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The Neurocognitive Networks of the Executive Functions

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1. Introduction

Executive functions are associated with complex mental operations, such as planning, internal ordering, time perception, working memory, inhibition, self-monitoring, self-regulation, motor control, regulation of emotion, motivation (Norman & Shallice, 1986; Luu & Tucker; 2000).

2. Definition of particular components of the executive functions:

- **Planning:** organizational process of creating and maintaining a plan and the psychological process of thinking about the activities required to create a desired goal on some scale
- **Internal ordering:** A condition of logical or comprehensible arrangement among the separate elements of a group
- **Time perception:** timing of sensory information from multiple sensory streams is essential for many aspects of human perception and action
- **Working memory:** is a system for temporarily storing and managing the information required to carry out complex cognitive tasks such as learning, reasoning, and comprehension. Working memory is involved in the selection, initiation, and termination of information-processing functions such as encoding, storing, and retrieving data; that is the ability to hold information in mind and manipulate it.
- **Inhibition:** that is the ability to concentrate to execute task and to ignore distraction; function needed for goal-directed behaviour
- **Self-regulation:** self-directed action that serves to alter the probability of a subsequent response so as to alter the likelihood of a future consequence.
- **Self-monitoring:** self-discipline

- **Regulation of emotions:** self-regulation of emotions
- **Motivation:** refers to a process that elicits, controls, and sustains certain behaviours

Actions are executive if they involve the “when” or “whether” aspects of behaviour, whereas nonexecutive functions involve the “what” and “how.”

The term *executive functions* seem to incorporate (Barkley, 1997):

- Volition, planning, and purposive, goal-directed, or intentional action
- Inhibition and resistance to distraction
- Problem-solving and strategy development, selection, and monitoring
- Flexible shifting of actions to meet task demands. Maintenance of persistence toward attaining a goal
- Self-awareness across time

3. Developmental aspects of executive functions

Mature cognition is characterized by abilities that include being able:

- to hold information in mind, including complicated representational structures to mentally manipulate that information, and to act on the basis of it
- to act on the basis of choice rather than impulse, exercising self-control by resisting inappropriate behaviors and responding appropriately
- to quickly and flexibly adapt behavior to changing situations

These abilities are referred to respectively as working memory, inhibition, and cognitive flexibility. Together they are key components of both “cognitive control” and “executive functions” (Davidson MC et al; 2006).

When studying executive functions, a developmental framework is helpful because these abilities mature at different rates over time. Some abilities peak in late childhood or adolescence while others progress into early adulthood. Furthermore, executive functioning development corresponds to the neurophysiological developments of the growing brain; as the processing capacity of the frontal lobes and other interconnected regions increases the core executive functions emerge (Lucca & Leventer 2008; Anderson 2002).

4. Childhood

Inhibitory control and working memory are among the earliest executive functions to appear, with initial signs observed in infants, 7 to 12-months old. Then in the preschool years, children display a spurt in performance on tasks of inhibition and working memory, usually between the ages of 3 to 5 years. Also during this time, cognitive flexibility, goal-directed behavior, and planning begin to develop (Lucca & Leventer 2008; Anderson 2002). Also between 8 and 12 months, infants are able to hold in mind for progressive longer period where a desired objects has been hidden, and are able to control their behavior so that they do not repeat a previously correct search that would not be wrong (Diamond

2006). Nevertheless, preschool children do not have fully mature executive functions and continue to make errors related to these emerging abilities - often not due to the absence of the abilities, but rather because they lack the awareness to know when and how to use particular strategies in particular contexts (Espy 2004). In the human brain, dendrites of pyramidal neurons in layer III of dorsolateral prefrontal cortex undergo their most dramatic expansion between the ages of 7^{1/2} and 12 months. Pyramidal neurons in dorsolateral prefrontal cortex have relatively short dendritic extents at 7^{1/2} months, but reach their full mature extent by 12 months (Koenderink, Uylings and Mrzljak; 1994). The level of glucose metabolism in dorsolateral prefrontal cortex increases during this period as well, approximating adult levels by 1 year of age (Chugani, Phelps and Mazziotta, 1987). One particularly important developmental change during this period might be increased levels of dopamine in dorsolateral prefrontal cortex. Dopamine is important neurotransmitter in prefrontal cortex and reducing dopamine in prefrontal cortex impairs performance on executive function task (Brozoski, Brown, Resnold and Goldman, 1979; Diamond, 2001).

