Education and the neurocognitive and neurobiological basis of mental flexibility

The development of mental flexibility can be influenced by a great many factors, including physical activity, environmental health and nutrition, and even sleep.

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Executive summary

- Flexibility has been broadly described as the ability to adjust one's thinking from old situations to new situations. It requires the ability to overcome habitual responses or ways of thinking in order to adapt to novel circumstances.
- Cognitive neuroscientists generally agree that flexibility is a component of executive functions, as it is related to many executive skills including impulse control, planning, and working memory.
- A collaborative brain network is activated during neurocognitive flexibility that includes the prefrontal cortex (PFC), basal ganglia, anterior cingulate cortex (ACC), and posterior parietal cortex (PPC).
- Physical activity, environmental health and nutrition, and sleep influence neurobiology that is required for optimal development of the brain structures responsible for flexibility.
- Flexibility and education share a reciprocal influence as methods of instruction can enhance skills related to flexibility, and flexibility enhances cognitive abilities linked with academic learning.
- Modes of instruction for enhancing flexibility include the use of hypertexts and group problem-solving activities.
- A controversial area of study involving flexibility involves commercial brain training programs.

Introduction

Mental *flexibility*, also known as *cognitive flexibility*, refers to the ability to adjust thinking or attention in response to changes in information or rules[1]. For example, in the province of Ontario, Canada, where I currently reside, it is legal to turn right on a red light (after stopping first, of course). However, a bit like going from Geneva to France, a short twenty-minute drive takes me over to the province of Québec where this is not permitted. I must be able to shift my thinking to a new set of rules and suppress my original association of turning right at a red light; if I don't, there can be dangerous consequences. Similarly, cognitive flexibility has been measured as the capacity to shift thinking from one task with a given set of rules and procedures to another task with a different set of rules and procedures[2]. A simple task used to measure children's capacity to switch thinking is to ask them to sort cards based on the color of the pictured objects. Then, ask them to switch to sorting based on the shape. To emphasize that such ability includes both the brain and a cognitive level, here, we prefer to use the term *neurocognitive flexibility*. However, for simplicity we will most often refer to it as flexibility.

This brief has three objectives: (1) to describe the essential aspects of neurocognitive flexibility that have been most agreed on in research; (2) to describe the neurocognitive and neurobiological conditions that are associated with flexibility; and (3) to describe how flexibility and education influence each other.

Neurocognitive flexibility across definitions and methods

Neurocognitive flexibility has been one of the most heavily studied topics in cognitive and developmental neuroscience, and consequently, one of the most widely defined. In this section we gather the commonalities across definitions and share the core features of the concept, how it is commonly measured, and the methods used for investigation (we suggest more references for the readers who want to dig deeper). Our purpose here is to give the gist and highlight the essential features of neurocognitive flexibility for the benefit of educators.

Cognitive flexibility has been measured as the capacity to shift thinking from one task with a given set of rules and procedures to another task with a different set of rules and procedures. A common test used to measure flexibility in children is the Wisconsin Card Sorting Test (WCST) which involves asking children to sort cards based on one set of criteria (e.g., color) then switch to another set of criteria (e.g., shape)[3].

It has been argued that flexibility is also a component of multiple classification, as originally described by psychologist Jean Piaget. During multiple classification tasks children are required to identify many aspects of objects, and resist focusing on a single aspect, known as centration[4]—what we commonly refer to as tunnel vision. Following our previous example, young children have difficulty spreading their focus and tend to zero-in on a single aspect of an object, such as color, and are unable to focus on both aspects of color and shape at once. Similarly, if an individual is centrated on one aspect, then she/he will be more cognitively inflexible.

Neuroimaging studies

Regardless of the different definitions, cognitive neuroscientists generally agree that flexibility is a component of executive functions, that is, a type of higher-order cognition involving the ability to control one's thinking. Executive functions include other aspects of cognition, such as impulse control, memory, emotional stability, planning, and organization. Neurocognitive flexibility is highly related with a number of these abilities (i.e., impulse control, planning, and working memory)[2]. Thus, when an individual is better able to suppress an association with an object and focus on other important aspects, she/he is also more cognitively flexible. This ability is often measured using the Stroop task where a participant is asked to read color words but is then required to switch their focus by stating the font color in which the word is written. This becomes increasingly difficult when repeated several times, and the meaning of the words does not correspond with the font colour (e.g., the word "black" written in the font color "red"; the expected correct response is red).

A great deal of research has been done on the brain processes associated with all these aspects of neurocognitive flexibility. Most of these studies are based on various neuroimaging methods. Especially, functional magnetic resonance imaging (fMRI) methods have revealed a variety of regions of the brain that are consistently activated together in tasks which require flexibility. This collaborative brain network includes most and foremost the prefrontal cortex (PFC), basal ganglia, anterior cingulate cortex (ACC), and posterior parietal cortex (PPC)[5], shown in Figure 1 (adapted from ref. [6]).

