

Karbach, Julia * a, b

Review Article

Abstract

Executive functions include a set of higher-level cognitive control abilities, such as cognitive flexibility, inhibition, and working memory. They support action control and the flexible adaptation to changing environments. Given that these control functions rely on the prefrontal cortex, they develop rapidly across childhood and adolescence. Importantly, executive control is a strong predictor for various life outcomes, such as academic achievement, socioeconomic status, and physical health. Therefore, numerous training interventions have been designed to improve executive functioning in children and adolescents, both in normally developing individuals and children suffering from neurocognitive and developmental disorders. Despite some encouraging findings revealing that executive control training benefitted untrained task and abilities, such as fluid intelligence and academic performance, recent findings regarding the transferability of training-induced performance improvements to untrained tasks are heterogeneous. This short review aims at providing a selective overview of developmental findings and discussing the effects of different types of executive control training in children and adolescents as well as the potential of cognitive training interventions for the application in clinical and educational contexts.

Key Words:

Executive functions; cognitive training; childhood; adolescence; cognitive plasticity.

Resumen

Plasticidad de las funciones ejecutivas en la infancia y la adolescencia: Efectos de intervenciones de entrenamiento cognitivo. Las funciones ejecutivas incluyen a un conjunto de capacidades de control cognitivo de alto nivel, tales como la flexibilidad cognitiva, la inhibición y la memoria de trabajo, que permiten el control de las acciones y la adaptación flexible a entornos cambiantes. Teniendo en cuenta que estos procesamiento se asocian al funcionamiento de la corteza prefrontal, su desarrollo también se da de manera rápida a lo largo de la infancia y la adolescencia. Es importante destacar que el control ejecutivo es un predictor significativo de diversos aspectos de la vida cotidiana tales como el rendimiento académico, el estatus socioeconómico y la salud física. En tal sentido, se han diseñado numerosas intervenciones para mejorar el funcionamiento ejecutivo en niños y adolescentes, tanto en condiciones de desarrollo normal como en las de trastornos del desarrollo y neurocognitivos. Algunos hallazgos recientes alentadores revelan que el entrenamiento de las capacidades de control ejecutivo produce un beneficio en el desempeño en tareas y habilidades no entrenadas, como en el caso de la inteligencia fluida y el rendimiento académico. No obstante, los resultados recientes en relación con la transferencia de las mejoras del desempeño entrenado a las tareas sin entrenamiento, son heterogéneos. Esta breve revisión tiene como objetivo principal proporcionar un resumen de los principales resultados de estudios del desarrollo del control cognitivo, y discutir los efectos de diferentes tipos de entrenamiento de tales capacidades en niños y adolescentes, así como el potencial de las intervenciones de entrenamiento cognitivo para su aplicación en contextos clínicos y educativos

Palabras claves:

Funciones ejecutivas; entrenamiento cognitivo; infancia, adolescencia; plasticidad cognitiva

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1. Executive functions

Executive function (EF) refers to a number of higher-order cognitive functions allowing individuals to flexibly regulate their thoughts and actions in the service of adaptive, goal-directed behavior. It includes three separable main domains that are moderately

correlated: Working memory (WM), inhibition, and cognitive flexibility (Miyake et al., 2000).

Infant research has shown that elementary forms of EF emerge within the first year of life (Diamond, 2006; Carpenter, Nagell, Tomasello, Butterworth, &

^a Department of Psychology, Goethe-University Frankfurt, Germany

^b Center for Research on Individual Development and Adaptive Education of Children at Risk (IDeA), Frankfurt am Main, Germany

*Send correspondence to: Karbach, J. E-mail: karbach@psych.uni-frankfurt.de

Moore, 1998), but the dimensional factor structure of EF changes qualitatively across development from a unitary structure (i.e., a single-factor structure) in preschoolers to multiple subcomponents in school-age children and adolescents (Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Wiebe, Espy, & Charak, 2008).

Developmental trajectories of EF are linked to maturational changes of prefrontal brain regions, parietal regions and basal ganglia (Bunge & Wright, 2007; Casey, Tottenham, Liston, & Durston, 2005; Luna, Padmanabhan, & O’Hearn, 2010). Behavioral improvements in EF are associated with synaptic pruning and increased myelination as well as experience-dependent synaptic strengthening (Bjorklund, 2005; Dawson & Guare, 2010; Sowell, Thompson, Tessner, & Toga, 2001). Moreover, age-related differences in structural maturation within the prefrontal cortex (Gogtay et al., 2004) are paralleled by changes in functional maturation and may therefore account for distinct developmental trajectories among EF (Bunge & Zelazo, 2006).

