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Hot and cool executive functions in children and adolescent with further exploration in ADHD context

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Abstract

The aim of this paper is to offer a broad review on current evidence about executive functions (EFs) with further context of ADHD in children. EFs are high-order neurocognitive processes required for effective, goal directed, and productive action. We review the most influential models of EFs and focus on the Hot and Cool distinction. The goal is to introduce in detail both the Cool and Hot subtypes with emphasis on Hot domain components that have been long time neglected. The review will shed light on the trajectories of typical EFs development of children from infants to adolescents, as well as indicate possible problematic stages and impairments of EFs during development. Special attention has been paid to ADHD diagnosis considering that ADHD affects both Hot and Cool subtypes because of its profile of EFs deficits and the fact that ADHD is a frequent neuropsychological complication in children seriously affecting their quality of life. Research indicates that EF skills can be cultivated through structured training and they are a promising target for therapeutic and preventive intervention. The deep understanding of functioning, interaction, localization, testing and development of Hot and Cool EFs are a promising fundament for further research. It could reveal new contexts helping to create effective interventions to improve the quality of life of people affected by neurodevelopmental diseases in childhood and adolesce.

Abbreviations:
Executive functions (EFs),
Working memory (WM),
Theory of Mind (ToM).

Introduction

EFs are a set of top-down neurocognitive mental processes individuals rely on to manage one's self and one's resources to achieve a goal, including the abilities to control attention, behaviors, thoughts, and/or emotions to attain a desired outcome (Lee *et al.* 2022; Nobre Paiva *et al.* 2023). They enable a person in independent, purposive, self-directed, self-serving and productive behavior (Lezak *et al.* 2012). EFs include abilities of goal formation and planning, carrying out the goal-directed plan, and through this finally perform an effective action (Jurado & Rosselli 2007). They specifically refer to higher-order cognitive functions required for goal-directed behavior (Goldstein *et al.* 2014) and provide control and coordination to lower-order cognitive brain functions (Stuss & Levine 2002). In comparison to cognitive functions that usually involve specific functions or functional areas, EFs tend to show up globally, affecting all aspects of behavior in the meaning „how" behavior is expressed (Lezak *et al.* 2012).

EFs are active when it is not enough to function automatically, but it is necessary to make an effort and concentrate (Diamond 2013). EFs encompass the cognitive processes that support complex, goal-directed behavior, particularly in situations or tasks that are novel, complex, or less structured, and require conscious effort and adaptive reactions (Fernández García *et al.* 2021; Procházka *et al.* 2021; Wilson *et al.* 2018; Zelazo *et al.* 2003). In this kind of more complex tasks, higher levels of activation of some parts of the EFs (e. g. planning) are required. According to the situation EFs vary in the level of engagement and in forms of expression (Stuss & Knight 2013).

Fs enable to focus attention, to resist distractors and tempting stimuli, to mentally process thoughts, to coordinate and regulate various psychological manifestations, to analyze relevant information, to generate meaningful alternatives, to reflect on the consequences of actions, to respond appropriately to new and unexpected challenges, to create and modify reactions based on feedback from the external environment (Diamond 2013). EFs are crucial for flexible and effective reasoning, problem-solving and social behavior, as well as self-organization abilities (Best & Miller 2010).

There are different levels or complexities of EFs. EFs can be divided into ***core executive functions*** (core EFs) (called simple skills or direct sub-components of EFs (Jones *et al.* 2016)) and ***higher-order executive functions*** (higher-order EFs) (complex skills). In this concept, core EFs are those we mentioned above, i. e. response inhibition, updating/working memory (WM), and shifting/flexibility. Higher-order EFs develop from core EFs and can be seen as an integration of core EFs. Higher-order EFs include planning (Clark *et al.* 2010), attention (Pronk *et al.* 2011), error monitoring (Diamond 2013; Jones *et al.* 2016). Some authors also added other complex processes such as mental organizing, initiation, persistence, self-regulation and self-monitoring (Gioia *et al.* 2003; S. Goldstein & Naglier 2014; Jones *et al.* 2016), problem solving, logical reasoning (deduction and induction), abstract reasoning, or creative thinking, as well as anticipation, self-awareness (Diamond 2013; Poon 2018). Nevertheless, there is no unambiguous incorporation of the functions. Other authors (Mäntylä *et al.* 2010) link shifting as a higher-order EFs, requiring updating and inhibition in order to switch mental sets.

