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Neural oscillatory mechanisms during novel grammar learning underlying language analytical abilities

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ABSTRACT

The goal of the present study was to investigate the initial phases of novel grammar learning on a neural level, concentrating on mechanisms responsible for individual variability between learners. Two groups of participants, one with high and one with average language analytical abilities, performed an Artificial Grammar Learning (AGL) task consisting of learning and test phases. During the task, EEG signals from 32 cap-mounted electrodes were recorded and epochs corresponding to the learning phases were analysed. We investigated spectral power modulations over time, and functional connectivity patterns by means of a bivariate, frequency-specific index of phase synchronization termed Phase Locking Value (PLV). Behavioural data showed learning effects in both groups, with a steeper learning curve and higher ultimate attainment for the highly skilled learners. Moreover, we established that cortical connectivity patterns and profiles of spectral power modulations over time differentiated L2 learners with various levels of language analytical abilities. Over the course of the task, the learning process seemed to be driven by whole-brain functional connectivity between neuronal assemblies achieved by means of communication in the beta band frequency. On a shorter time-scale, increasing proficiency on the AGL task appeared to be supported by stronger local synchronisation within the right hemisphere regions. Finally, we observed that the highly skilled learners might have exerted less mental effort, or reduced attention for the task at hand once the learning was achieved, as evidenced by the higher alpha band power.

1. Introduction

Second language (L2) learning can be characterised by a great deal of variability in the rate, efficiency and ultimate success. For some individuals, it requires strenuous efforts, whereas, for others, high levels of proficiency in an L2 can be attained with relative ease and little time investment. Understanding what factors are responsible for such variability among learners is important both for second language acquisition (SLA) theory building, and the applied efforts for learning and instruction improvements.

From a neurophysiological point of view, high-level cognitive functions such as language, necessarily depend on synchronised activity both between and within specific neural assemblies (Bressler, 1995; Bressler & Menon, 2010; Friederici & Singer, 2015; Maguire & Abel, 2013; Mesulam, 1998; Singer, 1993; Varela, Lachaux, Rodriguez, & Martinerie, 2001; Weiss & Mueller, 2003). Investigations into interactions taking place in different brain areas and the networks arising from them are invaluable for understanding the neural underpinnings of human communication. One possible way of exploring such interactions is to study the rhythms of the brain, their topographical properties, task- and state-dependent development, and dynamics. Such neural oscillations lie at the centre of coordinated activity of the brain and are seen as one of the fundamental mechanisms enabling learning and neural plasticity (Benchenane et al., 2010; Uhlhaas & Singer, 2010).

The goal of this paper is to investigate the initial phases of learning a new language, when completely new linguistic input is identified, analysed, processed, and – with various levels of success and different degrees of efficiency – learned. We are interested in the way such a learning process is reflected in neural oscillations over time and in the mechanisms responsible for variability between the learners. A technique well suited for investigating brain oscillatory architecture during language learning is electroencephalography (EEG) (cf. De Diego-Balaguer, Fuentemilla, & Rodriguez-Fornells, 2011; Reiterer, Pereda, & Bhattacharya, 2009; Wang, 2010). It offers a view on the

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nature of brain rhythms in different frequencies during information processing, and coherence or synchronisation analyses can be used to visualise the functional cooperation between cortical regions.

EEG signals recorded during a cognitive task can be indicative of synchronisation of local and distant cortical networks; the signal can be quantified by means of, for example, power spectrum or synchronisation analyses (cf. e.g. Siegel, Donner, & Engel, 2012; Wang, 2010). Spectral power variations reflect the number of neurons discharging at the same time (Kiiski et al., 2012; Klimesch, 1999), and are thus seen as a measure of local neuronal activity. Employing coherence analyses, EEG offers a view on functional cooperation between cortical regions: brain areas activated by a particular cognitive task exhibit increased coherence, and high coherence between two EEG signals is indicative of high cooperation (degree of information flow) and synchronisation between underlying brain regions within a certain frequency band (Weiss & Mueller, 2003).

Furthermore, there are various putative roles assigned to different frequency bands (see e.g. Uhlhaas & Singer, 2010 for an overview). For example, the beta band frequency (13–29 Hz) has been linked to long-range synchronisation (Kopell, Ermentrout, Whittington, & Traub, 2000), and within the language domain, to underlie such higher-order functions as semantic memory and syntactic binding (Bastiaansen, Magyari, & Hagoort, 2010; Weiss & Mueller, 2012). Gamma band frequency (30–40 Hz) is believed to be tied to for example perceptual processing, attention, and episodic memory formation (cf. Herrmann, Munk, & Engel, 2004; Reiterer et al., 2009). In the context of learning, Miltner, Braun, Arnold, Witte, and Taub (1999) found the development of gamma band coherence to be a signature of associative learning. They put forward that an increase in coherence in the gamma band "could fulfil the criteria required for the formation of Hebbian cell assemblies, binding together parts of the brain that must communicate with one another in order for associative learning to take place" (Miltner et al., 1999) and suggested it could be the case for other types of learning as well.