Cognitive neuroscientists have studied the development of neurocognitive flexibility with tasks ranging from simple to more complex. The findings suggest that there is a developmental continuum that spans from infancy to adulthood. The main topics studied include brain maturation, neuropathology, and aging.

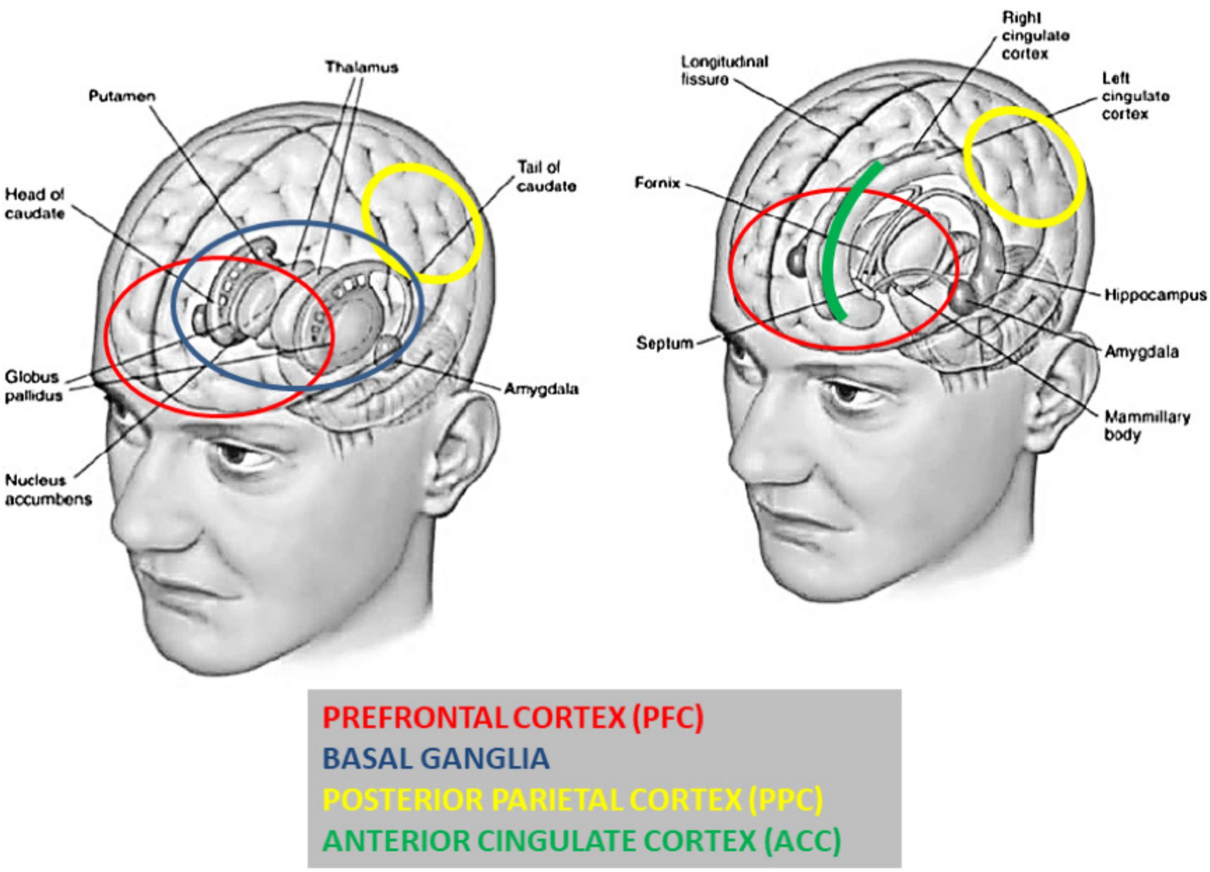

Figure 1. Neural networks associated with neurocognitive flexibility. Regions of the brain that are consistently activated

together in tasks which require flexibility. Adapted from Sejnowski, T. J., Poizner, H., Lynch, G., Gepshtein, S., & Greenspan, R. J. (2014).[6]

Neurobiological conditions

Neurocognitive flexibility has a lot to do with key areas of the neurobiology of human development (the study of more biological aspects of the brain development). This is because there are many neurobiological factors that need to be in place for the optimal development of the brain structures responsible for flexibility. These include: physical activity, environmental health and nutrition, and sleep.

