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Abstract

When adolescents enter secondary school, one of their main tasks is to expand their knowledge base (i.e. learn new subjects), acquire new cognitive skills (i.e. switching flexibly among the new demands), and get training in a variety of novel domains. However, not all adolescents deal successfully with these new challenges and some struggle with planning and organizing school tasks. In this chapter, we discuss the behavioral and neural changes that occur in executive functioning over the course of adolescence as one of the most important predictors of school success. We aim to unravel why some adolescents thrive and others struggle, if executive functions can be trained in adolescence, and what can be done to foster adapting to the new developmental challenges.

Introduction

Executive function is defined as the ability to control thoughts and actions for the purpose of achieving future goals (Diamond, 2013). It relies on our ability to keep information in mind (working memory), to respond to a changing environment (cognitive flexibility) and stop inappropriate actions or impulses (inhibition). When these functions work well in concert, this allows individuals to plan ahead and respond flexibly to a changing environment (Miyake et al., 2000). In this chapter we will focus on three questions: 1) how do executive functions develop during adolescence, 2) can executive functions be trained in adolescence, and 3) what are the implications of executive functions for school settings such as reading and mathematics performance.

The focus is on adolescence, which is a key transition period in development. Adolescence is defined broadly as the age range of 10-22 years, during which children show changes in physical, cognitive, affective and social domains (Steinberg, 2008). The first phase of adolescence is referred to as puberty, which spans approximately ages 10-14-years. Puberty starts roughly 1,5 years earlier for girls than for boys, and varies in onset between individuals (Shirtcliff, Dahl, & Pollak, 2009). Puberty is associated with extensive hormonal changes, which affects the physical appearance of adolescence, but also has effects on social-affective processes. Studies have shown that hormones have an impact on brain development, such that adolescents who are more advanced in puberty have more mature brain connectivity patterns (Ladouceur, Peper, Crone, & Dahl, 2012). The second phase of adolescence is defined as the age period of approximately 16-22-years, during which individuals develop mature cognitive and social goals and become independent members of society (Crone & Dahl, 2012).

The development of executive functions in adolescence

Whereas much is known about the development of executive functions in early and mid-childhood (Davidson, Amso, Anderson, & Diamond, 2006), relatively less attention has been devoted to the development of executive functions in adolescence. One of the seminal articles on executive function development across childhood and adolescence distinguished between three basic executive functions: working memory, shifting and inhibition (Huizinga, Dolan, & van der Molen, 2006), following Miyake et al. 's (2000) model on unity and diversity of executive functions in adults. The researchers estimated latent factors based on the shared variance between tasks that tapped into each of the three basic functions. A battery of tasks was administered to participants of the following ages: 7-years (n=71), 11-years (n=101), 15-years (n=111) and 21 years (n=94). Latent factors were obtained for working memory and shifting, and the results showed that working memory developed until the age of 21 years, whereas shifting was mature at age 15 years (Huizinga et al., 2006). These findings are consistent with other studies that have demonstrated that working memory performance increases over the whole period of adolescent development (Asato et al., 2006; Luna, Garver, Urban, Lazar, & Sweeney, 2004). In this same study, no common latent factor could be derived for the inhibition tasks (Huizinga et al., 2016). Inhibition was assessed using a stop-signal task, which requires the inhibition of a prepotent response, a Flanker task, which requires inhibition of irrelevant information, and a Stroop task, which requires inhibition of a conflicting stimulus property. Apparently, inhibition is a multifaceted construct and different types of inhibition do not necessarily correlate with each other. The developmental patterns were also distinct. Stop-signal inhibition and Flanker inhibition developed until age 15-years, consistent with several other studies that reported that inhibition improves until early adolescence (Prencipe et al., 2011).

Recent research showed that from late adolescence to early adulthood the three-factor structure of working memory, cognitive flexibility and inhibition is quite stable. This was evident in a 6-year longitudinal study that followed 840 individuals (Friedman, et al., 2016). These findings suggest that when entering adulthood executive functions are no longer changing.

An important question concerns if these relatively basic executive functions have predictive value for situations in which multiple executive functions need to be combined. For this purpose, basic executive functions tasks, or the latent factors of these functions, can be used used to test how well these basic executive functions predicted performance on more complex executive function tasks, such as the Wisconsin Card Sorting Task (WCST) and the Tower of London (ToL) task. The WCST requires participants to sort cards according to a certain response rule (e.g. match on color), and participants need to flexibly use feedback switch between sorting rules (Milner, 1963). The ToL task requires response planning by reordering visuospatial stimuli (Asato, Sweeney, & Luna, 2006). Prior studies reported that working memory is a significant predictor of WCST performance (Huizinga et al., 2006), and that flanker inhibition is a predictor for performance on the ToL, showing that this basic executive function has explanatory power for complex executive function tasks (see also (Asato et al., 2006)).

