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Review

Development and plasticity of executive functions: A value-based account

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Abstract

Executive functions are core to multiple aspects of daily cognitive, social and affective functioning. An extensive body of work has charted developmental trajectories and neural substrates of executive functions through the lifespan. Robust associations between executive functions early in life, and later, wellbeing and success has led to considerable efforts to improve executive functions through bespoke interventions. Here, we discuss recent findings on the role of cost-benefit computations in how executive functions are deployed in development. We propose leveraging these insights to design more effective interventions for improving executive functions.

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Introduction

Achieving one's goals, be they immediate or long-term, requires control of thoughts and actions. Executive functions (EFs) describe a cluster of cognitive operations that enable such goal-directed behaviour [1,2], through stopping pre-potent responses and impulses (inhibition), manipulating and remembering goal-related information (working memory) and responding flexibly to changes in the environments (cognitive flexibility). EFs during infancy and childhood have been of particular interest to researchers and clinicians as they are predictive of later emotional, behavioural, and social wellbeing [3]. In this review, we examine the development and neural underpinnings of EFs. We draw on recent insights on the role of (effort) costs and rewards to put forward a value-based account to EF development, with potential implications for intervention studies.

Development of EFs

Indicators of EFs emerge as early as infancy and undergo protracted development into early adulthood [4]. EFs develop particularly rapidly during early and middle childhood, before changing more steadily in adolescence [5–7]. Indeed, multiple studies have found that distinct domains of EFs mature at different stages [7,8]. Specifically, one study found that while children as young as 4-years old could inhibit response and remember information, the developmental progression of cognitive flexibility was longer with huge accuracy differences observed even between adolescents and adults [7]. These improvements in EFs during childhood may be underpinned by the maturation of late-developing cortices, particularly the prefrontal cortex [5,9], as well as parietal regions [5]. Extensive changes in frontal and parietal cortical volume and functional connectivity over development have been shown to mediate EF improvements [10,11]. However, in addition to shared neural substrates, separable brain regions related to the different domains of EF (i.e. inhibition, working memory, cognitive flexibility) have been identified [12,13]. Specifically, across all EF domains, activation was present in the bilateral frontal-parietal network, which has been proposed to be involved in modulating task-general aspects of EFs [12,14]. However, activity in regions such as the anterior cingulate cortex and inferior frontal gyrus was found to be particularly associated with inhibition [12,14,15]. In line with this, one study found that while working memory was associated with cortical thinning in areas, such as the superior parietal cortex, inhibition was primarily associated with cortical thinning in occipital and parietal regions, such as the pericalcarine cortex [11]. These findings are consistent with behavioural data reporting unitary yet distinct domains of EFs and may explain the differential developmental trajectories of executive function domains [7]. Taken together, childhood is a critical period for the development of brain regions that subserve EF abilities and, as such, might constitute a crucial developmental period to target the malleability of EFs.

Training EFs

Given the importance of EFs and their link to later-life wellbeing, efforts to improve EFs through targeted interventions has attracted considerable interest from researchers [16]. Particular attention has been paid to child development given that EFs are subserved by late-developing brain areas and thus argued to be particularly malleable during childhood [17,18].

Overall, however, findings from intervention studies to date remain mixed [19,20••]. Specifically, training studies have been successful at leading to near transfer (i.e. improvements within the same domain). For example, a meta-analysis showed that training studies based on a working memory intervention led to improvements in working memory [21]. However, interventions have been less successful in producing transfer to other, so-called far domains [19,21]. It has been argued that individual differences are likely to play a significant role in whether cognitive functions can be improved and if such improvements transfer to other domains [20••]. For example, motivation likely plays a crucial role in determining training success and the extent of training transfer. Indeed, previous research has shown better training success in children with gamified designs [20]. Furthermore, motivation has been found to be a moderating factor of training effectiveness, with one study showing that engagement was linked to producing and maintaining training improvements [22]. This suggests that investigating individual factors, such as motivation, could help provide an integrative account to improve EFs through training interventions. This could also help explain why some training designs may be better suitable for some children and not suitable for others.

