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Degree of automaticity and the prefrontal cortex

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The dorsolateral prefrontal cortex (PFC), with more anterior areas [Brodmann area (BA) 45, 47, and 10], has been known to be activated as cognitive hierarchy increases. However, this does not hold for highly automatic processes such as first language (L1), where the posterior region (BA 44) is known as the key area for the processing of complex linguistic hierarchy. Discussing this disparity, we propose that the degree of automaticity (DoA) is a crucial factor for the framework of functional mapping in the PFC: the posterior-to-anterior gradient system for more controlled processes and the posterior-confined system for automatic processes. We support this view with previous findings and provide a new perspective on the functional organization of the PFC.

Hierarchical processing in the PFC

Hierarchical processing refers to the view that processes in the superordinate level control, modify, and modulate processes in the subordinate level over a longer timescale [1–3]. Since the early 1950s, when the concept of hierarchical processing was introduced in relation to the domain of action planning [4], it has been further extended to various cognitive domains such as language and music. Within this scope, action has been characterized as being goal directed and hierarchically structured such that simple action gestalts integrate into progressively more elaborate actions in a hierarchy that involves different processes at the upper and lower levels corresponding to sequences and action chunks, respectively [5]. Language has been characterized as a hierarchical structure; syllables comprise phonemes, words are made up of syllables, phrases comprise words, and then phrases are assembled to build a sentence [3,6,7]. In the music domain, rule-based arrangement of musical sets results in a hierarchical structure; discrete acoustic sounds are assembled into harmonic sequences following a certain arrangement of chord functions [8,9]. Taking these observations together, it is suggested that human behavior is organized in several levels of hierarchy and that hierarchical processing is essential in human cognition [10–15].

Along with the accumulation of findings from various functional neuroanatomy and lesion studies, the neural basis of hierarchical processing has been found to involve the dorsolateral PFC [16]. Furthermore, the possible system for generating different levels of hierarchy in human cognition, more specifically in cognitive control (see Glossary), has been proposed to reside in the PFC [2,17–26]. One influential perspective on the cognitive framework suggests a topographic organization along a posterior-to-anterior axis in the PFC, with progressively anterior regions being involved in higher levels of hierarchical processing than posterior regions (Figure 1A) [23,27–30]. However, it is not always the case that this posterior-to-anterior gradient system stands to reason. The neural underpinning for hierarchical processing in L1 has been shown to involve a posterior region of the PFC; that is, BA 44 (Figure 1B) [31–33]. An increase in syntactic hierarchy leads to an increase of activation in BA 44 rather than to recruitment of more anterior parts of the PFC as suggested earlier in hierarchical processing for cognitive control (Figure 1C) [32]. What, then, is the reason for these disparate representations between hierarchy of cognitive control (the posterior-to-anterior gradient system) and hierarchy in L1 (the posterior-presiding system)?

Here, based on two overarching notions – hierarchy of cognitive control and automaticity – we propose a novel conceptual framework that DoA may play a critical role in the functional organization of the PFC: the posterior-to-anterior gradient system for more controlled processes with a low DoA and the posterior-confined system for automatic processes with a high DoA. The essential role

Glossary

Center-embedded sentence: a linguistic description of a sentence where phrases/clauses are inserted in other phrases/clauses [66,67]. It is described as having the most demanding hierarchical and recursive structure, with long-distance dependencies [35].

Cognitive control: a cognitive mechanism responsible for coordinating or guiding thoughts and behaviors in relation to current goals and intentions [2,27].

Dorsolateral PFC loop: corticostriatal–thalamocortical loops refer to five loops that are topographically organized and functionally segregated with selected cortical areas in the frontal lobe. These are reported to be involved in motor functions with motor and oculomotor loops and in nonmotor functions with dorsolateral, ventral/orbital, and anterior cingulate loops [68]. In particular, the dorsolateral PFC loop is recruited in cognitive aspects, including working memory, planning, rule-based learning, and sequence learning [58,61,69–77].

Early left-anterior negativity (ELAN): a language-relevant event-related brain potential component found between 120 and 200 ms in response to a syntactic phrase-structure error, thereby reflecting initial syntactic structure-building processes [78].

Early right-anterior negativity (ERAN): known as an electrophysiological marker of musical structure building that is mediated by the inferior frontal gyrus and superior temporal gyrus [79,80].