5. Preadolescence

Preadolescent children continue to exhibit certain growth spurts in executive functions. During preadolescence, children display major increases in verbal working memory, response inhibition, selective attention, goal-directed behavior and strategic planning (Brocki 2004; Anderson 2001; Klimkeit 2004). Between the ages of 8 to 10, cognitive flexibility in particular begins to match adult levels (Lucca 2003; Luciana 2002). However, similar to patterns in childhood development, executive functioning in preadolescents is limited because they do not reliably apply these executive functions across multiple contexts as a result of ongoing development of inhibitory control (de Lucca 2008).

6. Adolescence

During adolescence different brain systems become better integrated. At this time, youth implement executive functions, such as inhibitory control improve. Just as inhibitory control emerges in childhood and improves over time, planning and goal-directed behavior also demonstrate an extended time course with ongoing growth over adolescence. Likewise, functions such as attentional control, with a potential spurt at age 15, along with working memory, continue developing at this stage (Anderson et al, 2001).

7. Adulthood

The major change that occurs in the brain in adulthood is the constant myelination of neurons in the prefrontal cortex. At age 20-29, executive functioning skills are at their peak, which allows people of this age to participate in some of the most challenging mental tasks. These skills begin to decline in later adulthood. Working memory and spatial span are areas where decline is most readily noted (de Lucca et al, 2008).

8. The neurocognitive networks of the executive functions

Cognitive models typically describe executive functions as higher-level processes that exert control over elementary mental operations (Norman and Shallice, 1986; Luu and Tucker, 2002). A central position of the prefrontal cortex (PFC) and its cortical and sub-cortical connections in processing the executive functions have been suggested (Stuss and Benson, 1986; Badgaiyan, 2000). Ventromedial PFC is involved in decision-making processes, the dorsolateral portion has a role in working memory, planning and sequencing of behaviour. The caudal PFC is reported to be involved in attentional mechanism (Goldberg and Bruce, 1985). This theory was reviewed by Parkin (Parkin, 1998) who criticized the concept of the central position of the PFC in the executive functions. He suggested instead a pattern of extensive heterogeneity with different executive tasks associated with different neural substrates. In fact, several studies have documented the diversity of executive functions and related anatomy (Godefroy, 2003).

Recent findings show that executive functions and cognition are associated with a lot of other structures.

9. Methods of neurocognitive network research

9.1. Cognitive ERP

Endogenous event-related potentials (ERPs) are thought to reflect the neurophysiologic correlates of cognitive processes. The P3 component of ERPs, which is a target detection response, has been one most studied. This long-latency waveform (300 milliseconds range) may represent various functions, such as closure of sensory analysis, cognitive closure of the recognition processing, the attentional and decisional processes and the update of working memory (Roesler et al, 1986; Verleger et al, 1994, 2005; Comerchero and Polich, 1999).

The main ERP components were identified by visual inspection and quantified by latency and amplitude measures. P3-like waves were identified in the 250-600 milliseconds latency range.

In our study (Rusnáková et al, 2011) the occurrence of the local generators of P3 like potentials, elicited by a noise-compatibility flanker test was used in order to study the processing of executive functions, particularly in the frontal and temporal cortices.