EFs can be seen as a multifaceted mental concept containing different components which are interconnected (Barkley 2001). Since EFs are a sum of skills to control in order to achieve a goal, they are influenced by many mental contents (knowledge, beliefs, norms, values, preferences) which a child acquires in the process of development (Doebel 2020).

In general, EFs are associated with school readiness (McClelland *et al.* 2007; Montroy *et al.* 2019), academic performance, social competence, self-regulation, emotional regulation, but also with children's health and well-being (Ramos *et al.* 2023; Wilson *et al.* 2021). Ethical behavior and the concept of morality also represents an executive function (Ardila & Surloff 2006; Kochanska *et al.* 2000).

Impairment in EFs, even partially, may manifest in the incapability of satisfactory self-care, of maintaining normal social relationships, or of performing meaningful activity/work independently (Lezak *et al.* 2012). Poor EFs can be seen in the inability to respond appropriately to everyday challenges (Perner & Lang 1999). They can manifest specifically in examples of problem behaviors, problems with inhibition or conceptual transitions (Lezak *et al.* 2012), physical and relational aggression (McQuade *et al.* 2013; Poland *et al.* 2016). Many of these deficits are usually present in children with neurodevelopmental disorders.

Theoretical models of EFs

Over time, several models have emerged with their own concepts of EFs and possible subcomponents (Table 1.). Within the continuum of models, some theories view EFs as a single-factor construct (Duncan *et al.* 1997) while other multidimensional theories consider EFs to be composed of some number of independent elements (Stuss & Alexander 2000). Models referring to independent components do not understand EFs as components of higher cognitive functions, but as completely separate/independent functions that function alongside cognitive and affective processes and in joint interaction contribute to and shape human behavior (Lezak *et al.* 2012).

The situation in infants and children is very similar, some authors present EFs as a unified structure (Munakata 2004; Posner & Rothbart 2007; Wiebe *et al.* 2011; Zelazo & Müller 2002), while other researchers argue that EFs form a structure of dissociated components (Diamond 2013). Others postulated that there might be an integrated view where EFs would have a unitary structure with partially dissociable components (Huizinga *et al.* 2006; Miyake *et al.* 2000). There are currently two respected models related to EFs. The first divides EFs into inhibitory control, cognitive flexibility, and working memory (Diamond 2013) and second actual and influential model incorporates 3 key components of EFs, namely inhibition, shifting and updating when using confirmatory factor analyses (Miyake *et al.* 2000).

From the perspective of examining EFs in children and adolescents, it is meaningful to divide EFs according to their connection to emotions into Hot and Cool EFs (Semenov & Zelazo 2018; Zelazo & Carlson 2012).

Hot and Cool executive functions

Hot and Cool EFs differ in extent of involvement of emotions. The division is also supported in children by factor analysis (Montroy *et al.* 2019). Cool EFs represent a Cool, cognitive "know" system and Hot EFs represent a Hot, emotional "go" system (Metcalfe & Mischel 1999). The Cool system is motionally neutral, flexible, but slow, coherent, and integrated, episodic, and strategic. It is the location of self-regulation and

Tab. 1. Components, dimensions and concepts of executive functions. According to (Baggetta & Alexander 2016; Jurado & Rosselli 2007; Stelzer *et al.* 2014)

