



## Review

## Executive control in language processing

Zheng Ye<sup>a</sup>, Xiaolin Zhou<sup>a,b,c,\*</sup><sup>a</sup> Center for Brain and Cognitive Sciences and Department of Psychology, Peking University, Beijing 100871, China<sup>b</sup> Key Laboratory of Machine Perception and Key Laboratory of Computational Linguistics, Ministry of Education, Peking University, Beijing 100871, China<sup>c</sup> State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, China

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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 (Levelt 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

\* Corresponding author at: Department of Psychology, Peking University, Beijing 100871, China. Tel.: +86 10 6275 6599; fax: +86 10 6276 1081.

E-mail address: [xz104@pku.edu.cn](mailto:xz104@pku.edu.cn) (X. Zhou).

**Table 1**

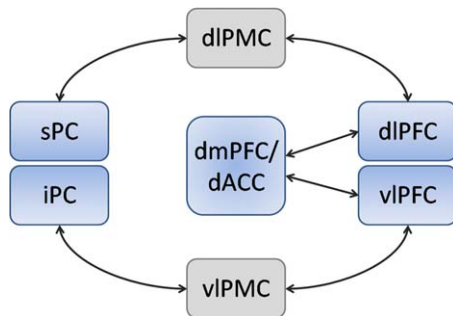
Definitions of some core concepts.

<b>Conflict/interference</b>
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.
<b>Executive control</b>
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.
<b>Conflict monitoring</b>
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.
<b>Conflict resolution</b>
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.
<b>Inhibition</b>
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

functions in language processing to a network of distributed subsystems, including frontal, parietal and sub-cortical structures, rather than a single brain area (e.g., LIFG).

There are three primary predictions if the general executive functions are recruited to control interferences from irrelevant representations in both perception and language domains. First, the neural correlates of control processes in language processing may partially overlap with those in perception and attention (Kan and Thompson-Schill, 2004; Ye and Zhou, submitted for publication). Second, individuals' differences in resolving representational conflicts of linguistic inputs may be predicted by their performances in resolving representational conflicts of perceptual inputs (Mendelsohn, 2002; Novick et al., 2005; Ye and Zhou, 2008). Third, bilinguals faced with managing the cross-language interference from an early age may develop enhanced control abilities and become adept at inhibiting irrelevant information and/or inappropriate response (Bialystok, 1999, 2001). In following sections, we will review existing evidence regarding the involvement of domain-general executive control in language processing. We will introduce how the control processes are applied in sentence comprehension (Section 3), word production (Section 4), and bilingual language processing (Section 5). Importantly, we will show how the above three predictions are supported by recent findings.

### 3. Conflict control in sentence comprehension

According to what are known as “syntax-first” (e.g., Ferreira and Clifton, 1986; Fodor, 1983; Frazier and Rayner, 1982) and “constraint-based” models (e.g., MacDonald et al., 1994; Marslen-Wilson and Tyler, 1980; Taraban and McClelland, 1988), sentences are always processed with full syntactic parsing and sentence meanings must be built upon syntactic frames. However, recent studies found that interpretations can be inconsistent with syntactic forms, especially when sentences are syntactically complex, non-canonical, or ambiguous (Christianson et al., 2001; Ferreira, 2003; Ferreira et al., 2002; Sanford and Sturt, 2002). For example, participants tended to paraphrase the double negative sentence “don't print that or I won't sue you” as “If some item were printed, the result would be a lawsuit” (Fillenbaum, 1971, 1974). One possibility is that other cognitive mechanisms such as heuristics are used in addition to syntactic algorithms (Bever, 1970; Ferreira, 2003; Townsend and Bever, 2001). On one hand, syntactic processes assign thematic roles (i.e., who-did-what-to-whom) on the basis of morpho-syntactic constraints. On the other hand, simple heuristics yield “quick and dirty” interpretations according to semantic associations (e.g., the plausibility heuristic, which treats a sentence as an unordered list of words and combines lexical items according to world knowledge) or syntactic habits (e.g., the NVN strategy, which assumes that the subject of a sentence is the agent of some action and the object is the patient or theme).

In many cases, syntactic algorithms and heuristics conspire towards a coherent interpretation. Occasionally, however, they give rise to incompatible sentential representations which compete for selection as the final interpretation (Novick et al., 2005; Thompson-Schill et al., 2005). For example, in implausible sentences such as “at breakfast, the egg would eat ...”, the syntactic algorithm points to an anomalous interpretation (at breakfast, the egg would eat something) on the basis of morpho-syntactic constraints (“would eat” rather than “would be eaten”). In contrast, the plausibility heuristic extracts content words (“breakfast”, “egg” and “eat”) and primes a likely interpretation (at breakfast, someone would eat egg) according to world knowledge (an egg can be eaten but cannot eat). Behaviorally, such linguistic conflicts lead to longer reading time (Braze et al., 2002; Murray and Rowan, 1998; Ni et al., 1998; Rayner et al., 2004) and greater possibility of misinterpretation (Ferreira, 2003).