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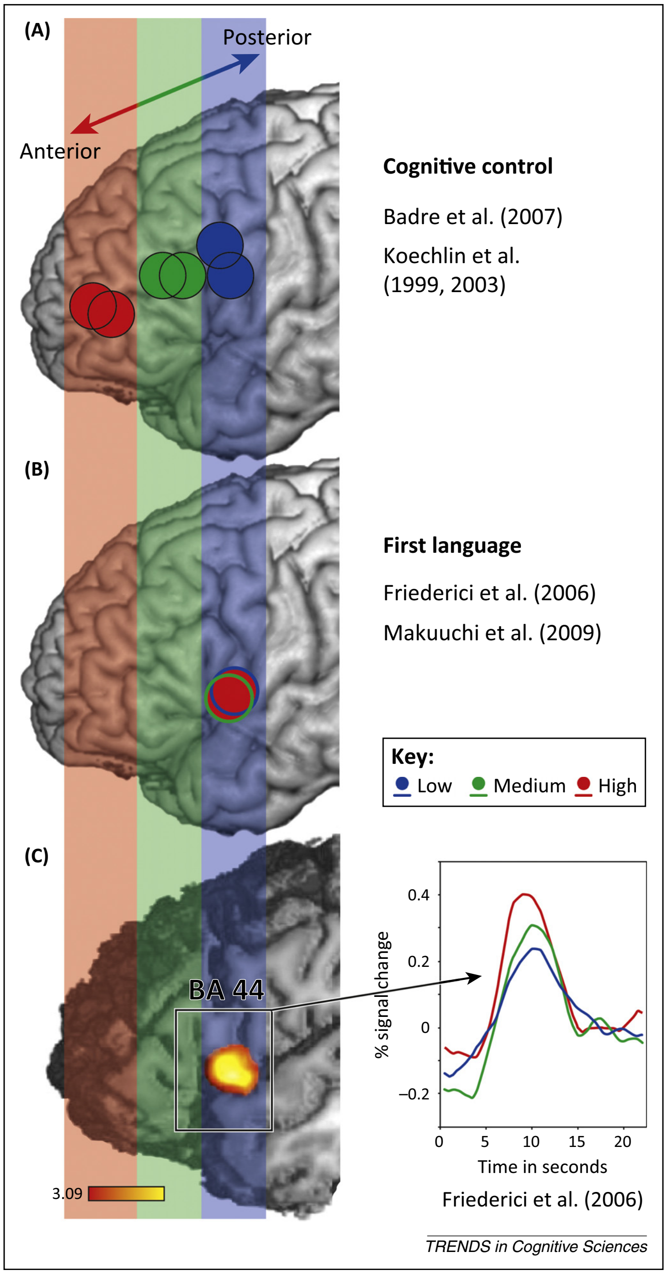

Figure 1. Posterior-to-anterior gradient system for cognitive control and posterior-presiding system for first language. In **(A)** and **(B)**, the approximate locations of the activation foci are provided in a schematic display with spheres centered on the coordinates of peak activation from previous studies. These spheres indicate activation from different levels of hierarchy (red, high; green, medium; blue, low). (A) Subregions in the prefrontal cortex (PFC) selectively contributed to the different levels of hierarchical processing; as the level of hierarchy became higher, activation was observed in a more anterior region of the PFC [23,29,30]. (B) Activation for hierarchical processing in first language (L1) was positioned in the posterior region of the PFC [Brodmann area (BA) 44] even when the level of hierarchy was high, indicating the posterior-presiding system within the PFC for L1 [32,33]. **(C)** There was a systematic increase of activation in BA 44 as the level of hierarchy in sentences of L1 increased. Different colored lines in the plot of percentage blood-oxygen level-dependent (BOLD) signal change indicate activation from different levels of hierarchy (red, high; green, medium; blue, low). Adapted, with permission, from [32].

of the DoA and its relation to the functional organization of the PFC can be traced back to the identification of two qualifications, 'newness' and 'complexity' [16]. Goal-directed behavior, which requires the involvement of the PFC, is characterized as being novel and demanding whereby the former qualification (newness) is a sufficient and necessary condition, whereas the second qualification (complexity) is not. This prominent viewpoint, in harmony with our proposal, also emphasizes the value of automaticity rather than complexity.

In the following section, we briefly review the influential models of hierarchical processing in cognitive control, demonstrating the organization of the posterior-to-anterior gradient in the PFC. Next, we examine a study comparing hierarchical processing and the role of automaticity in its functional mapping in the PFC for L1, second language (L2), and the non-language (NL) domain. We substantiate our proposal with previous neuroimaging studies in language development and L2. Lastly, we discuss the DoA and its relation to subcortical structures; that is, the basal ganglia.

Hierarchical processing in cognitive control

Numerous studies have demonstrated possible frameworks for generating different levels of hierarchies in cognitive control and their topographic maps in the PFC [2,17,18]. Here we discuss two influential theories: temporal abstraction and policy abstraction.

The first framework, temporal abstraction, suggests that a significant fraction of cognitive control is based on temporal framing and context, with three different levels in increasing ranking order: contextual, episodic, and branching control [17,28]. Contextual control denotes a synchronic dimension, which means that selecting an action depends on the stimulus response associations according to current context. Episodic control indicates a diachronic dimension, meaning that cognitive control depends on a discrete past event. Branching control refers to a polychronic dimension, or that selecting actions depends on the information conveyed by past events, which are maintained in a pending state and then reactivated later. These three levels form a cascade of top-down selective processes operating along the posterior-to-anterior axis of the lateral PFC, with the contextual, episodic, and branching controls subserved by the posterior lateral PFC, the anterior lateral PFC, and the frontopolar PFC, respectively [17,23,25,30,34].

The other framework, policy abstraction, describes a cognitive hierarchy ranked by different levels of abstractness [27]. Policy abstraction is related to the rules that govern other subrules such that a higher level of policy abstraction has more subcategories or more subordinate representations than a lower one. Multiple levels of abstractness were proposed by summing several constraints for appropriate action selections: the first level for selection between multiple competing actions (least abstract), the second level for selection between different response-level policies (more abstract), and so on up to multiple levels of increasing abstraction [29]. This multistage system of cognitive control is subserved by different areas supporting each level from the left dorsal premotor cortex (the lowest level) to the left anterior dorsal premotor cortex, to the left inferior frontal sulcus, and to the left frontopolar cortex (the highest level) [2,27].

Although the characteristics of the levels are defined to some extent in different ways in these two frameworks, both postulate a similar topographic mapping of the