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Research report

Whole-brain functional connectivity during acquisition of novel grammar: Distinct functional networks depend on language learning abilities☆

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HIGHLIGHTS

- We investigate individual differences in artificial grammar learning during fMRI.
- A data-driven approach to functional connectivity of the brain was adopted.
- Data collected during the task were decomposed into maps representing separate cognitive processes.
- We conclude that engagement of brain's networks during grammar acquisition is coupled with one's language learning abilities.

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ABSTRACT

In an effort to advance the understanding of brain function and organisation accompanying second language learning, we investigate the neural substrates of novel grammar learning in a group of healthy adults, consisting of participants with high and average language analytical abilities (LAA). By means of an Independent Components Analysis, a data-driven approach to functional connectivity of the brain, the fMRI data collected during a grammar-learning task were decomposed into maps representing separate cognitive processes. These included the *default mode*, *task-positive*, *working memory*, *visual*, *cerebellar* and *emotional* networks. We further tested for differences within the components, representing individual differences between the High and Average LAA learners. We found high analytical abilities to be coupled with stronger contributions to the *task-positive* network from areas adjacent to bilateral Broca's region, stronger connectivity within the *working memory* network and within the *emotional* network. Average LAA participants displayed stronger engagement within the *task-positive* network from areas adjacent to the right-hemisphere homologue of Broca's region and typical to lower level processing (visual word recognition), and increased connectivity within the *default mode* network. The significance of each of the identified networks for the grammar learning process is presented next to a discussion on the established markers of inter-individual learners' differences. We conclude that in terms of functional connectivity, the engagement of brain's networks during grammar acquisition is coupled with one's language learning abilities.

Abbreviations: AGL, artificial grammar learning; BOLD, blood-oxygenation-level-dependent; DMN, default mode network; EPI, echo-planar images; FEAT, FMRI Expert Analysis Tool; fMRI, functional magnetic resonance imaging; IC, independent component; ICA, independent component analysis; IFG, inferior frontal gyrus; L2, second language; LAA, language analytical ability; MELODIC, Multivariate Exploratory Linear Decomposition into Independent Components; PCA, principal component analysis; ROI, region of interest; SLA, second language acquisition; TE, echo time; TFCE, threshold-free cluster enhancement approach; TR, repetition time; VWFA, visual word form area.

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1. Introduction

The knowledge of a second language (L2) in today's globalised world seems more and more indispensable. High levels of proficiency in an L2 play an important role in many people's economic, social and private lives. No matter its importance however, language acquisition can be characterised by a great deal of variability in the rate, efficiency and ultimate success. Understanding the factors contributing to such variability can aid the efforts to describe the theoretical foundations of second language acquisition (SLA) and – from an applied point of view – in improving the outcomes of learning and instruction.

Like other high-level cognitive functions, language is governed by synchronized activity of distributed areas (cf. e.g. [1–6]). How different brain areas interact with each other, and what networks arise from those interactions is a question posed in more and more investigations into the neural architecture behind language processing and acquisition. Insights into the connectivity of the brain, both in terms of its structural (e.g. [7–13]) and functional networks (e.g. [14–23]), keep advancing our understanding of the neural foundations of human communication.

One powerful tool for exploring the connectivity of the brain is functional magnetic resonance imaging (fMRI). It offers a view on temporal correlations between the hemodynamic activity of different brain areas and can be used for visualising and quantifying functional connectivity patterns at rest or during cognitive tasks (cf. [22,24–29]).

With this paper, we wanted to explore the functional connectivity patterns during initial phases of L2 acquisition and networks' characteristics responsible for successful acquisition of a new language: a theme that has recently attracted interest in other studies in the context of language acquisition, which we briefly review below.

1.1. Functional networks of the brain and individual differences in L2 acquisition

Functional networks associated with vocabulary learning in a new language were investigated by Veroude et al. [22]. Functional connectivity of brain regions involved in phonological processing was measured during rest, before and after exposure to a new language. The authors showed that the recorded connectivity patterns differ between 'good' and 'bad' learners determined on the basis of their performance on a word recognition task after the scanning. Before the exposure to a new language, stronger connectivity between two sets of regions: the left supplementary motor area and the left precentral gyrus, and between the left insula and the left rolandic operculum was observed for 'good' compared to 'bad' learners. The authors interpreted this stronger connectivity as representing "a favourable disposition for the processing of the unknown language input" (p. 25). Furthermore, at the end of the task, good learners exhibited stronger functional connectivity between the left and right supramarginal gyrus, which was interpreted as an effect of exposure to the language itself and not a pre-existing difference between learners.