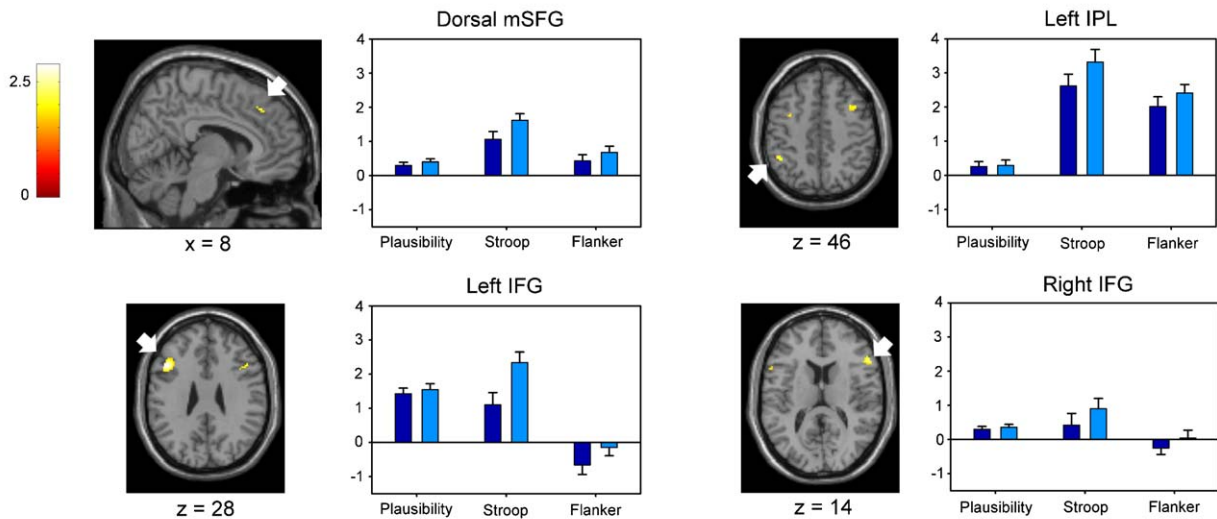
Then successful sentence comprehension relies on the regulation of multiple cognitive processes, including syntactic parsing and heuristic processing, which are managed in parallel according to distinct rules (Jackendoff, 2002, 2007; Kuperberg, 2007). To reach a final interpretation, the mechanisms of executive control may be employed to monitor the occurrence of conflicts and select among competing sentential representations (Novick et al., 2005; Thompson-Schill et al., 2005; Ye and Zhou, 2008). The monitoring processes may be triggered to reanalyze previous inputs and check for possible processing error (Van Herten et al., 2006; Vissers et al., 2007, 2008). If the conflict occurs because of the appearance of an unexpected expression (i.e., an expression against world knowledge or syntactic habits), rather than a processing error, the selection processes may be activated consequently to coordinate the outputs of syntactic parsing and heuristic processing. The monitor processes may be mediated by ACC, which is proposed to be responsible for detecting conflicts between incompatible response tendencies. In event-related potentials (ERPs), these monitoring processes may be reflected as P600 (a centro-parietal positivity appearing around 600 ms; see Kolk et al., 2003; Van Herten et al., 2005).

An alternative view suggested that such linguistic conflicts could be resolved within the language system, without the help from executive control mechanisms. Kuperberg (2007) proposed that if the heuristic processing generates an interpretation which is incompatible with the one given by the syntactic parsing, the heuristic processing will be terminated whereas the syntactic parsing is continued to establish the thematic relationship and guide the final integration. This view is consistent with traditional models of sentence comprehension (syntax-first and constraint-based models) in that syntactic processes may be challenged but can never be overridden by non-syntactic processes. However, this view may have problems in explaining why participants can generate interpretations inconsistent with syntactic forms, if the final integration is guided by syntactic processes in any way. Moreover, it does not specify the mechanisms responsible for detecting the conflict or terminating the plausibility heuristic.