Taken together, working memory shows a protracted development, which occurs over the whole period of adolescence, whereas inhibition and shifting show most pronounced improvement in early adolescence after which it stabilizes (Huizinga et al., 2006; Luna et al., 2004). These functions in turn predict performance on more complex flexibility and planning tasks.

Four recent studies tested how executive functions develop from early to late adolescence and seem to point towards optimal performance and more flexibility in adolescence relative to other ages (see Figure 1). One study examined cognitive learning based on performance feedback and working memory development in 208 participants between ages 8-27 years who were tested longitudinally across two measurements that were separated by 2 years. The researchers found that both cognitive learning and working memory peaked around 17 years of age, after which there was stable performance for some individuals and declines for other individuals (Peters, Van Duijvenvoorde, Koolschijn, & Crone, 2016). A second study examined divergent thinking and creative insight in children, adolescents and adults using a battery of verbal and spatial tasks. Whereas creative insight increased during early adolescence and stabilized in mid-adolescence, spatial divergent thinking was best in 15-16-year-old adolescents, after which it decreased in young adults (Kleibeuker, De Dreu, & Crone, 2013). Comparable findings were obtained for another spatial divergent task where 16-17-year-olds slightly outperformed 25-30-year-old participants (Kleibeuker, Koolschijn, et al., 2013). A fourth study examined age differences in a range of cognitive functions, including executive functions, across the whole age range of adolescence (ages 8-21-years, n=9,138). This study had a slightly different focus by testing age differences in within-subject variability in performance. They found that within-subject variability decreased between ages 8-13-years, after which it gradually increased again from age 17 to 21 years. Possibly, this suggests increased flexibility in whether or not executive functions are recruited for specific tasks. In other words, increased instability of cognitive functioning may indicate heightened amenability to environmental influences, because behavior is less stable. Interestingly, after age 13-years gender differences emerged, with larger variability in males than in females (Roalf et al., 2014).

The findings indicative of optimal performance and increased variability during late adolescence suggest that this developmental stage may be an optimal period for the development of executive functions, marking this time as particularly receptive for input. As such it may be a tipping point for positive vs. negative developmental trajectories (Crone & Dahl, 2012). This leads to the question whether adolescence is also a sensitive period in which executive functions can be enhanced.

Can executive functions be trained in adolescence?

Whether, and the extent to which executive functions can be trained has been the subject of intense empirical research. The key question in these studies is not only whether cognitive skills can be trained, but also whether such training improves not only the trained task (near transfer), but also to cognitive functioning in daily life (e.g., in school; far transfer). Initially, researchers presumed that transfer effects were limited. These effects were based, for example, on a large study including 11,430 healthy adult participants examined the effects of a 6 week-cognitive training in reasoning, memory, planning, visuospatial skills and attention. Whereas participants improved considerably on the trained task, the evidence for transfer to other domains (such as domains important for school performance) was limited (Owen et al., 2010). Furthermore, a developmental study that used a working memory practice task with varying difficulty levels also found significant practice benefits in the trained domain in 13-year-old adolescents, but no transfer effects to other domains (Jolles, van Buchem, Rombouts, & Crone, 2012). Similar effects were obtained for practice tasks in 7-9-year old children (Dunning, Holmes, & Gathercole, 2013).

However, recent insights show that whether far-transfer effects can be observed after cognitive training depends on what is actually being trained. Improved performance during training can be attributed to improvements in an underlying cognitive skills or merely reflect the use of an effective strategy for the specific task being trained (Diamond & Ling, 2016). Seeing that strategies are developed in response to meet specific demands of a certain task, the likelihood of a far-transfer effect is much smaller than in the case of training an underlying cognitive skill (see also Figure 3). It has recently been argued that training needs to be continually novel, complex and diverse and be motivating to maximize transfer to other domains (Moreau & Conway, 2014). Indeed, several studies found support for transfer effects of training in adults as long as the training was adaptive to the performance level of the participants (i.e., the task becomes more difficult when performance is improving) (Constantinidis & Klingberg, 2016; Corbett et al., 2015).

