Executive functions

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Introduction

Following William James' famous example of going upstairs to change and discovering himself in bed, cognitive psychologists have recognized that some actions require conscious effortful control, but others are executed automatically (and so can lead to 'capture errors' of the kind described by James). This distinction is not simply a contrast between simple and complex actions, as well-learned complex actions can be automatic (e.g., driving a car); nor between externally and internally driven actions as the latter can be based on internally driven automatic processes (e.g., memory recall). Instead, the distinction between controlled and automatic actions hinges upon three key features: the execution of novel versus familiar action sequences, making a choice between alternative responses versus executing a single action sequence, and the execution of acts that do / do not require access to consciousness.

The term 'executive function' (EF), therefore, refers to a complex cognitive construct encompassing the whole set of processes underlying these controlled goal-directed responses to novel or difficult situations, processes which are generally associated with the prefrontal cortex (PFC), the regions of which are shown in Figure 1. The cognitive importance of the PFC first became apparent through studies of First World War veterans, which demonstrated that soldiers with frontal lobe injuries were unimpaired on routine tasks, but had difficulty mastering new tasks or grasping the whole of a complicated task. This led to the view that EF was important for abstract or high-level thought, abilities only manifested in adulthood, and to the subsequent neglect of EF in childhood for much of the last century.

Luria's influence

Research into the development of EF can be traced back to the theoretical and empirical work of the Soviet psychologist Alexander R. Luria (1902–1977), who proposed a less ambitious but more practical role for the frontal lobes, namely, the responsibility for programming, monitoring, and regulating behavior. This view continues to be influential, and has been expressed computationally by the characterization of the PFC as a 'Supervisory Attentional System' (SAS). A recent version of this model is shown in Figure 2.

Luria's empirical work was equally seminal. In particular, his account of developmental improvements showing a peak between the ages of 4 and 7 in children's ability to plan, monitor, and regulate their behavior has been well replicated. In addition, several tasks developed by Luria (1966) in his work with adult clinical groups and with young children continue to be widely used. These include tasks such as the 'Go / No Go test' (in which the child must execute a response to stimulus A, but withhold this response when presented with stimulus B) and non-verbal Stroop tasks. Examples of non-verbal Stroop tasks include the picture-based 'Day/Night' task (in which the child must say 'Day' for a picture of the moon, and 'Night' for a picture of the sun), the Tapping game (in which the child must tap once in reply to two taps, and twice in response to a single tap), and the Hand game depicted in Figure 3.

Executive function tasks

Other EF tasks that are simple enough even for infants have since been developed. These include tests such as (i) the A-not-B test in which the infant is invited to retrieve an object that is hidden in location A for a few trials, and then hidden in a new location B (younger infants will continue to search at A, even when the object is visible at B); (ii) the object reversal test in which an established reward contingency is reversed (performance is rated by the number of trials needed to learn this reversal); and (iii) object retrieval tasks that tap the ability to perform a means-end action, such as making a detour around a barrier to retrieve a desired object. Both animal lesion studies and human imaging

studies indicate that particular clusters of tasks differentially activate distinct sub-regions of the PFC. For example, 'hot' (affectively laden) EF tasks that involve changing reward values (e.g., the object reversal task described above, and gambling tasks that involve high- and low-risk card decks) appear to activate the orbitofrontal PFC, whilst 'cool' EF tasks (e.g., working memory tasks that require processing as well as storage) activate the dorsolateral PFC (Fig. 1).

These simple tasks have also led to dramatic improvements in our understanding of the development of EF. For instance, it is now known that EF: (i) begins to emerge in the first few years of life; (ii) becomes fully mature in late adolescence and declines with normal ageing; (iii) sub-divides in children and adults in similar ways (in each case the three most widely reported factors are inhibitory control, attentional flexibility, and working memory / planning); (iv) shows stage-like age-related changes; and (v) has important consequences for other cognitive functions (e.g., early vocabulary development is strongly predicted by individual differences in the functioning of one component of working memory termed the phonological loop).