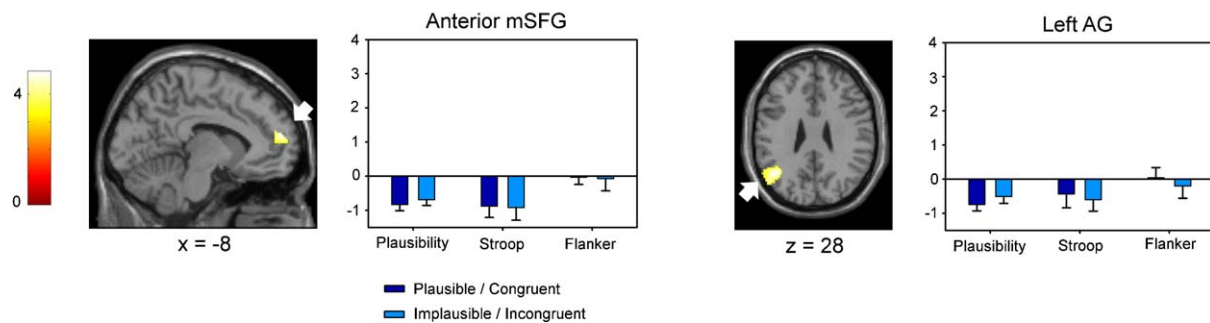
In a recent functional magnetic resonance imaging (fMRI) study (Ye and Zhou, submitted for publication), we explored to what extent the neural correlates of control processes in sentence processing are similar to those in perception and attention. We applied the sentence comprehension task, the flanker and the color-word Stroop tasks to the same group of participants. In the sentence comprehension task, participants were asked to indicate the meaning of the sentence, which described an event consistent (plausible, e.g., the dog bit the man) or inconsistent (implausible, e.g., the man bit the dog) with the world knowledge. In the color-word Stroop task, participants were asked to name the ink color of a color word, the meaning of which was consistent (congruent, e.g., word RED in red ink) or inconsistent (incongruent, e.g., word RED in green ink) with the ink color. In the flanker task, participants were asked to judge the direction of a central arrow, which was flanked on both sides by arrows in the same (congruent, e.g., → → → → →) or opposite (incongruent, e.g., ← ← → ← ←) direction. Across these tasks, participants had to control interference from heuristic-based interpretations, automatically retrieved word meanings, or irrelevant perceptual inputs. If executive functions are common to the conflict control across domains, the neural correlates of control processes in above three tasks may overlap in frontal and parietal regions (the overlapping logic, see Cabeza and Nyberg, 2002; Fan et al., 2003; Derrfuss et al., 2004; Marklund et al., 2007; Wager et al., 2005).

This prediction was supported by our observations. We found that a network of mPFC, left vlPFC and left lateral parietal cortex was recruited to monitor and resolve competitions among sentential representations. Within this network, dmPFC (BA8),

## (a) Plausibility, Stroop congruency and flanker congruency



## (b) Plausibility vs. Stroop and flanker congruency



**Fig. 2.** (a) Regions common to the plausibility and the congruency effects across three tasks. (b) Regions distinct for the plausibility effect as compared with the congruency effects in other two tasks. White arrows indicate the locations of activations. Bar plots show the beta values and the standard errors corresponding to the congruent/plausible (dark blue) and the incongruent/implausible (light blue) conditions across three tasks. mSFG, medial superior frontal gyrus; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; AG, angular gyrus.

vIPFC (BA44/45) and inferior parietal cortex (BA40) were constantly observed for the control processes in sentence comprehension and for those in the flanker and the Stroop tasks (see Fig. 2a). In contrast, anterior mPFC (BA10) and left angular gyrus (BA39) only showed up for the control processes in sentence comprehension (see Fig. 2b). Thus, for implausible sentences, both the domain-general and the domain-specific components seem to be employed to control the interference from world knowledge. The domain-general components, which are subserved by dmPFC, vIPFC and inferior parietal cortex, are responsible for regulating cognitive processes across domains and resolving conflicts between representations regardless of the input type. The domain-specific components, which are subserved by anterior mPFC and angular gyrus, are selectively related to the coordination of multiple linguistic processes (also see Ramnani and Owen, 2004; Sakai and Passingham, 2006). One might argue that the common areas are evolved because more efforts and cognitive resources are needed to process incongruent targets or implausible sentences. However, the increase of efforts and cognitive resources for such stimuli is the consequence of executive control, not the other way round.

A second case is the ambiguous sentence, in which referential (Van Berkum et al., 1999, 2007) or syntactic processes (MacDonald et al., 1994; Novick et al., 2005; Trueswell et al., 1994) themselves generate two possible interpretations, causing longer reading times and more comprehension errors (Ferreira et al., 2001; Kennison, 2001; Sekerina et al., 2004). For referentially ambiguous

sentences such as “Ronald told Frank that he had a positive attitude towards life”, the pronoun (he) could refer to either of the two mentioned characters (Ronald or Frank), leading to potential confusion. Both mPFC (BA10) and bilateral angular gyrus (BA39) were activated in response to the occurrence of conflicts among possible interpretations, although no coherent interpretation could actually be reached (Nieuwland et al., 2007). For syntactically (temporarily) ambiguous sentences, executive functions may be employed to suppress the preferred interpretation which is no longer supported by new inputs (Novick et al., 2005). For example, verbs such as “assert” could be followed by two possible structures, the direct object (e.g., the diligent disciple asserted the belief readily) or the subordinate clause (e.g., the worried friar asserted the belief would be justified). When encountering the context “the worried friar asserted the belief ...”, although the phrase “the belief” was temporarily ambiguous between being the direct object or the subject of subordinate clause, participants usually preferred the direct object interpretation because of its higher frequency (MacDonald et al., 1994; Trueswell et al., 1994). However, the incoming input “would be justified” was against the direct object interpretation. Participant then had to turn back to the subordinate clause interpretation and inhibit the preferred but incorrect interpretation. These control processes were supported by left dIPFC (BA9, Novais-Santos et al., 2007) and left vIPFC (BA44/45, Fiebach et al., 2004; Mason et al., 2003).