Physical activity, active play, and exercise have a role in promoting the formation and consolidation of new connections of many cortical and subcortical centres linked to flexibility, especially the prefrontal and frontal cortex. A review of the most recent intervention studies for children conducted at home, school, or other educational settings suggests that increasing physical activity may lead to greater improvements in flexibility[7]. In addition, a review of studies on aging also suggests that aerobic exercise and training could potentially serve as an intervention to slow down the decline of flexibility in old age through plasticity-inducing effects[8].

Environmental health and nutrition also have an important impact on the development of flexibility. In particular, severe exposure to air pollution can disrupt key brain connections that support flexibility[9], as do noise and other forms of environmental hazards[10]. Malnutrition and unbalanced nutrition can lead to various forms of stunting that delay the development of flexibility. Similarly, diets that are associated with iron deficiency and diabetes in children have detrimental impact on flexibility. Adolescents and young adults with anorexia nervosa have marked decreases in set-shifting abilities, possibly associated with incomplete maturation of prefrontal cortices associated with malnutrition[11]. Obesity has also been linked with reduced flexibility.

Sleep is another neurobiological factor that seems to have a wide influence on flexibility. In particular, the interaction of the preference of sleeping late in the night (which develops in many individuals starting with puberty up to early adulthood) conflicts with early morning school start times. The clash between sleep and school times practically leads to constant sleep deprivation and sleep debt in most countries. In North America alone, it has been estimated that daily sleep deprivation can range from two to four hours per day in school-aged children[12].

Relationships to education, two-way influences

As previously mentioned, cognitive flexibility is generally agreed to be a component of executive functions. Executive functions have been directly linked with school readiness and academic success, suggesting that flexibility may facilitate this relationship. Of interest, flexibility has also been related to the learning approach of *attention and persistence* in preschool children attending a Head Start program geared to families living in poverty. This in turn was associated with school readiness, suggesting that flexibility influences children to maintain focus and persist in learning activities[13]. In this sense, flexibility supports children's learning and prepares them for school. What are other ways that flexibility might support children's learning in the school setting?

Neurocognitive flexibility enhances language learning and reading by providing students the ability to switch between and/or simultaneously think about sounds and meanings[14]. This relationship is reciprocal, as children learning a second language show enhanced flexibility. Furthermore, flexibility stemming from additional language learning appears to support reading in the second language learned as well [see Figures 2, 15]. In this study, we discovered that native Italian-speaking children learning English as a second language showed better reading skills in English when compared with native English-speaking peers. We also discovered that bilingual children that had reading disabilities outperformed their monolingual counterparts and were much closer to the performance level of typically developing children. There is a general increasing consensus that the enhancing positive effects of bilingualism and multilingualism are mediated by neuroplastic changes in the same frontal areas of the brain responsible for executive functions and action regulation that mediate flexibility.

Finally, how children are taught to learn plays a role in the relationship between education and flexibility. A crucial aim of education is to help students acquire the ability to appropriately apply and adapt what they have learned to novel situations. This ability can be fostered through a teaching style focused on promoting flexibility by incorporating group problem-solving activities that require multiple perspectives. This is especially true in disciplines where information is complex and not straightforward[16], such as physics and genetics (and neuroscience!).

