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Broca's region: A causal role in implicit processing of grammars with crossed non-adjacent dependencies

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ABSTRACT

Non-adjacent dependencies are challenging for the language learning machinery and are acquired later than adjacent dependencies. In this transcranial magnetic stimulation (TMS) study, we show that participants successfully discriminated between grammatical and non-grammatical sequences after having implicitly acquired an artificial language with crossed non-adjacent dependencies. Subsequent to transcranial magnetic stimulation of Broca's region, discrimination was impaired compared to when a language-irrelevant control region (vertex) was stimulated. These results support the view that Broca's region is engaged in structured sequence processing and extend previous functional neuroimaging results on artificial grammar learning (AGL) in two directions: first, the results establish that Broca's region is a *causal* component in the processing of non-adjacent dependencies, and second, they show that *implicit* processing of non-adjacent dependencies engages Broca's region. Since patients with lesions in Broca's region do not always show grammatical processing difficulties, the result that Broca's region is causally linked to processing of non-adjacent dependencies is a step towards clarification of the exact nature of syntactic deficits caused by lesions or perturbation to Broca's region. Our findings are consistent with previous results and support a role for Broca's region in general structured sequence processing, rather than a specific role for the processing of hierarchically organized sentence structure.

1. Introduction

An important aspect of natural language processing is related to structured sequence processing (Christiansen & Chater, 2008; Gomez & Gerken, 2000; Petersson, Forkstam, & Ingvar, 2004; Reber, 1967). The connection between sequence- and natural language processing is most easily described within the domain of syntax. During fluent syntax processing, structured sequences of words are parsed incrementally and, when possible, immediately. This process gains robustness by prediction of syntactic features of expected words downstream in a sentence. One example is number agreement in English. Plural marking of a noun (the boys rather than the boy) predicts that the corresponding verb will be in the plural form (play rather than plays). Sometimes words which are syntactically dependent, are far apart in terms of sequential order, that is, the dependency is non-adjacent or long-distance. For example, the noun-verb pair boys-play forms a non-adjacent dependency in "The *boys* in the morning group *play* with Susan". Multiple non-adjacent dependencies can also be found in a single sentence. For instance, in "All the *animals* that *I* can *think* of *are* wild", the dependent noun-verb pair "*I-think*" is embedded in the intervening material between the noun and verb in the pair "*animals-are*". The challenge of maintaining predictions based on multiple non-adjacent dependencies makes these structures well-suited for studying the neural implementation of structured sequence processing.

Recent research has investigated different types of sentence-level dependencies and their relative processing difficulties. For instance, the computational process of syntactic unification (Hagoort, 2005; Vosse & Kempen, 2000) is more extended in time for sentences with non-adjacent compared to adjacent dependencies. This requires on-line processing memory, pointing to the close connection between memory resources and the processing of non-adjacent dependencies (Uddén, Ingvar, Hagoort, & Petersson, 2012). The costs on memory and processing for non-adjacent dependencies is in line with evidence showing that these dependencies are mastered relatively late in infant development. For example, Gómez and Maye (2005) showed that while 15-month-old children were sensitive to a simple non-adjacent dependency, this was not the case for 12-month olds

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(for a recent review, see Folia, Uddén, De Vries, Forkstam, & Petersson, 2011). Cotton-top tamarins (Newport, Hauser, Spaepen, & Aslin, 2004), squirrel monkeys (Ravignani, Sonnweber, Stobbe, & Fitch, 2013), and chimpanzees (Sonnweber, Ravignani, & Fitch, 2015) are capable of acquiring simple non-adjacent dependencies, but work with these non-human primates has also shown greater processing difficulties when non-adjacent dependencies are directly compared with adjacent dependencies (Fitch & Hauser, 2004).

Three FMRI studies suggest that the neural correlates of explicit non-adjacent dependency processing include Broca's region (Bahlmann, Schubotz, & Friederici, 2008; Friederici, Bahlmann, Heim, Schubotz, & Anwander, 2006; Makuuchi, Bahlmann, Anwander, & Friederici, 2009). However, FMRI only characterizes the correlation between a cognitive task and the measured blood oxygenation level dependent (BOLD) signal. The observed activations might differ in their causal relation to task performance. In the present study we investigated two main questions: (1) whether there is a causal connection between activity in Broca's region and the processing of non-adjacent dependencies using repetitive transcranial magnetic stimulation (rTMS) in an artificial grammar learning paradigm; and (2) whether implicit processing of adjacent and non-adjacent dependencies requires the involvement of Broca's region. By implicit processing, we mean information processing resulting from implicit learning. Implicit learning is defined as "the process whereby a complex, rule-governed knowledge base is acquired, largely without any requirements of awareness of either the process or the product of acquisition" (Reber, Walkenfeld, & Hernstadt, 1991). In particular, we note that implicit learning/processing happens in the absence of explicit strategies (e.g., problem solving). While the above FMRI studies are interesting as a first estimate of where non-adjacent dependencies are processed in an experimental setting with explicit instructions, we wanted to test whether these results could be extended to the more ecologically valid situation of implicit processing. We also investigate the potential causal connection between Broca's region and structured sequence processing in order to understand the functional organization of the inferior frontal cortex in general (Hagoort, 2005; Petersson et al., 2004; Uddén & Bahlmann, 2012).