Other cases include the strongly constraining sentence completed by a plausible but unexpected word (e.g., the children



went outside to look), which conflicts with the word most expected by the sentential context (e.g., the children went outside to play, see Federmeier et al., 2007). For all these cases, the control processes usually begin about 500 ms after the conflicts become overt (e.g., 500 ms after the onset of the “dog”, for the sentence “the man bit the dog”), reflected as a posterior positivity (between 500 and 900 ms, see Federmeier et al., 2007; Friederici et al., 1998, 2001; Kuperberg et al., 2003, 2006; Mecklinger et al., 1995; Van Herten et al., 2005, 2006; Vissers et al., 2007) or a anterior negativity (between 400 and 1500 ms, see Nieuwland and Van Berkum, 2006) in ERPs.

One primary predication of the general control view is that individual differences in resolving linguistic conflicts could be predicted by individual differences in resolving perceptual conflicts (Mendelsohn, 2002; Novick et al., 2005). This prediction was consistent with our recent ERP findings (Ye and Zhou, 2008), i.e., the resolution of conflicts between sentential representations is constrained by participants' control abilities in perception and attention as well as by the complexity of sentence structure (e.g., active vs. passive). In this study, we measured adults' control abilities with the color-word Stroop task and grouped them according to their behavioral performances. Participants showing smaller interference effects (the difference of reaction times between incongruent and congruent trials) were readers with higher control abilities, while participants showing larger interference effects were readers with lower control abilities. For readers with higher control abilities, a posterior positivity was observed between 350 and 850 ms when conflicts occurred in complex (passive) sentences (Fig. 3b), whereas an anterior negativity was observed between 300 and 600 ms when conflicts occurred in simple (active) sentences (Fig. 3a). For readers with lower control abilities, however, the posterior positivity was obtained for both simple and complex sentences (Fig. 3c). The posterior sustained positivity may reflect the detection (Van Herten et al., 2005, 2006; Vissers et al., 2007) and the resolution processes (West et al., 2005) in response to linguistic conflicts. The anterior negativity, which was similar to that observed for perceptual conflicts in the color-word Stroop task (Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; West et al., 2005), may reflect the suppression of the interfering heuristic-based representation. However, it is still an open question how the inhibition processes underlying the anterior negativity are different from the resolution processes underlying the posterior positivity. Further studies should address this issue.

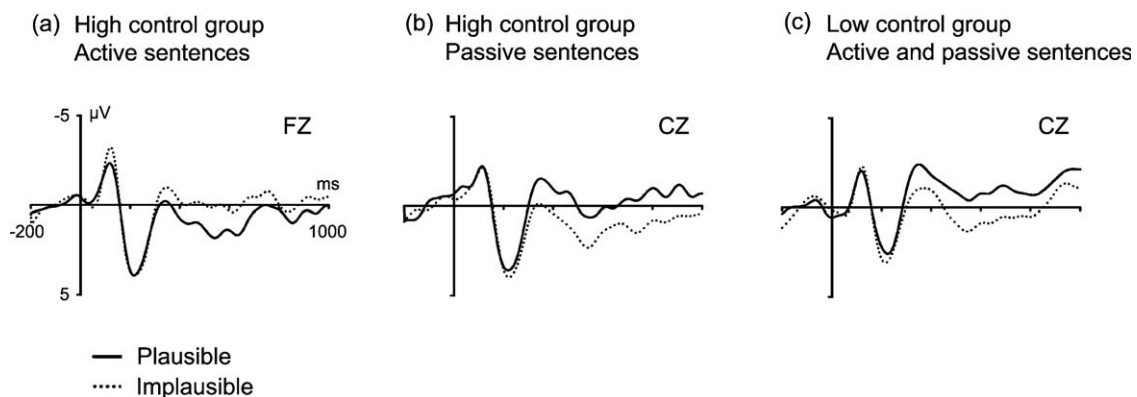
From the developmental perspective, moreover, young children's abilities in processing syntactically complex, non-canonical, and ambiguous sentences may be related to the maturational

change of their control abilities (Novick et al., 2005). The prefrontal cortex is one of the cortical areas last to mature in the course of individual development. The late maturation of prefrontal cortex leads to the slow progression of control abilities in children and adolescents (for a review, see Fuster, 2002), which may impact both perception and sentence comprehension. In the perceptual tasks demanding attentional controls (e.g., the Stroop task, the Go/NoGo task), children and adolescents are more susceptible to representational interference and less able to inhibit inappropriate responses than adults (Bunge et al., 2002; Rubia et al., 2006). Similar developmental patterns have been observed in sentence comprehension (Trueswell et al., 1999). When encountering temporally ambiguous sentences such as “put the frog on the napkin into the box”, adults and older children (8-year-old) temporarily consider “on the napkin” as the goal but quickly revise the interpretation after hearing “in the box”. Young children, however, hardly recover from the initial misinterpretation, although they have no difficulty in processing unambiguous sentences (e.g., put the frog that is on the napkin into the box).