Model/Author	Components/Dimensions of EF
Baddeley & Hitch (1974)	Central executive controls subprocesses such as phonological loop, visuospatial sketchpad and episodic buffer (Baddeley 2000).
Luria (1976)	Anticipation, planning, management and self-monitoring.
Lezak (1982)	Formulation of goals, planning, realization of plans and goals achievement, effectiveness of action.
Stuss & Benson (1986)	Anticipation, goal selection, planning, monitoring and use of feedback.
Norman & Shallice (1986)	Supervisory attentional system and 2nd level automatic and controlled processes.
Denckla (1994)	Interference control, flexible and effortful organization and strategic planning.
Lafleche & Albert (1995)	Concurrent manipulation of information: cognitive flexibility, concept formation, cue-directed behavior.
Borkowsky & Burke (1996)	Task analysis, strategy control, strategy monitoring.
Duncan et al. (1997)	A central factor i. e., general intelligence or working memory underlying executive functioning and the organization of goal-directed behavior.
Barkley (1997)(b	Behavioral inhibition, working memory, self-regulation, internalization and speech reconstitution.
Miyake et al. (2000)	Inhibition, shifting and updating.
Anderson et al. (2001)	Attentional control, cognitive flexibility, goal setting.
Delis et al. (2001)	Flexibility of thinking, inhibition, problem-solving, planning, impulse control, concept formation, abstract thinking, creativity.
Hobson & Leeds (2001)	Planning, initiation, preservation and alteration of goal-directed behavior.
Piguet et al. (2002)	Concept formation, reasoning, cognitive flexibility.
Elliot (2003)	Solving novel problems, modifying behavior in light of new information, generating strategies or sequencing complex actions.
Gioia et al. (2003)	Inhibition, shifting, emotional control, working memory and planning.
Zelazo et al.(2003)	Hot EFs - Emotional control or problem solving) and Cool EFs - Cognitive control or problem solving.
Banich (2004)	Purposeful and coordinated organization of behavior. Reflection and analysis of the success of the strategies employed.
Fisk & Sharp (2004)	Updating, inhibition, shifting and lexical access (i. e. word fluency).
Gilhooly & Fioratou (2009)	Inhibition and switching.
Garcia-Barrera et al. (2011)	Attentional control, behavioral control, emotional control and problem solving.
Diamond (2013)	Core processes EF: Inhibitory control, cognitive flexibility, and working memory. High level EF: Planning, reasoning, problem solving.
Goldstein & Naglier (2014)	Efficiency acquiring knowledge and solving problems with areas: attention, emotion regulation, flexibility, inhibitory control, initiation, organization, planning, self-monitoring, working memory

self-control. The Hot system is the basis for emotional processes, impulsive and reflexive passions, as well as fears. The balance between Hot and Cool systems is determined by the developmental level, the individual's self-regulatory dynamics and stress (Metcalfe & Mischel 1999).

The division between Hot and Cool EFs also builds on empirical evidence from developmental studies that have identified Hot and Cool EFs as distinct but correlated factors (Willoughby *et al.* 2011). Hot and Cool EFs are overlapping and ultimately form a functional coherent system (Zelazo & Cunningham 2007).

EFs play an important role in early academic performance (O'Toole *et al.* 2018). Cool EFs are often considered a predictor of intelligence, both fluid and crystalline (Todd *et al.* 2019; Wilson *et al.* 2021). Cool EFs are associated with academic achievement, including reading and mathematics, while deficits in Hot EFs might be a predictor of emotional and behavioral problems (Kim *et al.* 2013; Poon 2018). Some studies have shown that young children with severe problem behaviors exhibit explicit deficiency in Cool EFs (Poon & Ho 2014) proposing that deficits in Cool EFs may serve as a red flag for future problematic behavior (Riggs *et al.* 2004).

Both types of EFs are predictors of social competence. Both, Hot and Cool EFs processes also play an important role in the emotional regulation. EFs refer to processes such as experiencing, expressing, and modulating emotional experiences (McRae *et al.* 2012), Cool EFs via the inhibition component (Ciairano *et al.* 2007), and Hot EFs via delay of gratification and ToM (Theory of Mind) (Razza & Blair 2009).

Cool executive functions

We refer to Cool EFs as purely cognitive functions that are involved in cognitive-type problems in situations with absence of personal meaning (Vágnerová 2020). They are psychological processes involving purely logical and analytical thinking, critical analysis, or conscious control of thoughts and behavior, that are activated in abstract, low to non-emotionally colored conditions without context (Peterson & Welsh 2014; Poon 2018). They are defined as goal oriented cognitive processes such as ***inhibitory control, cognitive flexibility*** and ***update of information in working memory***. Some authors also mention ***planning*** as an ability that connects WM, inhibition, and intentional flexibility (Semenov & Zelazo 2018), and ***monitoring***, that are manifested in abstract non-emotional, non-contextual and analytical conditions (Peterson & Welsh 2014). Cool EFs make it possible to use a child's mental abilities, as a result of which, they are naturally an important prerequisite and indicator of school success (Tsermentseli & Poland 2016). Cool EFs test scores were significantly correlated with IQ, literacy and mathematics (Allan *et al.* 2014). Moreover, Cool EFs correlated with some aspects of temperament (e. g. effortful control) and intellectual functioning (Hongwanishkul *et al.* 2005). For the purpose of this paper, we stick to the 3 components model of Cool EFs which reflects the original Miyake *et al.* model of EFs (Miyake *et al.* 2000). Cool EFs contain 3 basic parts which are ***updating, inhibition***, and ***shifting*** (cognitive flexibility). This model was also supported in children (Lehto *et al.* 2003).