For instance, basic updating processes can be observed in 9 to 12 month-old infants, but the ability to manipulate items in *WM* develops later and over a longer time range (Diamond, 2013). WM performance at more complex tasks has been shown to improve linearly from pre-school age to adolescence (Gathercole, Pickering, Ambridge, & Wearing, 2004), with age differences varying as a function of complexity (Luciana, Conklin, Hooper, & Yarger, 2005). *Cognitive flexibility* shows the most protracted development and continues to improve into adolescence (Chevalier & Blaye, 2009; Diamond, 2013; Moriguchi & Hiraki, 2011; Zelazo, 2004). Evidence from task-switching studies showed that two components of flexibility - the ability to switch from one rule to another rule (i.e., switching *per se*) and the ability to maintain and select two (or more) rules – follow different developmental time courses (Crone, Bunge, van der Molen, & Ridderinkhof, 2006; Crone, Ridderinkhof, Worm, Somsen, & van der Molen, 2004; Huizinga & van der Molen, 2007; Karch & Kray, 2007; Kray, Eber, & Karch, 2008; Kray, Karch, & Blaye, 2012). For instance, Huizinga & van der Molen (2007) **reported that children’s set switching abilities reached adult levels by the age of 11, whereas set maintenance continued to improve by the age of 15.** *Inhibitory control* develops rapidly during the

preschool years and typically continues to improve into middle childhood (Best & Miller, 2010; Kray et al., 2012; Kray, Kipp, & Karch, 2009). However, some studies using computerized tasks reported continued improvement until adolescence or even young adulthood (Huizinga et al., 2006). Together these findings demonstrate that EF develops multidimensionally and multidirectionally, with different developmental trajectories for the distinct dimensions of EF (Karch & Unger, 2014).

Importantly, emerging EF is associated with many relevant life-outcomes: It is an excellent predictor for academic achievement in children (over and above IQ), socioeconomic status, as well as physical and mental health in later life (for a review, see Titz & Karch, 2014). In preschoolers, for instance, low EF is associated with poorer mathematical and literacy performance (Blair & Razza, 2007; Bull, Espy, Wiebe, Sheffield, & Nelson, 2008) as well as with difficulties regarding reading comprehension and mathematical skills in elementary school children (Borella, Carretti, & Pelegrin, 2010; van der Sluis, de Jong, & van der Leij, 2004). Therefore, many recent intervention studies have examined the effectiveness of cognitive training regimes designed to improve EF in childhood and adolescence (Jolles & Crone, 2012; Karch & Unger, 2014; Kray & Ferdinand, 2013; Titz & Karch, 2014). Moreover, behavioral and neural plasticity is particularly high in childhood and the brain areas serving EF (i.e., the prefrontal lobes) are especially sensitive to environmental influences in children (Bull et al., 2011). It is therefore not surprising that numerous training interventions targeted children and adolescents, both normally developing individuals and patients suffering from neurodevelopmental or psychiatric disorders that are characterized by significant cognitive deficits (e.g., ADHD or autism).

2. Training-induced plasticity of executive functions

Research investigating the benefits of cognitive training interventions showed that cognitive plasticity (i.e., training-induced changes in brain function and behavior) is considerable across the lifespan (Buitenweg, Murre, & Ridderinkhof, 2012; Diamond, 2012; Karch & Schubert, 2013; Strobach, Salminen, Karch, & Schubert, 2014; Karch & Verhaeghen, 2014). Numerous studies showed significant performance improvements on the trained tasks, and

oftentimes also revealed near transfer to tasks that were not explicitly trained but measured the same construct as the training task, and sometimes even far transfer to tasks measuring a different construct (Au et al., 2014; Karbach & Verhaeghen, 2014; Melby-Lervag & Hulme, 2013).

Despite these encouraging findings, the literature shows that transfer effects were not consistent across studies and these heterogeneous findings have inspired intense debates regarding the transferability of training-induced performance gains (Redick et al., 2013; Shipstead, Redick, & Engle, 2012). However, a closer look at the findings suggests that this seemingly inconsistent pattern of results reflects large differences regarding the type and intensity of the training regimes, the samples studied and the methodologies adopted across studies. Regarding the type of training, many researchers agreed to differentiate between at least three major approaches: *Strategy-based* training, referring to the training of task-specific techniques, such as memory training with mnemonic techniques. This type of training often resulted in large and long-lasting improvements on the training task, but only limited transfer (Rebok, Carlson, & Langbaum, 2007; Verhaeghen, Marcoen, & Goossens, 1992). *Multi-domain training* interventions engage multiple cognitive processes (e.g., game-based training), yielding broad but often small transfer effects (Basak, Boot, Voss, & Kramer, 2008; Karbach, 2014). Moreover, their complex nature makes it hard to determine which specific features of the training regime induced transfer. Finally, *process-based* training protocols are not task-specific since they target more general processing capacities supporting multiple cognitive operations, such as speed of processing or EF. Some process-based interventions, especially from the domain of EF, have resulted in very promising widespread transfer across the lifespan (Hertzog, Kramer, Wilson, & Lindenberger, 2008; Karbach & Schubert, 2013; Karbach & Unger, 2014; Kray & Ferdinand, 2013; Titz & Karbach, 2014), suggesting that process-based training might be more effective to support transfer than strategy-based interventions.

