser and Kotz, 2010).

While these results suggest that left pSTS/MTG, aIFG and probably also aSTS/MTG are engaged as sentential integration becomes more challenging, it is less clear how these regions interact and drive each other during sentence integration. The present study was designed to address this question. We thus relied on the well-established contextual integration paradigm described by Baumgaertner et al. (2002) to first identify changes in neural activity during contextual integration with varying demands. These results were then used to inform effective connectivity analyses that allowed us to investigate task-specific changes in the interaction between fronto-temporal areas by means of an exploratory dynamic causal modeling (DCM) approach. Note that DCM allows for the identification of the *direction* of influences exerted within a certain network and thus provides important insights into neurobiological mechanisms underlying observed differences in neural activity, which cannot be inferred using other connectivity analyses such as psychophysiological interactions (see Hartwigsen et al., 2015). DCM has been used in a variety of previous studies to investigate different aspects of language processing on both the word and sentence level (e.g., den Ouden et al., 2012; Hartwigsen et al., 2013a; Leff et al., 2008; Mechelli et al., 2005; Richardson et al., 2011). However, to the best of our knowledge, regional interactions during contextual integration have not been investigated so far.

Based on the results from the previous studies described above, we hypothesized that increasing integration demands should modulate task-specific activity in the left pSTS/MTG, aSTS/MTG and aIFG. Central to the present study, the comparison of high vs. low integration demands allowed us to investigate changes in the functional influence between these core regions for contextual integration. Specifically, we expected that unexpected but semantically legal completions might particularly draw on increased lexical integration demands subserved by temporal interactions. In contrast, anomalous completions should strongly require semantic control processes reflecting restructuring attempts in response to the impossibility to integrate the upcoming information into the sentential context. Anomalous endings might thus stronger rely on an interaction between left aIFG and pSTS/MTG.

To provide a comprehensive characterization of the network for contextual sentence integration, we further investigated the underlying anatomical connections within our fronto-temporal network of interest by means of probabilistic fiber tracking. This allowed us to assess whether task-specific effective connectivity might be mediated via distinct cortico-cortical connections.

Material and methods

Participants

17 healthy young volunteers (mean age = 25.5 years, standard deviation = 2.02 years) participated in the study. All subjects were right-handed (laterality index >95% according to the German version of the Edinburgh handedness test, (Oldfield, 1971)) native speakers of German with normal or corrected-to-normal vision. They had no history of neurological or psychiatric illness, no drug or alcohol abuse, no current pregnancy, no chronic medical disease, and no contraindication to MR-scanning. Subjects gave written informed consent prior to the experiment. The experiment was approved by the local ethics committee of the University of Leipzig.

Task and stimuli

The aim of this study was to investigate the neural basis of lexico-semantic integration. An experimental paradigm well suited for this purpose is the cloze paradigm. This paradigm allows modulation of the semantic integration demands by varying the expectancy of the final word in a sentence context. The sentence final word can either be (1) expected, (2) unexpected, (3) semantically incorrect (anomalous) or (4) a pseudoword. This leads to four experimental conditions, e.g. (1) "Der Schreiner baut den Tisch." ("*The carpenter builds the table.*") (expected ending); "Der Schreiner baut den Turm." ("*The carpenter builds the tower.*") (unexpected ending) (3) "Der Schreiner baut den Wein." ("*The carpenter builds the wine.*") (semantically incorrect ending) (4) "Der