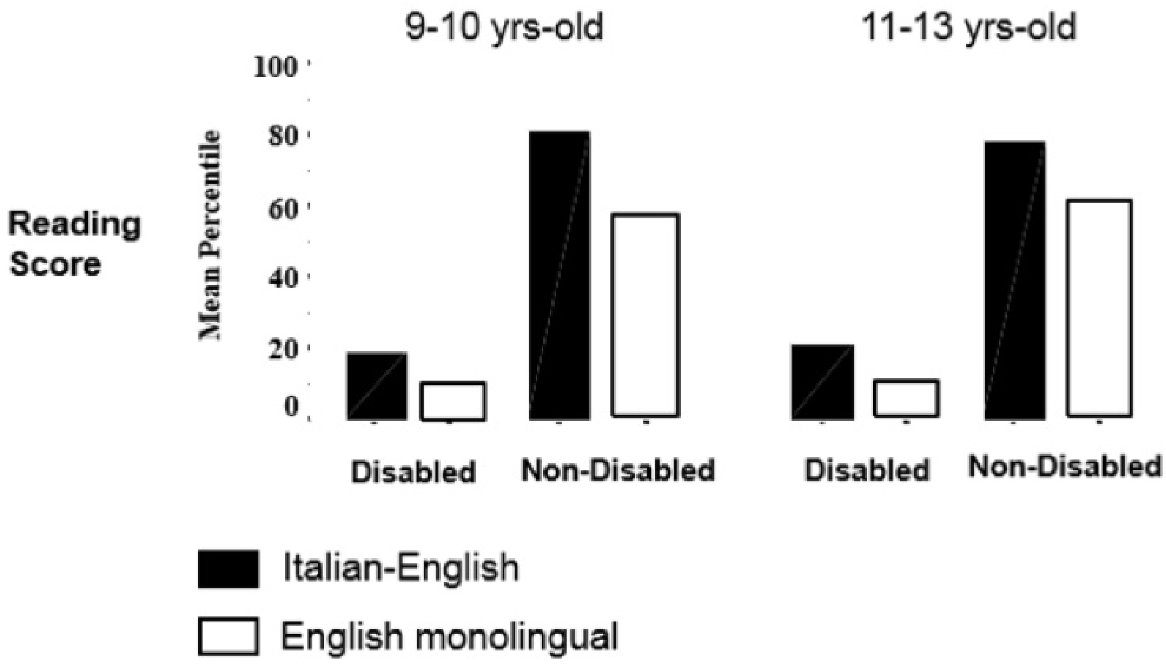

Figure 2. Exposure to Italian benefits English reading scores. Flexibility stemming from additional language learning appears to support reading in the second learned language. Adapted from D'Angiulli, A., Siegel, L. S., & Serra, E. (2001).[15]

The role of new technologies in curriculum design

The internet allows for complex information to be presented in various ways while maintaining a coherent format. In countries where students are regularly exposed to computers and have access to the internet, it makes sense to incorporate this technology into the classroom. Teachers may find incorporating information and communications technology (IT) into the classroom intimidating as it may be relatively foreign to them. Alternatively, teachers who have grown up in the digital generation (the digital "natives") may be overly confident yet unfamiliar with how to best use IT for student learning. In order to confidently incorporate new technologies into the classroom, teachers will require training and support[17].

Perhaps, the most important aspect of IT for flexibility as applied for education is the so-called New Media Literacy (also called digital or internet literacy). That is the ability to access, understand, and create communications. It involves more than the knowledge of how to use the technology since it requires critical analysis and creative production related to media. Accordingly, it involves what we may call *judgment*, broadly defined as the ability to critically assess the reliability, validity, and credibility of information from different sources and media, often many sources. This definition includes all the metacognitive and cognitive abilities involved in complex decision-making, and therefore is very much related to flexibility. That is, during learning in educational settings the user of IT and media is required to engage in information problem-solving activities that involve three components: (1) The individual's abilities, such as language and background knowledge; (2) the context of the activity, if it is done collaboratively or with a tutor and with certain time requirements; (3) the resources available, such as the type and quality and amount of information (e.g., whole web or preselected sources), and access devices, such as menus, search engines, and hypertexts[18].

An example of a new media literacy tool that supports neurocognitive flexibility is *hypertext*. The internet is known for hypertext that delivers information alongside connections and associations (e.g., hyperlinks). Often while reading an article online, readers are presented with hyperlinks that direct them to sites providing additional or new information. Readers then return to the original article and incorporate this new information and enhance their understanding. This is a clear example of flexibility in action as the reader alternates back and forth between different sources of information. *Hypermedia* that is readily available on public online platforms take this approach to a higher level, integrating several technologies (e.g., videos, music, audio recordings) that are embedded in hypertext platforms[19]. Students can be provided the same sense of freedom to research class material.

These *cognitive flexibility hypertexts* (CFH) present material in a format that promotes initiative and exploration. The open-ended format allows students to research material at their own pace, and to bounce back and forth between sources to incorporate new information and form connections with previous knowledge, however educators play a key role in scaffolding student learning by monitoring their progress and facilitating comprehension. In order for CFH platforms to be effective instructional tools in assisting students to transfer knowledge across learning domains, they must be grounded in a theoretical model of cognitive flexibility and supported by scientific research[20].

Many other specific skills are required to participate in the new media culture that are directly associated with flexibility, such as: *multitasking*, the ability to scan and shift focus as needed to salient details; *transmedia navigation*, to follow information across multiple modalities, sources, and media; and finally *networking*, the ability to search, synthesize, and disseminate information negotiation and to navigate across diverse digital communities, understanding and respecting multiple views and alternative norms and rules[18].

Public awareness of neurocognitive flexibility has increased in the last twenty years, resulting in a dramatic increase of online brain training programs marketed to the public. Programs claim to train speed, accuracy, memory, attention, cognitive flexibility, and problem-solving, among others. An example of a working memory training program geared to children to improve academic achievement is *Cogmed*[21], however the effectiveness of this program has been debated[22]. Presently, evaluating the efficacy of such programs requires further research and analysis before any clear benefits can be determined. Given the many complexities surrounding academic performance, we encourage educators to apply extreme caution and skepticism when deciding to implement a program that guarantees high rates of academic success, without solid support from peer reviewed research.

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