



Review

Executive control in language processing

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ABSTRACT

During communication, speakers and listeners need the mechanisms of executive control to organize thoughts and actions along internal goals. Speakers may use executive functions to select the right word over competing alternatives to refer to the concept in mind. Listeners may use executive functions to coordinate the outputs of multiple linguistic processes to reach a coherent interpretation of what others say. Bilinguals may use executive functions to control which language is to use or to switch from one language to another. The control mechanisms recruited in language processing may be similar to those recruited in perception and attention, supported by a network of frontal, parietal and sub-cortical brain structures. Here we review existing evidences regarding the involvement of domain-general executive control in language processing. We will explain how executive functions are employed to control interference in comprehension and production, within and across languages.

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1. Introduction

During communication, speakers and listeners have to organize thoughts and actions in accordance with internal goals. If a speaker intends to refer to the first meal of the day, he/she needs to pick the right word “breakfast” rather than “lunch” or “supper” and prepare the appropriate articulation for the selected word (Levett et al., 1999). If the speaker knows more than one language, he/she needs to determine which language to use and prevent the production of words in the unselected language (Green, 1986, 1998). If a listener hears an implausible sentence which is inconsistent with his/her

world knowledge (e.g., at breakfast, the egg would eat, etc.), he/she needs to decide which to believe, what he/she hears or what he/she knows. If the listener reads an ambiguous sentence which has more than one interpretation (e.g., *Ronald told Frank that he had a positive attitude towards life*), he/she needs to bias towards one of them, before he/she can respond to the speaker. Our elaborate sensory and memory systems provide detailed information about what others say and what we know of languages and realities. Our flexible motor systems make it possible to say or to write whatever we intend to. However, the rich source of information and the large number of behavioral options introduce great potentials of interference and consequently, require attentional control and voluntary coordination.

To deal with possible interference and confusion, human beings have evolved the mechanisms of executive control (for definitions of related concepts, see Table 1) which can regulate and guide

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Table 1

Definitions of some core concepts.

Conflict/interference
An internal state caused by the incompatibility of multiple representations or the opposition of action tendencies. In the domain of language processing, conflicts usually appear between simultaneously activated lexical items or sentential representations within or across languages.
Executive control
General cognitive processes that regulate and guide cognitive processes in sensory, memory and motor systems along internal goals. Executive control is composed of at least two components, conflict monitoring and conflict resolution.
Conflict monitoring
Processes that monitor for the occurrence of conflicts in information processing. The conflict monitoring processes evaluate current levels of conflicts and trigger compensatory adjustments of processing pathways.
Conflict resolution
Processes that aim at eliminating sources of conflicts. The conflict resolution processes enhance task-relevant information and suppress task-irrelevant information, organizing behaviors among internal goals.
Inhibition
Processes that suppress an active representation or action tendency.

cognitive processes in sensory, memory and motor systems along internal goals (Miller, 2000; Miller and Cohen, 2001). The speaker may use executive functions to select the right word over competing alternatives and inhibit the tendency of producing an inappropriate word (Badre et al., 2005; Thompson-Schill et al., 1997). He/she may also use executive functions to control which language is to use or to switch from one language to another at any given time (Hernandez et al., 2001; Price et al., 1999; Rodriguez-Fornells et al., 2005). The listener may use executive functions to select among competing interpretations according to the communication goal (e.g., to grasp what the speaker really says and ignore what one already knows, see Novick et al., 2005; Ye and Zhou, 2008).

2. Mechanisms of executive control

The mechanisms of executive control recruited to resolve competitions between representations in language processing may be similar to those recruited to resolve competitions between representations in perception and attention (Abutalebi and Green, 2007; Bialystok, 2001; Kan and Thompson-Schill, 2004; Novick et al., 2005; Ye and Zhou, submitted for publication). In perception and attention, the general executive functions are mediated by a network of frontal, parietal and sub-cortical structures (see Fig. 1; Derrfuss et al., 2004; Dosenbach et al., 2007; Duncan and Owen, 2000; Nee et al., 2007; Wager et al., 2005), which are structurally and functionally connected.

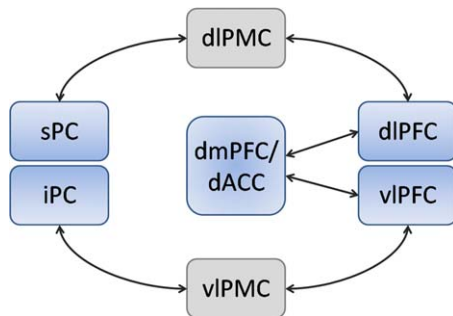


Fig. 1. A network of executive control. dmPFC, dorsal medial prefrontal cortex; dACC, dorsal anterior cingulate cortex; dIPFC, dorsal lateral prefrontal cortex; vIPFC, ventral lateral prefrontal cortex; dIPMC, dorsal lateral prefrontal cortex; vIPMC, ventral lateral prefrontal cortex; sPC, superior parietal cortex; iPC, inferior parietal cortex. Black arrows indicate possible pathways of information processing.