A valuation-based framework for executive function development

In recent years, motivation has been suggested to play a key role in how EFs are deployed. This has led to a re-examination of EFs, less as competencies or abilities that change as a function of cortical maturation but more as resources that are recruited depending on the context [23–25•]. It has been argued for instance that inhibition of responses or manipulation of information is cognitively effortful, requiring attention and resources [2]. The use of EFs is thus highly sensitive to the value associated with the goal and the effort costs associated with the action to obtain it [26, 27••]. One prominent theory posits that the decision to exert effort may be based on cost-value computations linked to the exertion of cognitive effort [27••]. Specifically, given limited resources, individuals may compare the cost and value associated with effort exertion to decide if the effort is worthwhile. Doing so allows for efficient allocation of effort ensuring resources are not unnecessarily used or misapplied [27••]. Developmentally, children as young as 4-years have been documented to be sensitive to effort expenditure [28]. It is thus plausible that EF performance can at least, in part, be explained by motivation rather than abilities. Indeed, previous studies have shown that effort exertion explains performance, which in turn can explain task performance variability attributed to individual and developmental differences in ability [7,29–35]. Indeed, there have been documented age differences in effort sensitivity [31•, 36]. Specifically, when subtle prompts about effort were provided, only older children were able to direct their behaviour to avoid effort [31•, 36]. However, when effort costs were made explicit, children as young as 5 were able to avoid unnecessary effort exertion [30, 31•]. This suggests that any observed developmental patterns are contingent on how explicit task demands are made. It emphasises that especially when task demands are made explicit, children of all ages avoid effort, which may influence their performance on demanding tasks.

The reward has also been shown to exert a prominent influence on performance on EF tasks [37]. Consistent with observed neural signatures, adults have been shown to allocate more control on trials predicted to be more rewarding [38]. Similarly, children as young as 4-years old have been found to perform significantly better on EF tasks when they were informed about the reward they would receive or provided with reward-related feedback [23,24]. Developmental changes in reward sensitivity and their influence on EF performance have been shown to be linked to the continued maturation of corticostriatal connectivity from childhood to adulthood [39].

In sum, EF performance is, in part, based on the cost of performing the action or mental operation and the value associated with the goal. It is thus plausible that incentives offered for task performance do not adequately offset effort costs associated with EF tasks [30, 31•]. Therefore, children, in particular, may choose not to exert effort in EF tasks, given the limited cognitive resources available to them [40]. Such rational allocation of limited resources could be interpreted as poor abilities. The recently proposed Learned Value of Control model suggests that individuals estimate the value of exerting control based on the features of an environment [41]. Individuals gather information from their environment to estimate the degree to which control should be allocated [41] (i.e. learning to exert more control after performance is rewarded [42]). This a capacity for using and integrating changing information in the environment to dynamically adjust behaviour. Such an account poses a plausible framework for how children learn the cost-value associated with exerting control.

The key in designing interventions aiming to improve EF abilities may thus lie in focussing on associative learning strategies that rely on the accumulation of information to learn if effortful control is necessary. Such a mechanistic approach could potentially be more effective at leading to transfer in and outside the lab. The aim of an intervention aimed at improving EFs should therefore not necessarily focus on simple quantitative increases in improvements (i.e. greater working memory span; faster stop-signal reaction times), but rather target the *optimal use* of EFs, such as increasing the efficiency with how limited resources can be used to obtain desired outcomes.

Implications for adolescence

Adolescence is a crucial phase where more complex EF skills such as performance monitoring and emotion regulation mature [43,44]. Despite improved EFs, adolescence is also marked by a peak of mental health problems [45]. With rising social pressure and the onset of puberty, adolescence is a period of heightened vulnerability to experience socio-affective problems, such as depression and anxiety [46••]. Improving EFs could be integral to better mental health outcomes. For instance, mental health problems, such as depression and anxiety, are characterised by increased levels of rumination and worry [47,48]. Poorer attentional control could lead to individuals being more vulnerable to such dysfunctional cognitive styles [48]. Indeed, abnormal attentional control and emotion regulation has been demonstrated to play a significant role in vulnerability to depression and anxiety [47,48]. Tackling these EFs may be crucial to improve emotional wellbeing. Indeed, interventions based on working memory have shown promise in improving depression and anxiety in both clinical and non-clinical adolescent populations [49,50]. Strikingly, improvements in depression were found to be modulated by greater frontal-parietal network activity, a network implicated in both EFs and also emotional control specifically [49].

While we observe these poor emotional outcomes in adolescence, an earlier preventive strategy might be necessary. Indeed, one article showed earlier self-regulatory abilities to be associated with later self-regulation in adolescence [51]. More directly, another article found that children with impulsivity problems were more likely to have anxiety and emotional problems in adolescence [46••]. This suggests that although mental health problems peak in adolescence, vulnerabilities for these problems can be identified in childhood, which reinforces the need for interventions to prevent later mental health problems by tackling potential EF dysfunction in childhood [3,51].

Conclusions and future directions

Childhood EFs are an important predictor for behavioural, emotional and social wellbeing later in life and particularly in adolescence. Prior work has focused on enhancing EF abilities but with limited success. We suggest that examining EF as value-based may offer a radical shift in understanding EF development. Intervention designs could benefit hugely from this and could target training motivation and effort expenditure. Training these core mechanisms may improve the optimal use of EFs and transfer them into real-life contexts. Better training effectiveness could lead to better EFs and reduce mental health vulnerabilities in adolescence.

Conflict of interest statement

Nothing declared.

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- • of special interest
- •• of outstanding interest

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