The test performed with arrows comprised a simpler congruent and a more difficult incongruent task. The two tasks activated the attention and several particular executive functions i.e. working memory, time perception, initiation and motor control of executed task. The incongruent task increased demand on executive functions, and beside the functions common for both tasks an inhibition of automatic responses, the reversal of incorrect response tendency, the internal ordering of the correct response and the initiation of the target-induced correct response was involved. In seven epilepsy surgery candidates (4 males and 3 females), ranging in age from 26 to 38 years, multi-contact depth electrodes

were implanted in 590 cortical sites. We focused on local sources of P3-like potentials. Only the “phase reversal” and “steep voltage change” were considered to be generators of the studied potentials, because of their significance as the accepted signs of proximity to generating structure (Vaughan et al., 1986; Halgren et al., 1995a, b).

The components of Event Related Potentials

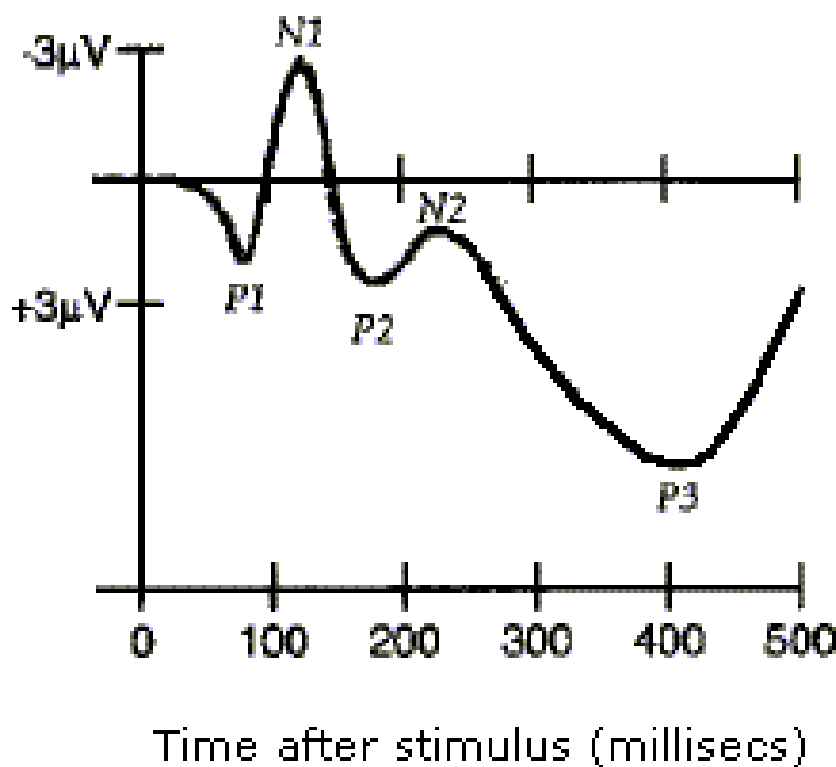


Figure 1.

In the two tasks, the P3 like potential sources were displayed in the mesial temporal structures; the lateral temporal neocortex; the anterior and posterior cingulate; the orbitofrontal cortex and dorsolateral prefrontal cortex. The P3 like potentials occurred more frequently with the incongruent than with congruent stimuli in all these areas. This more frequent occurrence of P3 sources elicited by the incongruent task appeared significant in temporal lateral neocortex and orbitofrontal cortex.

9.2. Event-related synchronization and desynchronization (ERD/S)

Event-related synchronization and desynchronization (ERD/S) represents a quantitative nonlinear EEG signal analysis method that enables to evaluate the changes of the background activity in any frequency ranges. These changes are related to an external or internal stimulus and are linked to the brain activation. It is widely used in the neuroscience

research as a form of functional brain mapping. Especially the intracerebral recording data analysis have a big importance.