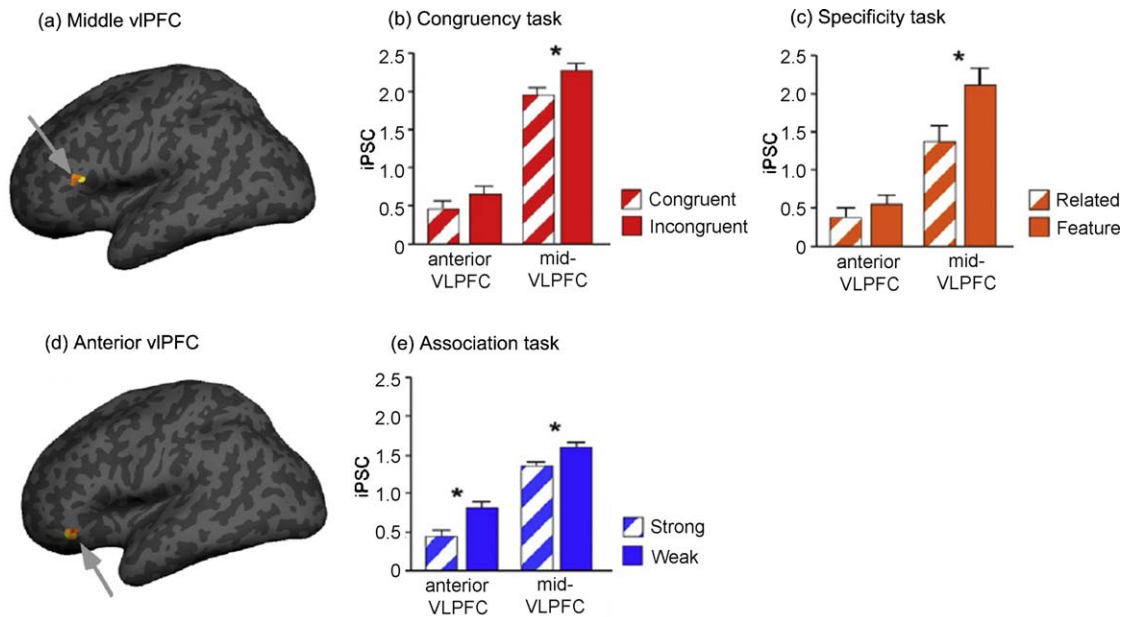
#### 4. Conflict control in word production

To speak appropriately, people have to search and pick the right words according to contexts. Sometimes the right words are automatically activated by cues in our environment (e.g., words appearing in others' utterances). In other situations, however, speakers must voluntarily retrieve the right words from semantic memory and sustain them against competing alternatives (Badre and Wagner, 2007; Moss et al., 2005; Thompson-Schill et al., 2005). For example, participants were asked to generate a verb related to a noun (Thompson-Schill et al., 1997), which was associated with many items without any clearly dominant response (high selection, e.g., the noun “rope” is associated with verbs such as “hang”, “tie”, “enclose” and so on), or few items with a clear dominant response (low selection, e.g., the noun “kite” is selectively associated with the verb “fly”). The selection demands increased for nouns with many verbs because of higher competitions among candidates. The selection processes were mainly supported by left middle vLPC (BA45). Patients with focal lesions of this region could not make a response when the cue noun had many associates (i.e., could not select a verb over alternatives), although they performed comparably to normal people when the cue noun had few or only one dominate associate (Thompson-Schill et al., 1998).

Such selection processes have been observed in different semantic tasks which commonly require attentional control to resolve competitions among lexical representations (Badre et al., 2005; Gold et al., 2006). For example, in the congruency task (Badre



**Fig. 3.** For readers with higher control abilities, grand average ERPs showed (a) an anterior negativity for conflicts occurring in active sentences and (b) a posterior positivity for conflicts occurring in passive sentences. (c) For readers with low control abilities, ERPs showed the posterior positivity for conflicts in both active and passive sentences. Solid lines represent the plausible condition and the dotted lines the implausible condition.