Given that executive functions are still improving considerably and reaching stability across adolescence, this may be a period where adaptive training has most benefits. In terms of studies on adolescence, studies have mostly focused on the domain of working memory, and observed that adaptive training of working memory was associated with performance improvements on both the trained task and showed transfer to reasoning skills in participants ages 7-15-years with Attention Deficit Hyperactivity Disorder (ADHD) (Klingberg, Forssberg, & Westerberg, 2002), and in participants aged 7-12-years with ADHD (Klingberg et al., 2005). Training effects were also found for adaptive training programs in 7-9-year-old children with poor working memory with transfer to other working memory tasks (Dunning et al., 2013; Holmes, Gathercole, & Dunning, 2009).

It has recently been suggested that training and transfer effects might be enhanced during specific developmental periods. A recent meta-analysis on working-memory training indeed showed that age was a significant moderator variable of the extent of training benefits, with larger effects observed at younger compared to older ages (Melby-Lervag & Hulme, 2013). Another meta-analysis of studies into training executive functions and their transfer effects also looked at far-transfer effects with age in an age range from 1 to 90 years (Wass, Scerig, & Johnson, 2012). The authors showed that transfer effects decline with age and are largest during childhood and early adolescence. None of these studies however, included mid to late adolescents, so it remains to be determined how training is beneficial in this specific age range.

What are the implications of executive function training for scholarly tasks?

Probably one of the most important forms of transfer for children and adolescents is transfer to school performance. It may be beneficial to train executive functions to improve general abilities such as reading and mathematics. Several studies have examined the relation between executive functions and scholastic performance measures such as reading and mathematics as outcomes measures (Alloway & Alloway, 2010; Blair & Razza, 2007). One of the executive functions that plays arguably the most vital role in academic learning is working memory. Children and adolescents who have poor working memory are at risk for poor school performance, as these children often also perform poorly on reading and mathematics (Blair & Razza, 2007; Gathercole, Pickering, Knight, & Stegmann, 2004; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Raghubar, Barnes, & Heckt, 2010; Swanson & Jerman, 2006).

In recent years the question has been addressed if adaptive training of executive functions also has benefits for academic performance. One study showed that 9-10-year-old children who participated in a working memory training study showed benefits in the trained domain, and additionally showed better mathematics performance than the control group 6 months later (Holmes et al., 2009). It should be noted that the control group was not included in the 6 months follow up, so it is possible that some of the effects can be related to test-retest effects. Another recent study examined if these training effects were also observed in more ecologically valid settings. In this study, 9-11-year-old children followed teacher-administered working memory training. Improvements were observed in both working memory performance, as well as academic performance including mathematics (Holmes & Gathercole, 2014). A study that included children aged 8-11-years observed that working memory training was associated with improvement in reading (Loosli, Buschkuehl, Perrig, & Jaeggi, 2012). Similar effects were found for younger children of 7-9 years of age following 14 sessions of adaptive working memory training (Karback, Strobach & Schubert, 2015). A training study with children with special educational needs and attention problem aged 9-12 years also showed benefits of reading comprehension that persisted until at least 6 months after the training had ended (Dahlin, 2011). The same author found improved performance in mathematics following a 5-week working memory training in boys with attentional problems aged 9-12 years (Dahlin, 2013).

These findings suggest that working memory training can be beneficial in a school context. It is yet to be determined if the same training benefits are also observed when working memory is trained in adolescents rather than children, and there is still debate about effects sizes of training outcomes (Gathercole, Dunning, & Holmes, 2012; Hulme & Melby-Lervag, 2012; Roberts et al., 2016), but this research provides promising starting points.

The neural correlates of executive functions

One way to better understand which mechanisms develop in which order and how they contribute to real-life cognitive functioning is by studying neural development. The brain matures considerably during child and adolescent development, in terms of its structure, connections and functions (Mills & Tamnes, 2014). When it is shown that training enhances cognitive functioning, neuroimaging may help to determine exactly which process is being improved by the training, such as through increasing working memory capacity, switching to a better strategy, or becoming better at suppressing interfering stimuli. This might also help in determining which types of training will result in far transfer effects. Brain imaging and patient studies have consistently observed that executive functions put demands on the frontal and parietal cortices (Miller & Cohen, 2001) (see Figure 2).

Executive functions such as working memory, inhibition and switching put demands on overlapping regions within the frontal cortex (specifically dorsolateral and ventrolateral prefrontal cortex), suggesting that despite the differences between these processes, they also rely on overlapping neural areas (Kim, Cilles, Johnson, & Gold, 2012; Niendam et al., 2012).