Current research topics

This rapid progress in our understanding of the basic development of EF has exciting consequences, and there are now several hot topics for research. Firstly, impairments in the control of action contribute to the behavioral problems that set children on a trajectory toward deviance, delinquency, and anti-social conduct. For instance, in a study of 'hard to manage' 3- and 4-year-olds, individual differences in EF were significantly associated with antisocial behavior (Hughes *et al.*, 2000). Studies that deepen our knowledge of normative age-related improvements in EF may therefore help to identify children with poor regulatory control who could benefit from intervention programs, and so has clear societal importance. Thus, interest in early EF is closely tied to the growth of the new discipline of developmental neuropsychology. In particular, impairments in EF are thought to play a key role in several childhood disorders, including Attention-Deficit Hyperactivity Disorder (ADHD) and autism, though the latter is more controversial.

Secondly, studies with children offer the promise of differentiating the components of EF. In particular, the technique of manipulating task parameters may be especially fruitful in studies of children, since their relatively limited processing capacity makes them more sensitive to effects of increased demands for particular functions. This provides a direct solution to the low discriminant validity shown by traditional EF tasks.
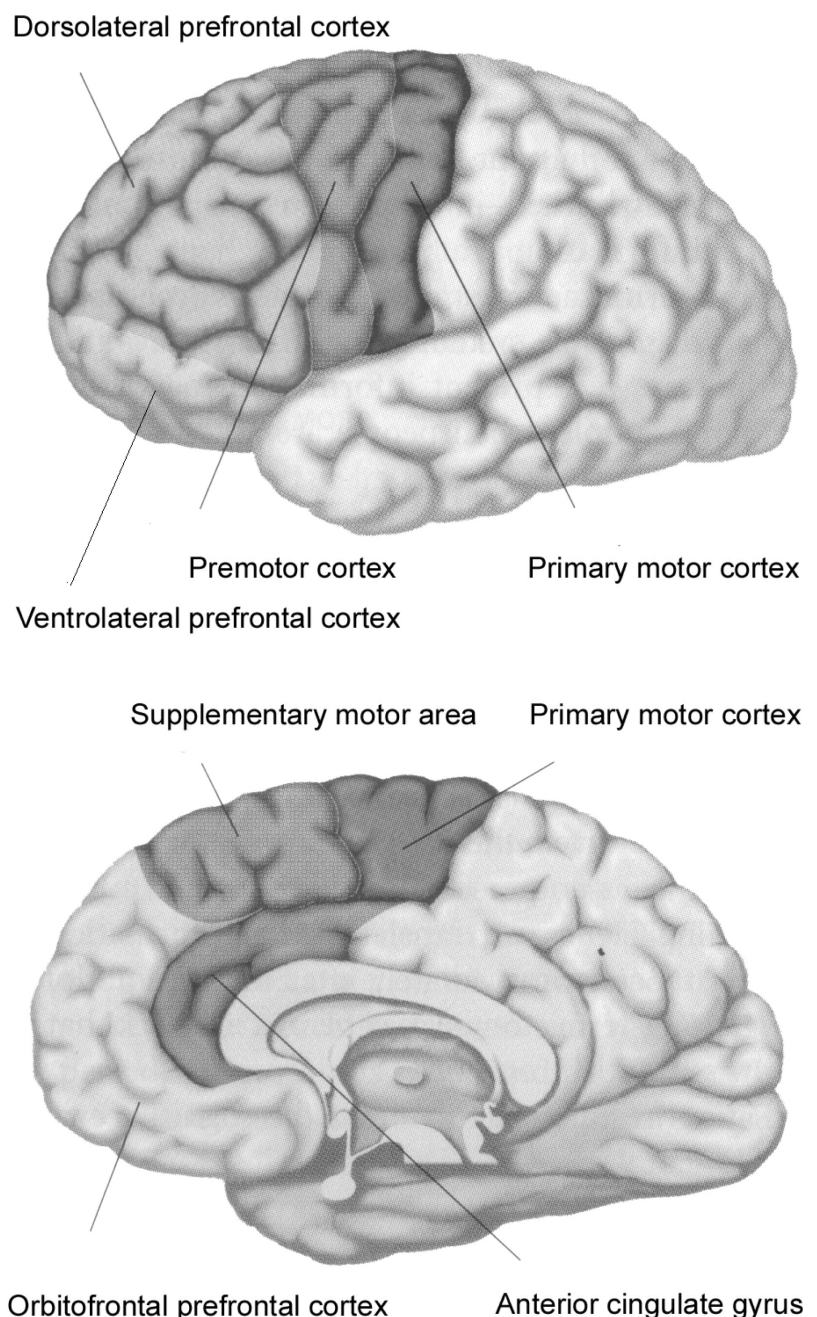

Figure 1. Surface and medial views of the brain, showing key regions of the prefrontal cortex.