The causal role of Broca's region in language processing has been studied in the vast literature on Broca's aphasia, but there is still no consensus on whether Broca's region plays a causal role in syntactic comprehension. For instance, Dronkers (2000) argued that lesions restricted to Broca's area never lead to persistent Broca's aphasia and that damage of the tissue in the surrounding frontal cortex is necessary for more extensive symptoms than transient mutism. The grammaticality judgments of Broca's aphasics are often largely unaffected by the lesion, although sentence comprehension can be poor (Linebarger, Schwartz, & Saffran, 1983). In addition to production impairments, Broca's aphasics are sometimes regarded as having a specific receptive syntactic disorder. What constitutes this receptive disorder remains an open question (Caramazza & Zurif, 1976; Grodzinsky, 2000; Linebarger et al., 1983; Martin, Wetzel, Blossom-Stach, & Feher, 1989). Testing causal brain function with TMS rather than lesions is advantageous since TMS combines systematic target locations with the absence of any adaptive changes as a reactive response to the lesion itself. The demonstration of a causal connection between Broca's region and implicit processing of non-adjacent dependencies would therefore be a step towards clarification of the exact nature of a potential receptive syntactic deficit caused by lesions or perturbation of Broca's region.

Having introduced the main motivation for the current study, we will specify the experimental paradigm and its relation to the neurobiology of language. Artificial grammar learning (AGL; see below for a concrete description of the task) is a well-established paradigm commonly used to investigate implicit structured sequence processing (Forkstam & Petersson, 2005; Stadler & Frensch, 1998). The implicit aspect of AGL makes it a suitable model for structural aspects of language acquisition in a laboratory setting (de Vries, Christiansen, & Petersson, 2011). For example, the aspects of natural language syntax that are acquired as a consequence of supervised teaching are negligible compared to what is acquired spontaneously through exposure to well-formed examples, as in implicit AGL (Folia, Uddén, et al., 2011). Consequently, investigating the localization of *implicit* processing of non-adjacent dependencies increases the relevance of AGL results in relation to natural language. At the same time, we wanted to use the AGL paradigm because it provides a relatively uncontaminated window onto the neurobiology of structured sequence processing (e.g., no semantics in a linguistic sense) as an important aspect of syntax (Gomez & Gerken, 2000; Petersson et al., 2004; Reber, 1967). There are examples of studies where the sentence-level semantics complicate the interpretation of FMRI results on the processing of non-adjacent dependencies (Makuuchi et al., 2009). Additional homologies between implicit AGL and natural language acquisition have been demonstrated during the course of development (Gerken, 2006; Gervain, Nespor, Mazuka, Horie, & Mehler, 2008; Gómez & Maye, 2005; Santelmann & Jusczyk, 1998). Moreover, individual differences in non-adjacent dependency processing in natural language and statistical learning of non-adjacent dependencies in abstract sequences are correlated (Misyak, Christiansen, & Tomblin, 2009). Together, this evidence suggest a strong link between natural language processing and implicit sequence learning (cf., Christiansen, Louise Kelly, Shillcock, & Greenfield, 2010).

In this study we address the neurobiology of non-adjacent dependency processing in an AGL rTMS experiment. The studies, briefly outlined above, used considerably simpler grammars and less ecologically relevant paradigms, compared to the grammars and paradigm used in this study. Our paradigm improves on some of these aspects by: (1) using the largest artificial language size tested so far, both in terms of sequence lengths and the number of sequences participants were exposed to; (2) testing the most complex patterns investigated so far, with multiple non-adjacent dependencies with additional variance in pre- and postfix sequences with adjacent dependencies; (3) using an extended period of acquisition over several days in an implicit learning paradigm, which allows for natural abstraction and consolidation processes to take place (Nieuwenhuis, Folia, Forkstam, Jensen, & Petersson, 2013); and (4) as in natural language acquisition, not instructing participants to extract regularities nor providing any type of performance feedback.

In the acquisition phase of AGL, participants are exposed to sequences generated from a complex rule system in a cover task. Participants are then instructed to classify novel items as grammatical, or not, based on their immediate intuitive impression, or guessing based on their "gut feeling". Gut feeling is referred to in order to minimize explicit problem solving strategies, which might lead to poor classification performance, for example, because irrelevant or incorrectly inferred rules are applied (Whitmarsh, Udden, Barendregt, & Petersson, 2013). The AGL paradigm used in the present study is designed to test implicit processing (Folia & Petersson, 2014). This is achieved by making the task substantially more difficult than is typically the case. Under this condition, explicit processing will typically be less successful than implicit processing. Furthermore, the types of violations we use exclude the possibility of successful classification based on explicit strategies such as counting, repetition monitoring, or equivalent (de Vries, Monaghan, Knecht, & Zwitserlood, 2008). The acquisition phase was also considerably longer than in earlier studies of non-adjacent processing (Bahlmann et al., 2008; de Vries et al., 2008; Friederici et al., 2006) allowing consolidation and abstraction processes to take place over at least a week. Importantly, we measured implicit acquisition by adding an implicit test to the initial test phase, using a preference instruction (Forkstam, Elwér, Ingvar, & Petersson, 2008). Here, participants are never informed about the existence of a grammar but