**Fig. 4.** (a) Common activation in middle vLPFC (BA45) from the contrasts of incongruent/related vs. congruent/feature conditions across tasks. (b and c) Bar plots showing percent signal changes and standard errors corresponding to the congruent/feature and incongruent/related conditions. (d) Selective activation in anterior vLPFC (BA47) from the contrast of strong vs. weak conditions in the association task. (e) Bar plots showing percent signal changes and standard errors corresponding to the weak and strong conditions. (Adapted from Badre et al., 2005.)

et al., 2005), participants were asked to select the target which was more similar to the cue (congruent, e.g., to select “coal” over “leek” for the cue “tar”), or which was less similar to the cue (incongruent, e.g., to select “leek” over “coal” for the cue “tar”). To select the target which is incongruent with the cue, participants had to inhibit the potent association between the cue (e.g., tar) and the distracter (e.g., coal). In the specificity task (Badre et al., 2005), participants were asked to select a target based on its global relatedness to the cue (related, e.g., to select “league” over “jade” for the cue “ivy”), or its similarity to the cue along a relevant dimension (feature, e.g., to select “coal” over “leak” for the cue “tar”). To judge feature similarity, participants must select the relevant feature, rather than using all information available as in the judgment of global relatedness. The shared selection processes were reflected as a common activation on left middle vLPFC (BA45) in all these tasks (Fig. 4a–c, for a review, see Badre and Wagner, 2007).

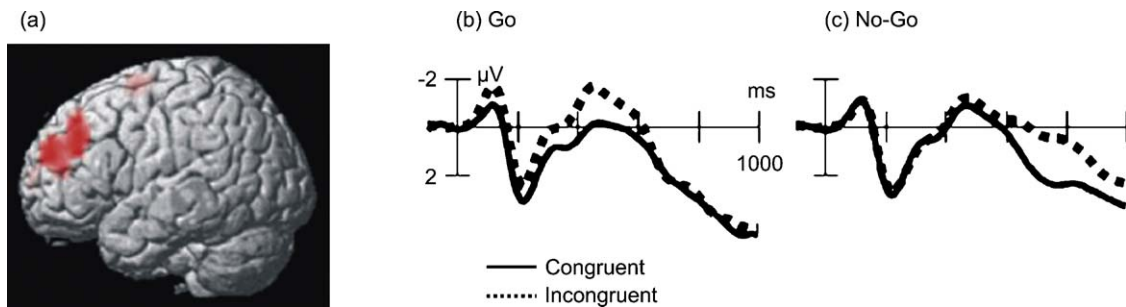
Executive functions are involved not only to operate on the outputs of retrieval processes, but also to control accesses to lexical items stored in semantic memory (Badre and Wagner, 2007). For example, in the association task (Badre et al., 2005), participants were asked to select the target which was strongly associated with the cue (strong, e.g., to select “flame” over “bald” for the cue “candle”), or weakly associated with the cue (weak, e.g., to select “halo” over “exist” for the cue “candle”). When the association between the cue and the target is relative weak, automatic retrieval processes are insufficient to access the relevant information. In this situation, participants must voluntarily search the semantic memory to find the right words. Such controlled retrieval processes were subserved by left anterior vLPFC (BA47, see Fig. 4e and f). To sum up, subregions of left vLPFC may take different roles in executive control during word processing, with middle vLPFC supporting the general selection among active lexical representations and anterior vLPFC supporting the controlled retrieve of lexical items with relevant features.

## 5. Conflict control in bilingual language processing

For bilinguals, representations of two languages partially overlap on cortex level (for reviews, see Franceschini et al.,

2003; Perani and Abutalebi, 2005). One concept activates semantic or even phonological representations of lexical items in both languages (Colomé, 2001; Costa et al., 1999, 2000; Hermans et al., 1998). To begin a conversation in one language, bilingual speakers may use executive functions to select the target language and to control interference from active representations in the non-target language (Abutalebi and Green, 2007; Green, 1986, 1998; Rodriguez-Fornells et al., 2006). For example, in a Go/noGo task (Rodriguez-Fornells et al., 2005), proficient German–Spanish bilinguals were asked to respond when the name of the picture in the target language (e.g., German) began with a consonant (the go trial) and to withhold a response when the name began with a vowel (the no-go trial). In one half trials, the names of the picture in both languages led to the same decision (congruent, e.g., “Esel” vs. “asno”, “donkey” in German vs. Spanish, both words led to the no-go response), while in the other half, they gave rise to opposite decisions (incongruent, e.g., “Erdbeere” vs. “fresa”, “strawberry” in German vs. Spanish, the German led to the no-go response, but the Spanish led the go response). To respond appropriately in incongruent trials, bilinguals must direct attention to the phonological representations in the target language and to suppress the behavioral tendency led by the activation of the non-target language. Such control processes were supported by left dIPFC (BA9/46) and supplementary motor area (SMA, BA6) (Fig. 5a), appearing between 300 and 600 ms in go trials (Fig. 5b) and between 600 and 800 ms in no-go trials (Fig. 5c).