Developmental comparison studies have provided consistent evidence for protracted development of brain activity across adolescent in the frontal-parietal network for several executive functions including working memory (Satterthwaite et al., 2013) and inhibition (Rubia et al., 2013; Vink et al., 2014). This pattern was also observed for higher-order cognitive learning tasks that placed demands on several executive functions (Peters et al., 2016). Neural responses in the prefrontal and parietal cortex during executive functioning tasks were found to be predictive for academic tasks such as mathematics in participants aged 6-16-years. Notably, neural activity predicted future mathematical performance even better than behavioral testing alone (Dumontheil & Klingberg, 2012). Similar results were previously found in a study showing that structural and functional brain imaging measures were additional predictors of children’s gains in reading decoding ability over the school year beyond behavioral measures alone (Hoeft et al., 2007). Together, these studies suggest that the core network in the brain that is important for executive functions in adulthood is developing until late adolescence and seems relevant for predicting school performance.

The theory of interactive specialization describes the way in which these neurodevelopmental changes may take place (Johnson, 2011). According to this theory, at a young age children use cortical regions for a variety of cognitive functions. Over the course of child and adolescent development, brain regions become more specialized to perform a specific cognitive function. This specialization occurs by a process of activity-dependent interaction and competition between regions. This theory makes important predictions for developmental changes in the influence of training on neural functions and resulting transfer effects. Thus, the wider the set of cognitive functions associated with a brain region (as is the case in younger children and adolescents), the more extensive the transfer should be following training.

Brain plasticity and training executive functions

Insight into the mechanisms of training executive functions has been obtained by examining changes in brain responses before and after training. It is thought that in adults training of working memory increases connections between these brain regions which results in more efficient processing (Constantinidis & Klingberg, 2016).

Very few studies have examined neural responses before and after training in children and adolescents. One prior study used a working memory practice paradigm (non-adaptive) with several hours of training during 6 weeks, which was administered in 12-13-year-old adolescents (Jolles, Grol, Van Buchem, Rombouts, & Crone, 2010). Before training, participants showed less activity in dorsolateral prefrontal cortex than adults. After 6 weeks of training, activity in dorsolateral prefrontal cortex was enhanced in adolescents and they no longer differed in activity patterns and behavioral performance from adults. It should be noted that there was no evidence for transfer to other domains, so possibly this study was more successful in training a strategy suitable to the specific trained task, rather than a broader underlying skill.

A recent study examined effects of working memory training on brain connectivity in children aged 8-11-years by studying resting state magnetroencephalography (MEG) changes, a direct measure of neural activity. In this study, 13 children received 20-25 sessions of adaptive working memory training over a period of 4-5 weeks, and 14 children received placebo (non-adaptive) training. The adaptive training group increased more in performance compared to the placebo group on the trained task, and moreover showed transfer to a non-trained working memory task. The trained group also showed increases in connectivity patterns between right lateral prefrontal cortex and left occipital cortex. The extent of connectivity changes was predictive of training outcomes (Astle, Barnes, Baker, Colclough, & Woolrich, 2015). This study provides the first direct measure of training effects on the neural level in children and early adolescents.

Longitudinal studies can also provide important insight into mechanisms that predict change over time. A longitudinal imaging study examined how neural activity during a working memory task was related to changes in working memory capacity 2 years later. This study found that activity in and white-matter connectivity with the striatum was predictive of future working memory capacity (Darki & Klingberg, 2015). Interestingly, a study in adults also found that training was associated with increases in striatum activity (Jolles et al., 2010). An important neurotransmitter that is often associated with working memory training, dopamine, has its main receptors in the striatum (Darki & Klingberg, 2015; Ullman, Almeida, & Klingberg, 2014), so possibly this implies that the striatum is an important region in the development and plasticity of working memory development.

One possible explanation for these developmental shifts in brain activity patterns is that in the developing brain, children rely on a wider network of brain regions to improve in certain cognitive functions. Mere practice may result in more activity in regions such as dorsolateral prefrontal cortex (Jolles et al., 2012). Larger executive control improvements over time may be associated with reliance on compensatory brain regions such as the striatum (Backman et al., 2011; Darki & Klingberg, 2015) and connections with regions outside prefrontal cortex (Astle et al., 2015). Following predictions from the interactive specialization theory, adaptive training in the developing brain may result in activity changes in a wider network than in adults, or alternatively, in more specialized activity (reflecting more adult-like activity) in a localized network of brain regions (Johnson, 2011). These are all questions that should be addressed in future studies.