Because such tasks are typically complex and multi-componential, different clinical groups may perform equally poorly for different reasons. For example, ADHD and autism have quite different clinical presentations, and yet both groups show substantial EF deficits (scoring ≈ 1 standard deviation below control groups). At first glance, one might therefore expect EF impairments to be rather non-specific. However, studies that adopt an information-processing approach (involving simplified tasks that allow comparisons based on specific rather than global performance measures) have revealed both quantitative and qualitative
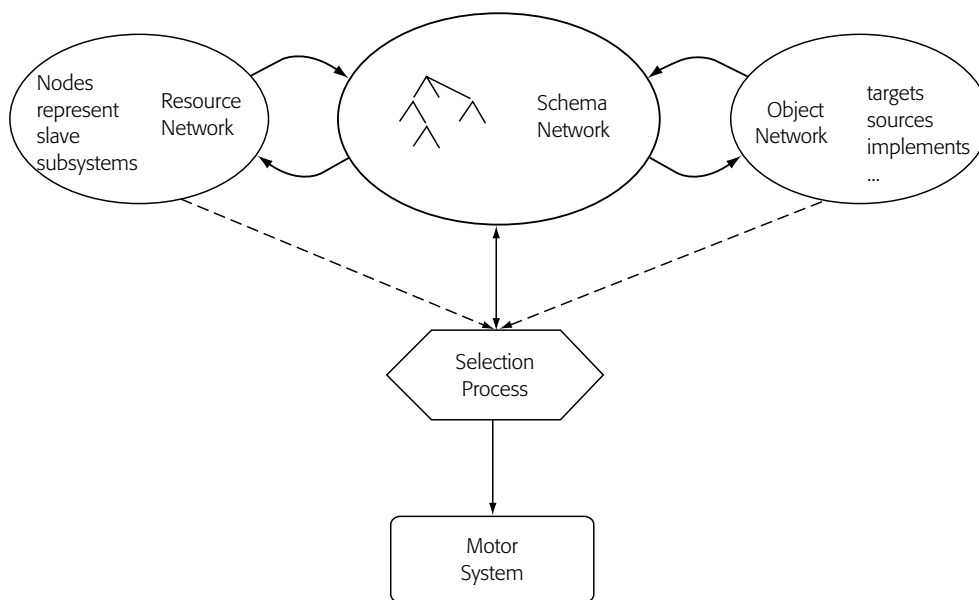
Figure 2. The Cooper and Shallice implementation of the 'Supervisory Attentional System' model. At the center of the model is a hierarchically structured network of interactive action schemas that compete for activation. Schemas receive excitation and inhibition from various sources, including higher-level schemas, the representation of the environment, and competing schemas. The model has been applied to a range of tasks, including preparing coffee and packing a lunchbox. From R. Cooper & T. Shallice, 2000. Contention scheduling and the control of routine activities. *Cognitive Neuropsychology*, 17, 297–338.
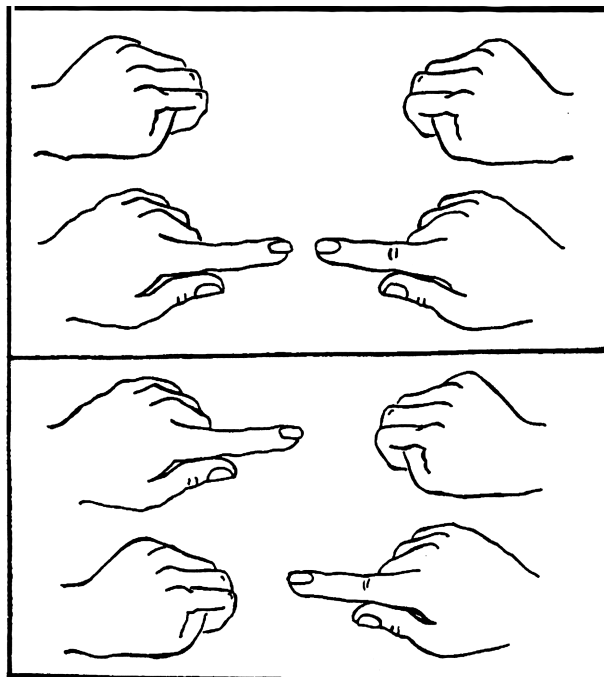

Figure 3. Luria's Hand game. Above is the control 'imitation' condition. Below is the test 'conflict condition' in which the child has to show a fist if presented with a finger, but point a finger if shown a fist. Performance is scored by the number of correct conflict trials/12.

distinctions between EF impairments in these two disorders.

