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Sentence understanding depends on contextual use of semantic and real world knowledge

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ABSTRACT

Human language allows us to express our thoughts and ideas by combining entities, concepts and actions into multi-event episodes. Yet, the functional neuroanatomy engaged in interpretation of such high-level linguistic input remains poorly understood. Here, we used easy to detect and more subtle "borderline" anomalies to investigate the brain regions and mechanistic principles involved in the use of real-world event knowledge in language comprehension. Overall, the results showed that the processing of sentences in context engages a complex set of bilateral brain regions in the frontal, temporal and inferior parietal lobes. Easy anomalies preferentially engaged lower-order cortical areas adjacent to the primary auditory cortex. In addition, the left supramarginal gyrus and anterior temporal sulcus as well as the right posterior middle temporal gyrus contributed to the processing of easy and borderline anomalies. The observed pattern of results is explained in terms of (i) hierarchical processing along a dorsal-ventral axis and (ii) the assumption of high-order association areas serving as cortical hubs in the convergence of information in a distributed network. Finally, the observed modulation of BOLD signal in prefrontal areas provides support for their role in the implementation of executive control processes.

Introduction

Human language, in conjunction with other sensory input, constitutes an important source of information that helps us to interact safely and successfully with our environment. To *make sense* of linguistic input, i.e., to associate it with known objects, concepts, actions, and events, we can draw upon a myriad of relations that comprise our extensive semantic knowledge. An individual's semantic knowledge, or semantic memory, is grounded in and continuously shaped by perceptual experience. It not only enables the linking of word forms to objects, individuals, actions and abstract concepts, but also provides information on their respective attributes, purposes or intentions, and the associations among them. As such, semantic memory plays an important role in guiding action.

One of the prevailing questions addressed in recent neurobiological models of semantic memory is how modality-specific aspects of memory (e.g., reflecting different sensory, motoric or affective dimensions) are bound together and whether, in addition to the binding of these components, there is evidence for modality-independent "hubs" or "convergence zones" (Damasio, 1989; Damasio et al., 2004; Martin, 2007; Patterson et al., 2007; Binder and Desai, 2011). The model proposed by Binder and Desai, for example, differentiates between low-level modal and high-level supramodal convergence zones: "*Modality-specific sensory, action, and emotion systems (…) provide experiential input to high-level temporal and inferior parietal convergence zones (…) that store increasingly abstract representations of entity and event knowledge*" (Binder and Desai, 2011). From this perspective, high-level convergence zones, particularly those involving parts of the inferior parietal lobule (IPL), are deemed important for the emergence and use of event knowledge by serving to bind together a wealth of modality-specific information converging onto entities and events that interact in space and time to make up a particular episode. Numerous studies on language processing have used descriptions of very simple events (e.g., "*The man on vacation lost a bag and a wallet*"; Humphries et al., 2007) to investigate semantic processing at the single sentence level, and many of these studies have implicated the angular gyrus and in some cases the adjacent supramarginal gyrus as critical regions (Ni et al., 2000; Friederici et al., 2003; Newman et al., 2003).

Beyond the level of semantic knowledge required for the interpretation of these simple events, however, semantic memory must also encompass information on broader episodes arising from the combination of multiple events. Here, we use the term scenario to denote such complex sets of events. Scenarios can describe a wide array of topics, covering a continuum that ranges from unique personal experiences or particular historic events (e.g., the Titanic's maiden voyage) to recurring patterns of events that can be generalized in so-called event schemata or cognitive

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scripts (e.g., hosting a dinner party). Independent of whether they describe unique or generalizable situations, scenarios are defined by the involvement of specific entities and their respective roles in the series and/or co-occurrence of individual events.

However, little research has been conducted to date examining the functional neuroanatomy underlying the processing of such complex stimuli: the majority of studies on semantic processing using language have generally focused on single words that vary along different dimensions or on the comparison of semantically congruent and incongruent single sentences (e.g., Ni et al., 2000; Newman et al., 2001; Vandenberghe et al., 2002; Friederici et al., 2003; Humphries et al., 2006, 2007). Moreover, at the sentence level, these types of manipulations typically involve a word or phrase that has a poor fit to the global context (e.g., "*The thunderstorm was ironed*" vs. "*The shirt was ironed*"; example from Friederici et al. (2003)). Given the lack of semantic association between the incongruent element and the surrounding context, it is unclear whether these types of experimental manipulations are adequate for tapping into the neural mechanisms of higher-level semantic processing. One might argue that changes in brain activity in response to such incongruent words or phrases embedded in single sentences reflect a lack of normally (ecologically) occurring contextual priming as opposed to an evaluation of message-level plausibility.