Future directions

Several compelling questions arise from these studies that should be addressed in future research. First, even though many behavioral studies have focused on the development and plasticity in children, early adolescents, and adults, there are few studies that examined training effects in mid to late adolescence. Yet, developmental studies suggest that this may be an optimal window for working memory training, given possible enhanced cognitive performance (Peters et al., 2016), variability (Roalf et al., 2014) and flexibility (Crone & Dahl, 2012). Future studies are needed to examine training effects in this important transition period in life.

Second, little is yet understood about the commonalities between different executive functions and whether there are benefits to training them in concert rather than separately (Ang & Lee, 2010), even though neuroscience studies have shown that many of these functions put demands on the same neural regions (Niendam et al., 2012). To date, most studies have focused on working memory training, but possibly far-transfer effects to e.g. school performance will only be found using more complex executive functioning training. Previous work suggests that complexity is an integral part of the success of cognitive trainings (Diamond & Ling, 2016). While researchers tend to isolate specific components of executive functions, future studies ought to assess the interactive and super-additive components of combining trainings across executive function domains. These questions can be addressed by examining training effects of single domain and multiple domain programs and their effects on behavior and brain activity.

Conclusions

In the past decades the development of executive functions has been extensively studied, especially in young children and early adolescence, and to a lesser extent in mid- to late adolescence. These studies were consistent in showing that working memory improves over the teenage years, whereas inhibition and shifting develop before mid adolescence (Huizinga et al., 2006; Luna et al., 2004; Roalf et al., 2014). Neuroscience studies have elaborated on the neural mechanisms underlying these developmental improvements. These studies found that the prefrontal and parietal cortices, which are important for executive functions in adults, show a protracted development during adolescence (Luna, Padmanabhan, & O'Hearn, 2010), which are correlated with performance changes (Peters et al., 2016; Satterthwaite et al., 2013). However, activities in other regions of the brain, such as the striatum, are important for performance improvements as well (Darki & Klingberg, 2015). Possibly, these changes can be understood in terms of the interactive specialization theory

(Johnson, 2011). That is to say, children and adolescents may rely on a wider network of brain regions than adults during cognitive processes.

Important starting points have been made for understanding executive function development in terms of increased potential for flexibility and plasticity in adolescence. Using training paradigms, it was found that extensive and adaptive training enhances executive functions. The training is considered successful in case executive functions are trained as a skill, such that training transfers to other domains that make use of the same resources (Klingberg, 2010, 2014; Moreau & Conway, 2014).

Many of the studies to date focused on children and adolescents who have poor working memory, such as children with learning disabilities or children with ADHD, and these groups show pronounced benefits of training (Spencer-Smith & Klingberg, 2015). An important question concerns whether training only leads to enhancements in children who are behind in development, or if executive functions can be trained in everybody. Also known as compensation versus magnification accounts of the effects of training (Titz & Karbach, 2014), this calls for addressing questions of who benefits most from cognitive trainings and why. Unraveling these individual sensitivities will most likely be crucial to understand why there is variability in training outcomes and which type of training works for whom.

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Figure Captions

Figure 1: a) Predicted patterns (solid lines, and 95% confidence intervals in dashed lines) of cognitive learning and working memory based on 2-year longitudinal data from 208 participants between ages 8-27 years (Reprinted with permission from Peters et al., 2016), b) 4 age groups compared cross-sectionally on visual-spatial fluency showing best performance at age 15-16-years (Reprinted with permission from Kleibeuker et al., 2013), and c) within individual variability in accuracy (left) and speed (right) decreases and increases between ages 8 and 21 years (Reprinted with permission from Roalf et al., 2014).

2: Brain regions implicated in executive functions. aPFC= anterior prefrontal cortex, slPFC = superior lateral prefrontal cortex, dlPFC= dorsolateral prefrontal cortex, vlPFC= ventrolateral prefrontal cortex, frontal MC= frontal middle cortex.

Figure 3: Schematic overview of outcome, transfer type and neural mechanisms of training properties. Whereas repetitive training schedules will likely only train task-related strategies, this can lead to near transfer effects as long as other tasks require similar strategies. Such training effects will likely result in the recruitment of additional strategy specific brain regions. When training schedules are adaptive, novel, complex and diverse there is a greater likelihood of an underlying skill being trained, with more extensive effects for far transfer. Such training effects will likely result in strengthening of functional networks required for training.