The same control mechanisms may be employed to manage the activations of lexical items in different languages and to regulate the activations of different words in one language (Abutalebi and Green, 2007; Rodriguez-Fornells et al., 2006). In the language switching task (Hernandez et al., 2000, 2001), for example, early Spanish–English bilinguals were asked to name pictures according to the cue. In the between-language condition, participants were asked to name pictures of objects in English if it was cued with the word “say”, or in Spanish if it was cued with the word “diga” (“say” in Spanish), switching between languages on successive trials. In the within-language condition, participants were asked to name pictures (e.g., a boy is eating a hotdog) in English as the action depicted (e.g., eat) if it was cued with the word “to”, or the objects



**Fig. 5.** (a) Activations in left dorsal lateral prefrontal cortex (dlPFC, BA9/46) and supplementary motor area (SMA, BA6) from the contrast of incongruent vs. congruent conditions. (b and c) Grand average ERPs showing negativities for incongruent vs. congruent conditions in go and no-go trials. Solid lines represent the congruent condition and the dotted lines the incongruent condition. (Adapted from Rodríguez-Fornells et al., 2005.)

undergoing the action (e.g., hotdog) if it was cued with the word “the”, switching between action and object names on successive trials. For both the between-language and the within-language conditions, the switching processes were subserved by left dlPFC (9/46), left vlPFC (BA45/44/6) (Hernandez et al., 2000, 2001; Price et al., 1999), anterior cingulate cortex (ACC, BA24/32), and left caudate (part of basal ganglia, see Abutalebi et al., 2008). The common neural correlates suggested that the general executive functions are recruited to control the activations of lexical items, no matter whether these words are from the same language or different languages. Evidences from a case study (Fabbro et al., 2000) confirmed the crucial roles of left lateral PFC and ACC in maintaining the communication goal (e.g., which language in use) and inhibiting the unselected language. During communication, the bilingual patient S.J. with a lesion encompassing the left lateral PFC and ACC would pathologically switch to a language, of which the listener had no knowledge at all.

On the other hand, bilingual listeners and readers are sensitive to the occurrence of their languages in environment. They would be distracted by a change in language when reading word pairs in mixed languages (e.g., trout-Lachs, English–German), even though they were only required to judge the meaning of the second word. This sensitivity, as reflected by the activation patterns in left caudate (Crinion et al., 2006) and left dlPFC (Chee et al., 2003), may lead to potential interference. In this case, bilingual listeners use executive functions to direct their attention to the target language and filter out interfering words in the non-target language (Rodríguez-Fornells et al., 2002). For example, proficient Spanish–Catalan bilinguals were asked to indicate whether a word began with consonant or vowel when hearing the target language (e.g., Spanish), but to withhold a response when hearing the non-target language (e.g., Catalan) (Rodríguez-Fornells et al., 2002). In ERPs, bilinguals’ inhibition-related negativities were not affected by the frequencies of words in the non-target language, indicating that they could reject the non-target language before lexical access. Such efficient control processes were subserved by left lateral prefrontal cortex (BA45/9) and ACC.

Another important prediction of the general control view is that, bilinguals faced with managing the cross-language interference from an early age, may develop enhanced abilities of executive control (Bialystok, 1999, 2001). Consistently, early bilinguals have showed to be more proficient (with faster responses) than monolinguals in suppressing task-irrelevant information (Bialystok et al., 2004; Carlson and Meltzoff, 2008) and inhibiting habitual response tendency (Bialystok et al., 2006). Bialystok et al. (2005) examined the neural basis of bilingualism advantages in perception and attention with magneto-encephalography (MEG). In their study, fluent bilinguals and monolinguals were asked to press the right button if a red square appeared and the left button if a green square appeared (the Simon task, see Lu and Proctor, 1995; Simon and Ruddell, 1967). In congruent trials,

the target square appeared on the same side of button pressing (e.g., red square on the right side), while in incongruent trials, the target appeared on the opposite side of button pressing (e.g., red square on the left side). The irrelevant spatial position would interfere with the rule-directed response, leading to more response errors and longer response times. Bialystok et al. analyzed two bands of signals, the theta band (4–8 Hz), which is associated with attentional control (Hald et al., 2006; Ishii et al., 1999), and the alpha band (8–15 Hz), which is associated with signal processing (Hari et al., 1997; Schürmann and Basar, 2001). In the theta band, the activity patterns for incongruent versus congruent trials were similar for bilinguals and monolinguals, but were stronger in bilinguals. In the alpha band, faster responses in bilinguals were associated with more activations of left dlPFC (BA8) and left vlPFC (BA45/47), whereas faster responses in monolinguals were associated with more activations of left dlPFC (BA9). It is possible that bilingual and monolingual people use a similar network to deal with conflicts. However, the management of two language systems leads to subtle difference in interference control (stronger theta effects) as well as changes in signal processing (different alpha effects).