The different EEG frequency bands can also reflect various strategies employed for learning. De Diego-Balaguer et al. (2011) investigated the dynamics of synchronisation properties of the EEG signal during auditory language learning. In a study employing exposure to an artificial language, they found that increased long range gamma band phase coherence between frontal, temporal, and parietal regions accompanied successful learning of rules embedded in the presented speech stream. On the other hand, poor rule learners exhibited greater local synchrony in the gamma range and increased theta-band (4–8 Hz) coherence over the course of the task. Different learning strategies for the two groups were thus suggested based on both behavioural and neurophysiological data. Whereas successful learning was driven by rule extraction (and coupled with long range gamma band coherence), the poor learners seemed to apply a more memory-oriented, template-matching strategy during learning, reflected in local gamma power and theta-band coherence increases.

Within the framework of SLA, coherence of the EEG signals was investigated by Reiterer et al. (2009), Reiterer, Pereda, and Bhattacharya (2011) who explored differences in EEG synchronisation measures in the gamma band range between second language speakers of English with high and low proficiency who were listening to first (L1, German) and second language input. The authors reported different patterns of synchronisation for the two groups, involving more extensive networks in the right hemisphere for participants with low L2 proficiency during processing of English input, and an inverse relationship between L2 proficiency and synchronisation density: high proficiency was coupled with lower synchronisation (Reiterer et al., 2009). Further investigation into the gamma band phase synchrony (Reiterer, Pereda, & Bhattacharya, 2011) by means of coarse-graining of Markov chains (Allefeld & Bialonski, 2007) and phase lag index (Stam, Nolte, & Daffertshofer, 2007) revealed differences between low and high L2 proficiency participants during second language processing. The group with less L2 expertise displayed stronger and broader network patterns than the high proficiency group, especially in fronto-parietal areas of the left hemisphere. The authors noted that differences between the two groups of learners might have reflected pre-existing individual differences in the linguistic abilities of the participants, rather than differences in L2 proficiency only.

Within the field of SLA, such individual differences in linguistic abilities are referred to as language aptitude. Language aptitude is a relatively fixed ability of an L2 learner to acquire a language. It is a strong predictor of achievement in L2 (Dörnyei & Skehan, 2003; Ellis, 2008; Sawyer & Ranta, 2001) and plays an important role both in instructed (de Graaff, 1997) and naturalistic (Abrahamsson & Hyltenstam, 2008; DeKeyser, 2000; Harley & Hart, 2002; Robinson, 1997) language learning. Traditionally, language aptitude has been operationalised by means of standardised test instruments aiming at capturing learners' abilities underlying L2 acquisition. Such tests typically consist of a number of different parts, underscoring the multi-componential nature of language aptitude of which four sub-components are traditionally distinguished: rote learning memory, phonemic coding ability, inductive language learning ability and grammatical sensitivity, the two latter also referred to as language analytic ability (LAA) (cf. Abrahamsson & Hyltenstam, 2008; Carroll, 1981; Dörnyei & Skehan, 2003; Ellis, 2008; Sawyer & Ranta, 2001; Skehan, 2002). In recent years, the theoretical construct of language aptitude has also been investigated from a neuroscientific perspective, with the aim of indicating the aspects of brain functioning that underlie the different aptitude components (Hu et al., 2013; Kepinska, de Rover, Caspers, & Schiller, 2017; Prat, Yamasaki, Kluender, & Stocco, 2016; Xiang, Dediu, Roberts, Norris, & Hagoort, 2012).

In this study, drawing on the construct of language aptitude, we wanted to *a priori* control for individual variability between the learners, and explore the neural mechanisms of language learning coupled with high and moderate abilities. In our approach, we focused on one of the most important elements of L2 acquisition, namely novel grammar learning. Our aim was to explore how the sub-component of language aptitude crucial for grammar acquisition (i.e. the LAA), influences initial phases of L2 learning and the properties of the EEG signal measured during such a task. To this end, we employed an experimental design previously used in research investigating the neurobiological basis of language acquisition, namely an Artificial Grammar Learning (AGL) paradigm. The design of our experiment was based on the study of Opitz, Ferdinand, and Mecklinger (2011), where the artificial language BROCANTO was used (cf. Friederici, Steinhauer, & Pfeifer, 2002; Opitz & Friederici, 2003). In studies employing the BROCANTO language (e.g. Brod & Opitz, 2012; Friederici et al., 2002; Hauser, Hofmann, & Opitz, 2012; Opitz & Friederici, 2003, 2004, 2007; Opitz et al., 2011) participants are presented with sentences constructed according to its rules and are instructed to extract the underlying grammar. The paradigm consists of learning and test phases. During learning, participants are presented only with grammatically correct sentences. In the test phases, both grammatical and ungrammatical sentences are presented and participants are asked to give a grammaticality judgement on the sentences.

Previous fMRI studies employing this paradigm concentrated on temporal changes in brain activity, and on the underpinnings of two types of knowledge acquired over the course of AGL: rule and similarity knowledge. Opitz and Friederici (2003) reported decreasing activity of the hippocampus and increasing activity of the left inferior frontal gyrus as a function of time and performance during the task. Opitz and Friederici (2004) extended these results by suggesting that the hippocampus and right IFG support grammar learning when the acquired knowledge is based on similarity; the left ventral premotor cortex was coupled with rule knowledge (Hauser et al., 2012; Opitz & Friederici, 2004). Furthermore, a recent experiment from our group investigating individual differences in grammar learning (Kepinska et al., 2017) pointed to right fronto-parietal involvement underlying superior skills