Thirdly, there is converging evidence for a functional link between EF and 'theory of mind' (ToM) defined as the ability to attribute mental states to oneself and others: (i) pronounced impairments in both EF and ToM among children with autism; (ii) the developmental synchrony of improvements in both EF and ToM among typically developing pre-schoolers; and (iii) robust correlations between individual differences in EF and ToM, even with effects of age and IQ controlled. Since the topic of ToM continues to attract intense research interest, the nature and significance of its association with EF is a matter of considerable debate.

Empirically, there is longitudinal evidence for a predictive association between individual differences in EF at age 4 and in ToM one year later (even controlling for initial ToM), but no association between early ToM and later EF (Hughes, 1998). This asymmetry suggests a direction of influence (EF → ToM), but findings from intervention studies are needed to establish a causal path. In addition, it may be that associations between EF and ToM are specific rather than global. For example, Carlson & Moses (2001) have reported particularly strong associations between inhibitory control and ToM. Further support for this view comes from the findings in several imaging studies, demonstrating that ToM tasks activate the orbitofrontal PFC (the subregion previously identified as important in inhibitory control). Since individuals with autism are known to show profound impairments of ToM, this finding suggests that research into EF impairments in autism should focus on 'hot' EF tasks that are associated with the orbitofrontal PFC (previous research in this field has

generally employed traditional 'cool' EF tasks that are typically associated with the dorsolateral PFC). Thus, one positive consequence of the debate surrounding the relation between ToM and EF is the integration of brain-based research with studies of both normative and atypical development.

Methodological challenges

Despite the various advances outlined above, it should be emphasized that EF research remains besieged by methodological problems. In particular, much more work is needed to achieve a fine-grained analysis of the distinct components of EF. This fractionated approach is also important as a solution to the homunculus problem raised by terms such as 'effortful control,' since it allows EF to be compared with a set of automatic tools, rather than an engineer. In addition, it is very difficult to design 'pure' tests of EF, or even tasks that show good test-retest reliability (an inherent problem with EF research is that any task is only novel once). Progress in our conceptual understanding of EF depends critically upon innovative and rigorous solutions to these methodological challenges.

Conclusions

The challenges for future research in the above areas are vast and varied. However, one that deserves a special mention is the need to investigate whether contrasts in EF help explain differences in the form and severity of behavioral symptoms. Research on this topic may enable us to elucidate *specific* links between EF and behavior. Such links may be best described in terms of distinct behaviors, such as reactive versus proactive forms of aggression (for disruptive behavior disorders), or catastrophic responses to change versus ritualistic routines (for autism). Alternatively, links between EF and behavior may be clearest for specific contexts (e.g., peer interactions that are not scaffolded by familiar routines). Addressing the relationship between variability in EF and in behavior also provides a promising alternative to simply comparing diagnostic groups, in that disorders with overlapping symptoms (e.g., ADHD and Conduct Disorder) may show relative rather than absolute differences in EF. For many reasons then, research that combines innovative task

manipulations with valid and reliable observational methods is vital.

Questions

1. To what extent do executive function deficits explain differences in the form and severity of behavioral symptoms?
2. Can distinct types of executive function deficit be identified with different disorders?
3. How do individual differences in executive function relate to individual differences in other cognitive skills, such as theory of mind or verbal ability?

See also:
Theories of the child's mind; Magnetic Resonance Imaging; Cross-sectional and longitudinal designs; Cognitive development in infancy; Cognitive development beyond infancy; Aggressive and prosocial behaviors; Brain and behavioral development (II); cortical; Attention; Autism; Behavioral and learning disorders; Cognitive neuroscience; Ethology; Jean Piaget

Further reading

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