Brain imaging study
of learning mechanisms of abstract structures :
an experimental testing of the Bayesian brain hypothesis.

The purpose of this thesis is to study the learning mechanisms by which the human brain discovers the fundamental principles of a perceptual or conceptual field. For example, how do children discover that numbers operate in an orderly linear structure? Is it pure coincidence that numbers, and also other linear dimensions, their distances and their comparisons, are systematically represented in the parietal region of the cortex (Nieder & Dehaene, 2009)? In addition, how do adults discover that the positions of objects on a surface, or the complex numbers might be represented by a Euclidian plane? Finally, how do we infer the grammatical rules of a new language? In this case, why is another cortical region, Broca's area, activated throughout the learning path, and only for languages respecting the principles of universal grammar (Musso, et al., 2003)?

The ability to identify the abstract and deep structure underlying a domain is essential for mathematical activities. It also seems to be part of the fundamental skill set of the human species. Even people without an education and without a knowledge of the mathematical language have abstract structural intuitions and are able to infer the organizing principles of numbers or space spontaneously (Dehaene, Izard, Pica, & Spelke, 2006; Dehaene, Izard, Spelke, & Pica, 2008). However, the mechanism of this learning process remains unknown. Consequently, its study should give a more precise idea of the flexibility and limits of the rules accessible to human beings (which could have major consequences in the field of ergonomics), and may also lead to the conception of new learning algorithms to approach or reproduce human performance.

Recently, Kemp and Tenenbaum (2008) proposed a computational model of structural learning. They suggest that the human brain: (1) generates in parallel vast spaces of hypothesis hierarchically organized; (2) uses a Bayesian algorithm to choose the most relevant model of a given domain. Each new example updates the plausibility of all internal models and the most plausible is gradually chosen. Given a matrix of similarity between several items, their algorithm quickly identifies the best deep structure able to describe it.

In this thesis, we will put to the test the validity of this model, comparing its performances to those of human subjects involved in the learning process of abstract mathematical structures. (1) We will propose to volunteers a learning situation in which they will be led to detect, in a few minutes, the organization principle underlying geometrical stimuli. (2) By behavioral methods (like reaction time or eye movements), we will measure the speed with which subjects find out the stimuli structure and their ability to extrapolate to new stimuli. In these experiments, we will test occidental adults, with or without a mathematical education, and also children and subjects from under-educated populations (experiments led in Amazonia in collaboration with Pierre Pica). (3) We will measure, by imagery techniques (fMRI and MEG), the evolution of brain activity in parallel with the evolution of the field understanding. We postulate that different brain regions could be involved, depending on what structure was found out: intraparietal cortex for linear structures, retinotopic visual areas for planar structures, left frontal region (Broca's area) for tree structures. (4) We will also perform an fMRI study of the neural correlates of mathematical reflection and intuition among mathematicians who have learnt abstract structures for many years. We will compare different domains of Mathematics (arithmetic, algebra, analysis, topology and geometry), in order to examine if they recruit similar or different cortical structures. (5) We will design a detailed mathematical model which has the potential to replicate the above-mentioned results, using the model of Kemp and Tenenbaum (2008). Finally, we will propose, if it is possible, a neural implementation of this model.

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