In a previous intracerebral depth electrodes study (Bočková et al., 2007) the neurocognitive network in the frontal and lateral temporal cortices was investigated by a visual-motor tasks of writing of single letters. The first task consisted of copying letters appearing on a monitor. In the second task, the patients were requested to write any other letter. The cognitive load of the second task was increased mainly by larger involvement of the executive functions. The task-related Event Related Desynchronization/Synchronization (ERD/ERS) of the alpha, beta and gamma rhythms was studied. The alpha and beta ERD/ERS linked specifically to the increased cognitive load was present in the PFC, the orbitofrontal cortex and surprisingly also the temporal neocortex. Particularly the TLC was activated by the increased cognitive load. It was suggested that the TLC together with frontal areas forms a cognitive network processing executive functions. The test used in Bočková's study consisted from an original and rather complex task, with involvement of several executive and non-executive processes. In consequence, the interpretation was rather complex. In order to confirm the suggested involvement of the TLC in the central executive we decided to perform the present study with a test that has been commonly used for studying executive functions

In conclusion, in Bočková et al. cognitive intracerebral studies was documented using ERD/S methodology the involvement of the lateral temporal neocortex in the neurocognitive network of executive functions.

9.3. Functional magnetic resonance (fMRI)

During the last decade occurred brisk development of the method of functional MRI which maps of regional changes of cerebral perfusion and indirectly assesses also the neuronal activation in the examined parts of the brain. It's contribution to investigations of cognitive functions is not quite unequivocal so far. In the study of Brázdil et al. (2003) auditory "oddball" task examination was performed in 10 healthy volunteers using the method of "event-related" functional MRI (efMRI). The authors compared the assembled results with the results of previous efMRI and intracerebral ERP studies with the objective to evaluate the extent of agreement between areas with haemodynamically significantly different response to rare target stimuli and known intracerebral generator of the P3 potential. Both methods proved the activation of several areas in particular the parietal and frontal lobe (lobulus parietalis superior, inferior, gyrus supramarginalis, gyrus cinguli, of the lateral prefrontal cortex, gyrus temporalis superior and of the thalamus). Consistent with the assumed significant role of the neurocognitive network for directed attention in the course of detection of target stimuli in the majority of these structures a more marked haemodynamic response was observed on the right side. Against expectation in the presented experiment nor in any previous efMRI studies a significant haemodynamic response to target stimuli was not proved at the side of the most marked P3 generator in the amygdalohippocampal complex. Different results were also obtained on examination of

further areas, e.g. rostral cingulum. Thus although the contribution of efMRI to recognition of the neuroanatomical correlate of mental processes is extremely high, it is unable to provide alone a complete map of activated cerebral areas in the course of cognitive operations. The reason is most probably the inability to reflect fully transient short-term mentary method and it's results must be evaluated with maximum caution (Brázdil et al; 2003).

10. Conclusion

Intracranial and neuroimaging studies demonstrated a widespread distribution of cognitive ERPs in multiple cortical and subcortical regions in the human brain. The participation of the frontal, temporal and parietal cortices, in addition to the cingulate and mesial temporal regions, the basal ganglia and thalamus, has been shown with visual, auditory and somatosensory stimuli (Halgren et al., 1995 a,b, 1998; Clarke et al., 1999, 2003; Smith et al., 1990; Baudena et al., 1995; Lamarche et al., 1995; Brázdil et al., 1999, 2003; Rektor et al., 2001 a,b, 2004, 2007; Bočková et al 2007; Rusnáková et al. 2011).

Based on other studies (Baláž et al, 2008; Rektor et al, 2009; Bočková et al.), even subthalamic nucleus (STN) is a part of widespread neurocognitive network. Cognitive activities in the STN could be explained by existence of hyperdirect cortico-STN pathway. Certain effect of deep brain stimulation (DBS) on cognitive performance is possibly caused by a direct influence on 'cognitive' parts of STN (Rektor et al, 2009).

In conclusion, reviewed studies, confirm theory of widespread and complex neurocognitive network of the executive functions.

Abbreviations

EEG: electroencephalography

ERD/ERS: Event Related Desynchronization/Synchronization

ERPs: event-related potentials

fMRI: functional magnetic resonance imaging

efMRI: event-related functional magnetic resonance imaging

FT: Flanker test

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