In a study investigating brain connectivity patterns in a group of Persian speakers learning new vocabulary in French, Ghazi Saidi et al. [18], showed that network integration levels decreased as proficiency for L2 increased, thus reflecting more automatic processing of the L2. Furthermore, Yang et al. [23] recently investigated the development of brain networks as a function of short-term tonal L2 learning experience and reported functional connectivity results relating to successful acquisition of novel words. The successful learners in their study were identified on the basis of behavioural performance after the training, but due to their high accuracy on the sound discrimination task prior to training, they were hypothesized to be "well suited to learning a vocabulary in which lexical tones make up the critical information" (p. 45). At the level of brain connectivity, the successful learners demonstrated more integrated networks both before and after the training: in comparison to the non-learners, their frontal-temporal network was stronger at the first time-point, whereas at the second, they could be characterized by strong global, as well as local connectivity, and automatic lexical processing of acquired word knowledge driven by the inferior parietal lobule.

Learning novel words is undeniably one of the most important building blocks of acquisition of a new language. The brain's functional connectivity underlying another crucial subcomponent of language learning, namely the acquisition of grammatical rules, was investigated by Antonenko et al. [17] and Dodel et al. [21]. In their study, Antonenko et al. [17] used an artificial grammar learning (AGL) task to explore the ability to extract grammatical rules from new material in healthy older adults and found an opposite relationship between AGL task performance and resting-state functional connectivity of left and right BA 44/45: lower performance was tied to stronger inter-hemispheric functional coupling. Processing of syntax in L2 by bilinguals was explored by Dodel et al. [21] who showed that regions associated with syntax and language production – left inferior frontal gyrus (IFG), putamen, insula, precentral gyrus, and the supplementary motor area – were more functionally connected in L2 than in L1. The strength of this functional connectivity was modulated by participants' syntactic proficiency: the functional connectivity network was less present in less proficient bilinguals.

With the present experiment, we aimed at concentrating on novel grammar learning, and capturing whole-brain functional connectivity correlates of the process of new syntax acquisition in its initial phase. Similarly to Antonenko et al. [17], we employed an AGL paradigm in order to ensure that our data represent the neurobiology of syntax acquisition and processing, without the interference of semantics, phonology or pragmatics, and are not influenced by prior exposure (cf. e.g. [30–32]). In particular, we chose a paradigm enabling an investigation into rule learning in real time, in which learning is simultaneous to the recording of fMRI data. The chosen artificial language BROCANTO [33–39] is based on a set of pronounceable pseudo words, combined in ways following rules found in many natural languages. The paradigm can thus be seen as a model for language learning, though a highly controlled one (see section 2.2 for a further description of the paradigm).

1.2. Language aptitude and language analytical ability

Next to investigating the functional connectivity patterns present during the acquisition of novel grammar, we wanted to explore more fully, what in previous language acquisition connectivity studies was interpreted as a "favourable disposition" [22] of L2 learners or being "well suited" to learn a particular aspect of an L2 [23]. Within the field of second language acquisition, a bulk of research has been dedicated to investigating pre-existing differences between learners, and L2 learning success has repeatedly been linked to the notion of language aptitude (cf. e.g. [40–42]).

Language aptitude is defined as an individual, relatively immutable cognitive ability particular to language learning, which is a combination of skills that are fairly independent from each other. The multi-componential nature of language aptitude can be found in tests measuring it. For example, the LLAMA Language Aptitude Test (LLAMA) [43], consists of four parts: (1) a vocabulary learning task, (2) a test of phonetic memory, (3) a test of sound-symbol correspondence and (4) a test of grammatical inferencing, being a measure of language analytical ability (LAA). LAA is relevant for pattern identification during SLA, which involves analysing and processing new linguistic input [44]. Arguably, LAA is