Moreover, lifelong experience of bilingualism may also attenuate the decline of executive functions in aging or dementia (such as Alzheimer’s disease; see Stern, 2003, 2006 for reviews). Bilinguals show less age-related losses in the efficiency of inhibitory processes (e.g., smaller conflict effects) than monolinguals (Bialystok et al., 2004). It is proposed that atypical brain pathways may be recruited in compensation for dysfunction in aging or brain damage (see Buckner, 2004; Stern, 2006). However, it still needs further exploration on how bilingualism (and other socio-cultural factors such as education and occupational attainment) leads to neural compensation during pathological brain processes.

## 6. Conclusion and further directions

The emergences of language and executive control are important results of human evolution. With language, human can create an infinite variety of meanings by using a finite number of words. With executive control, they can orchestrate thoughts and actions along internal goals. The neural basis of language processing partially overlaps with that of executive control over frontal, parietal and sub-cortical structures (e.g., Broca’s area and basal ganglia). However, it is rarely explored how the language system and the control system interact during daily life or in the brain. Here we try to understand these two systems as a network rather than isolated brain functions.

In previous sections, we reviewed recent studies contributing to our knowledge about executive functions involved in language processing. During communication, speakers and listeners have to deal with interferences from irrelevant lexical items, unselected



languages, and competing sentential interpretations. To prevent from confusion, executive functions, which are mediated by the network of frontal, parietal and sub-cortical structures, are recruited to select the right words over alternatives (Section 4), to bias toward the target language or switch from one language to another (Section 5), and to sustain the most reliable sentential interpretation against competing candidates (Section 3). Executive functions employed to resolve conflicts among representations in language processing are similar to those employed to resolve conflicts among representations in perception and attention. The control processes in language processing partially share the neural basis with those in perception and attention. Moreover, there are correspondences between individuals' abilities in resolving linguistic conflicts and their abilities in resolving perceptual conflicts. On the one hand, individuals' differences in controlling interfering sentential representations could be predicted by their performances in controlling interfering perceptual information. The developmental pattern of individuals' abilities in recovering from initial misinterpretations correlates with the developmental progression of executive functions and the maturational change of the prefrontal cortex. On the other hand, bilinguals faced with managing the cross-language interference from an early age could develop enhanced control abilities and become more resistant to pathologic brain processes which result in the decline of control efficiency.

However, considerable work remains to specify the cognitive and neural mechanisms of executive functions in language processing. One question is whether speakers and listeners use the same control mechanisms to deal with interfering linguistic representations in production and comprehension. If executive functions are general in nature, the control processes in production and comprehension may partially share the neural basis. Moreover, individuals' control abilities in production may be related to their control abilities in comprehension. The developmental pattern of individuals' abilities in managing two languages may correlate with the late maturation of prefrontal cortex and slow progression of executive functions. Another question is whether bilinguals and monolinguals use the same control mechanisms to resolve competitions among representations of linguistic and perceptual inputs. Although bilinguals were observed to use similar control mechanisms for within-language and between-language switching (e.g., Hernandez et al., 2001), it remains unclear whether the management of two language systems would lead to changes in the neural basis of control processes. Last but not least, it needs to be clarified how the control processes interact with the linguistic processes in language processing. For example, how multiple linguistic processes are monitored and regulated by the supervisory control mechanisms and how feedbacks are transferred from the language system to the control system? We believe that, as studies continue to provide evidence regarding executive functions involved in language processing, we will gain additional insight into these fundamental questions.

In the current review, executive functions are assumed to be supported by a network of distributed brain areas, including frontal, parietal and sub-cortical structures, each component making a distinct contribution to executive control (for a discussion of the distributed view, see Hommel et al., 2004). However, these structures are not equally recruited in language processing and the underlying mechanisms linking these structures remain a mystery. For example, recent fMRI studies did not find activation of sub-cortical structures during the processing of implausible or ambiguous sentences (e.g., Nieuwland et al., 2007; Novais-Santos et al., 2007; Ye and Zhou, submitted for publication). One critical issue is how to characterize the role of each component and the interaction between them in language processing which demands attentional control. To address this

issue, further studies should establish contacts between previously separated fields, including investigations of behavioral performance, brain imaging of healthy and pathologic people, researches on cognitive development, aging and dementia. Another important issue is how to understand the multiple roles of one brain area, especially left middle VLPFC (Broca's area) in language processing and executive control. Activations of Broca's area have been observed not only in building hierarchical structures during sentence comprehension (Friederici, 2002; Grodzinsky and Friederici, 2006), but also in selecting among competing lexical/sentential representations held in working memory (Badre and Wagner, 2007; Badre et al., 2005; Novick et al., 2005; Thompson-Schill et al., 2005). Moreover, previous studies also suggested its role in constructing hierarchical organization of action planning (Koechlin and Jubault, 2006; Koechlin and Summerfield, 2007). Considerable work remains to specify the cognitive and neural mechanisms of Broca's area, in order to reach an account which can explain above mentioned observations across different domains and tasks.

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