Within this network, dorsal medial prefrontal cortex/dorsal anterior cingulate cortex (dmPFC/dACC) is anatomically connected with dorsal (dIPFC, see Tomassini et al., 2007) and ventral lateral prefrontal cortex (vIPFC, see Anwander et al., 2007; Croxson et al., 2005). The dmPFC/dACC is crucial for maintaining internal goals, monitoring conflicts and adjusting cognitive processes in sensory, memory and motor systems (Botvinick et al., 1999, 2001; Carter et al., 1998; Dosenbach et al., 2006, 2007). Lateral prefrontal cortex is anatomically connected with parietal cortex via lateral premotor cortex (PMC), with dIPFC connected with superior parietal cortex via dorsal lateral PMC and vIPFC connected with anterior inferior parietal cortex via ventral lateral PMC (Petrides and Pandya, 2002; Rushworth et al., 2006; Tomassini et al., 2007). Lateral prefrontal cortex may provide bias signals to parietal regions to guide neural pathways which establish proper mappings between sensory inputs, internal states and behavioral outputs (Miller and Cohen, 2001; Nyberg et al., 2003; Rajah et al., 2008). To be more specific, dIPFC may respond to feedbacks (e.g., errors) from trial to trial and direct attention to stimulus-response mappings stored in posterior regions (Barber and Carter, 2005; Curtis and D'Esposito, 2003; Liston et al., 2006; MacDonald et al., 2000; Marklund et al., 2007), while vIPFC (especially Broca's area, Brodmann Area 44 and 45) may control the interference from potent but irrelevant information (Badre and Wagner, 2007; Kan and Thompson-Schill, 2004) and guide posterior processors which hold stimulus-response mappings (Brass and von Cramon, 2004; Derrfuss et al., 2004, 2005). Parietal cortex may signal lateral prefrontal cortex when there are conflicts between representations of multiple inputs (Dosenbach et al., 2007; Liston et al., 2006; Marklund et al., 2007) and maintain representations of stimulus-response mappings (Hester et al., 2007; Thoenissen et al., 2002). The ACC may evaluate and signal the occurrence of conflict in downstream cognitive processes (Botvinick et al., 1999, 2001; Carter et al., 1998). Finally, with excitatory and inhibitory cortical connections, the basal ganglia is associated with the planning of sequential events (e.g., actions; Graybiel, 1997, 2000) and the suppression of competing alternatives (Longworth et al., 2005).

This network was constantly observed in perceptual tasks which required attentional control. For example, it is involved when participants were asked to name the ink color of a color word while the ink color was inconsistent with the meaning of that word (e.g., word RED in green ink; the color-word Stroop task, see Stroop, 1935; MacLeod, 1991), or when they judged the direction of the central arrow, which was flanked by arrows in the opposite direction (e.g., $\rightarrow \rightarrow \leftarrow \rightarrow \rightarrow$; the flanker task, see Eriksen and Eriksen, 1974), or when they switched from performing one task to another (Derrfuss et al., 2004, 2005; Egner et al., 2007; Fan et al., 2003; Nee et al., 2007; Peterson et al., 2002; Wager et al., 2004, 2005).

Proposals that the mechanisms of executive control may also be involved in language processing have recently appeared in relation to sentence reading (Kuperberg, 2007; Novick et al., 2005; Thompson-Schill et al., 2005; Ye and Zhou, 2008, submitted for publication), word production (Thompson-Schill et al., 1997; Badre and Wagner, 2007) and bilingual language processing (Abutalebi and Green, 2007; Rodriguez-Fornells et al., 2006). For example, Thompson-Schill and colleagues (Novick et al., 2005; Thompson-Schill et al., 2005) suggested that middle vIPFC (left inferior frontal gyrus, LIFG in their studies) may be responsible for implementing conflict control when representational conflicts arise. This region may act to bias activation patterns of alternative representations to prevent misunderstanding or to correct error. Here we try to bridge the three language domains (i.e., sentence comprehension, word production and bilingual language processing) to reach a coherent picture. Different from previous studies (e.g., Novick et al., 2005; Thompson-Schill et al., 2005), we attribute the general executive

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