There are, however, other semantic anomalies, termed "anomalies at the borderline of awareness" or simply "borderline anomalies" (Sanford et al., 2011) that represent an interesting exception. Borderline anomalies – the "Moses Illusion" being the most famous example – are particularly hard to detect because the anomaly-inducing word has a strong semantic relationship to the meaning of the words and even to the propositional content of the context. In other words, the critical word is closely associated with the scenario as a whole but it does not constitute the correct filler for the "slot" in which it occurs. Borderline anomalies frequently include incorrect but closely related protagonists who perform or are affected by a described action while in other cases the action itself may be incorrect but again strongly associated with the scenario as a whole. The original Moses Illusion ("*How many animals of each kind did Moses take on the ark*?") is an example of a distorted question that falsely presents the biblical figure Moses as the builder and sailor of the ark. Due to the high degree of semantic similarity (in most people's semantic memory) between Moses and Noah, the correct agent for the role, very few people notice the anomaly (Erickson and Mattson, 1981). Other studies have embedded these types of semantic illusions in more elaborate context, thus creating the types of scenarios under discussion here:

> "*A pay dispute between lorry drivers and their employers reached a crisis in negotiation; even the professional mediators seemed dejected. After five days of discussion the government rejected outright the final conciliatory pay-offer and halted the talks*".
>
> [Sanford et al., 2011]

In this case the incorrect term *government* is again closely related to the global scenario but its assigned role is unexpected given what we know about these kinds of situations. Scenarios of this type thus permit investigation of language comprehension in a way that requires the application of higher-level event knowledge, as it is not confounded with a lack of semantic association between the critical word or phrase and the overall scenario.

To date, several studies have investigated the processing of borderline (and easy to detect) anomalies using EEG, eye-tracking or fMRI. The fMRI study by Raposo and Marques (2013) contrasted obvious semantic anomalies with more subtle incongruencies in single sentences (e.g., "*It was the terrible stepmother who tried to kill Cinderella with a poisoned apple*"). The authors found higher levels of BOLD activity for subtle anomalies compared to true statements in the right IPL, which they link to processes of generating and integrating inferences. Comparing detected to undetected subtle anomalies increased activity in the dorsolateral prefrontal cortex, orbitofrontal cortex and insula, which they link to conflict monitoring and error detection. However, the choice of it-cleft structures as a means of directing the listeners' attention to a particular part of the sentence strongly discourages the integration of all involved components into a global meaning — the very process we aim to investigate. Moreover, it is unclear whether neural responses to isolated it-cleft sentences are reflective of brain mechanisms underlying ecological language comprehension, as these structures cannot be felicitously uttered without supporting context.

The EEG and eye-tracking studies contrasted obvious and borderline anomalies embedded in sentence pair structures or short paragraphs (Daneman et al., 2007; Bohan and Sanford, 2008; Sanford et al., 2011; Bohan et al., 2012; Tune et al., 2014). The results of these studies have provided important insights into the time course of semantic processing in context but they only allow limited conclusions about the underlying neural circuitry.

Thus, given the scarcity of functional neuroimaging studies focused on the question of how the brain accomplishes the interpretation of complex scenarios including the integration of multiple events and the evaluation of the derived global message against real-world knowledge, the neural mechanisms and circuitry involved in implementing these processes remain insufficiently characterized. Our study attempts to close this gap by taking advantage of the properties of contextually embedded borderline anomalies that cannot be categorized as anomalous based on a lack of semantic priming and therefore require a thorough semantic analysis and the application of world knowledge. As such, they provide a novel way of studying the brain mechanisms that support ecological language comprehension.

The present study

In the present study we set out to investigate the neuroanatomical substrates underlying the use of semantic knowledge in understanding sentences in context, with a particular focus on the interpretation of scenarios that call for extensive evaluation. More precisely, we were interested in identifying the set of brain regions and mechanistic principles implicated in the application of real-world event knowledge to sentence interpretation, i.e., the assessment of whether a described relation between events and their respective participants is consistent with expectations derived from previous experience. Further, we aimed to tease apart changes in brain activity that are the result of high-level comprehension processes from those that reflect processes at lower levels, e.g., effects of lexical-semantic associations. Finally, we aimed to address these issues in a way that would provide group-level results of high anatomical precision.

The experimental design and analysis of the present study address our specific goals in the following ways. We contrasted two different types of scenarios that were created by embedding borderline anomalies and easy (obvious) anomalies in a richer context. Each anomalous sentence was paired with a closely matched non-anomalous control sentence, thus yielding a 2×2 design with factors Plausibility (anomalous vs. non-anomalous) and Scenario Type (borderline vs. easy). Our study design builds on the logic that plausible, non-anomalous scenarios are more likely to confirm our expectations, whereas implausible, anomalous scenarios correspond less closely to our beliefs and assumptions about the world. The use of borderline anomalies is key to our goal of tapping into the mechanisms implementing high-level comprehension processes, since, in contrast to easy to detect anomalies, they cannot be classified as being anomalous simply based on the poor semantic fit of a single word or phrase to the broader semantic context. This specific design has been adapted from that successfully employed in several EEG studies (Tune et al., 2014; Sanford et al., 2011).

Based on results from previous EEG and eye-tracking studies suggesting that detected and non-detected trials are processed differently (Bohan and Sanford, 2008; Sanford et al., 2011; Bohan et al., 2012; Tune et al., 2014), we used a plausibility judgment task that would