Considering these differences and the limited comparability of previous results, it is surprising that some existing meta-analyses have averaged over studies including different types of training as well as both healthy and cognitively impaired samples

(Hindin & Zelinski, 2012; Karr, Areshenkoff, Rast, & Garcia-Barrera, 2014; Melby-Lervag & Hulme, 2013). It is therefore not unexpected that the results only provided limited evidence for transfer of cognitive training. In contrast, recent meta-analytic findings that focused on more homogeneous sets of studies (such as comparable types of training and training samples) have yielded more encouraging findings: Particularly process-based trainings from the domain of WM and other dimensions of EF induced sizeable near and far transfer to untrained tasks and abilities in younger and older adults (Au et al., 2014; Karbach & Verhaeghen, 2014). However, meta-analytic evidence regarding the effectiveness of cognitive training in childhood and adolescence is still missing. Nevertheless, recent training studies focusing on children have investigated transfer of training from applied perspectives that are particularly important for educational and clinical purposes, because they investigated whether cognitive training benefits academic abilities and whether it effectively compensates cognitive impairments in children suffering from attention-deficit/hyperactivity disorder (ADHD).

3. EF training in clinical and educational settings

The cognitive and neural plasticity uncovered in the field of cognitive training research certainly has important implications for applied settings, such as clinical or educational programs. Even though the number of well-controlled training studies is still limited, findings from basic research may be very informative for the design of applied training programs. Many studies have investigated children suffering from ADHD, a disorder that typically includes the three behavioral core symptoms inattention, impulsivity and hyperactivity (Barkley, 1997). In addition, children with ADHD usually show cognitive impairments in terms of WM, inhibitory control, and attention that affect academic development, vocational success, and social interactions (Shah, Buschkuhl, Jaeggi, & Jonides, 2012). Therefore, many cognitive training studies have aimed at compensating cognitive and behavioral symptoms and supporting the social and scholastic development of children with ADHD.

For instance, one recent study showed that task-switching training supported inhibition and WM in 7-12 year-old boys with ADHD (Kray, Karbach, Haenig, & Freitag, 2012). A number of other studies have

applied the Cogmed training battery that has been designed to improve WM and EF (www.cogmed.com; see also Klingberg et al., 2005). Twenty-five sessions of training resulted in performance benefits on untrained WM tasks as well as measures of inhibition and fluid intelligence and even a reduction of parent-rated symptoms of inattention and hyperactivity/impulsivity (Klingberg et al., 2005; Beck, Hanson, Puffenberger, Benninger, & Benninger, 2010). However, it should also be noted that recent reviews and meta-analyses suggest that the effects of WM training in children with ADHD may not be that far reaching (Chacko et al., 2013; Rapport, Orban, Kofler, & Friedman, 2013). Thus, studies providing a more fine-grained analysis of the mechanisms underlying transfer of cognitive training and individual differences therein is clearly needed in order to determine which type of training may be most beneficial for children suffering from ADHD. The existing results nonetheless show considerable cognitive and neural plasticity in this group, indicating that the individual benefits of well-tailored cognitive interventions may be considerable.

Research on academic achievement has repeatedly confirmed EF, and particularly WM, as important prerequisites for academic achievement and performance in the classroom. In fact, EF have been shown to explain at least as much variance in academic achievement as intelligence (Titz & Karbach, 2014), which is usually considered the most powerful predictor of academic success. Considering the important role of EF for academic development, one may assume that even small increases in EF **functioning might improve children's academic performance.**

Still, recent studies indicated that 25 sessions of Cogmed WM training yielded no benefits in terms of reading or mathematical reasoning abilities in children with low WM ability (8-11 years of age; Dunning, Holmes, & Gathercole, 2013; Holmes, Gathercole, & Dunning, 2009). In contrast, a recent study from the same group showed that teacher-administered Cogmed training improved performance on standardized tests for English and math in 6th grade (Holmes & Gathercole, 2013), indicating that training-induced gains transferred to ecologically valid measures of academic achievement in low-achieving students. These findings are consistent with results indicating that students with

special educational needs and attention problems (9-12 years) benefitted from Cogmed training in terms of reading comprehension and basic number skills (Dahlin, 2011, 2013). However, 32 sessions of training on an interactive WM training game called Jungle Memory yielded no transfer to tasks assessing arithmetic and spelling in children with learning difficulties (mean age = 10.10 years) (Alloway, Bibile, & Lau, 2013).

Two recent studies in normally developing children have applied tasks from the Braintwister WM training battery (Buschkuhl, Jaeggi, Kobel, & Perrig, 2008). After 10-14 sessions of training, both studies consistently showed improvements on standardized tests of reading in students between 7 and 11 years of age (Karbach, Strobach, & Schubert, 2014; Loosli, Buschkuhl, Perrig, & Jaeggi, 2012).

In sum, recent findings indicated that cognitive training might indeed compensate EF deficits in children with ADHD and support academic performance. Yet, it is obvious that these effects are not consistent across studies and it is unclear to what extent they may be modulated by age-related differences in social and emotional processes or by motivational components (cf. Doerrenbaecher, Mueller, Troeger, & Kray, 2014). The existing findings are nevertheless encouraging because they demonstrate the potential of cognitive training for improving daily life performance outside of the lab.

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