Working memory in the context of Cool EFs is mainly the processes of maintaining, manipulating, and updating ***auditory*** and ***visual-spatial*** information in WM (Fernández García *et al.* 2021).Updating information aims to maintain task-relevant information (Wilson *et al.* 2021). ***Updating*** is an active monitoring of information (Leshem *et al.* 2020) meaning tracking incoming stimuli and replacing old information with new information (Engelhardt *et al.* 2015). Updating functions allow not only replacing or updating current WM content with new content, but also suppressing or inhibiting content that is no longer relevant to task requirements (Carriedo *et al.* 2016).

Cognitive flexibility is also called shifting, switching, attention control (Tan & Lumeng 2018). It is an ability to shift attention between attributes of a stimulus and responses (Miyake *et al.* 2000; Zelazo 2015). It is a rapid transition between cognitive operations (Engelhardt *et al.* 2015), task sets and strategies (Wilson *et al.* 2021), as well as thoughts, action, and perspectives (Pellizzoni *et al.* 2021), no matter whether the transition is spacial or a shift to a perspective of a different person. Cognitive flexibility enables quick and flexible adaptation to changing conditions and thinking creatively "outside the box" (Diamond 2013). Cognitive flexibility consists of two separate processes ***set-shifting*** and ***task-switching*** (Dajani & Uddin 2015). ***Set-shifting*** is an ability to think about a stimulus. It enables shifting attention between different properties of one stimulus depending on changing instructions, or switching between rules within a task (Fernández García *et al.* 2021). ***Task-switching*** means switching the way of reaction to a stimulus. It is the ability to switch between tasks when there are different tasks for stimuli based on a changing rule. Set-shifting tasks activate a lower level of cognitive flexibility while task-switching tasks activate a significantly more complex cognitive flexibility (Dajani & Uddin 2015).

Inhibition is also called inhibitory control and is closely connected with impulsivity (Tan & Lumeng 2018). Mostly, it refers to the ability to inhibit potential reactions or dominant responses to particular distractive stimuli through dampening or overriding of prepotent responses (Engelhardt *et al.* 2015; Perone *et al.* 2018; Wiebe *et al.* 2011). It is also an ability to suppress those activities or information that are not necessary for the target activity (Carpendale *et al.* 2018). This does not regard only the irrelevant or distracting information but also previously relevant ones (Logan *et al.* 1984). It is the ability to effectively control mental processes (thoughts and memories), emotions and behavior and to take alternative action (Pellizzoni *et al.* 2021). Inhibitory control can be divided into the ability of ***response inhibition***, an ability to inhibit an automatic or initial prepotent (predominant) response to an event to create a delay in responding (Barkley 2001) and into the ability of ***interference suppression***, an ability to resist distractor interference in a conflict task also called interference control or resistance to distraction (Fernández García *et al.* 2021). It is a protection of self-directed, executive responses that emerge within a delay, as well as the goal-directed behaviors they generate, from interference by rival reactions or events (Barkley 2001). This type of inhibition is considered a more complex skill, since there is also a conflict in responses and a process of filtering incongruent stimulus information (Gandolfi *et al.* 2014). Barkley adds a third process, related to inhibitory control - ***sensitivity to error***, ability to interrupt an ongoing response that turns out ineffective which allows a delay in the decision to carry on with responding (Barkley 2001).

Diamond offers another, more detailed view on inhibition which in some parts overlaps with the previous one. There are two main groups, ***interference control*** and ***response inhibition***. ***Interference control*** consists of 2 subgroups, ***inhibition of attention*** and ***cognitive inhibition***. ***Inhibition of attention*** is an interference control at perception level. It is also called selective or focused attention, executive attention or attentional control, or attentional inhibition (Diamond 2013; Reynolds & Romano 2016). ***Cognitive inhibition*** represents inhibitory control of thoughts and memories including resisting unwanted thoughts or memories, extraneous information, inclusive intentional forgetting (Anderson & Levy 2009), resisting proactive interference from earlier retrieved information (Postle *et al.* 2004), and retroactive interference from later presented information. ***Response inhibition*** at the behavioral level reflects in self-control and discipline. It involves controlling not only behavior itself but also emotions initializing this behavior. It allows to resisting temptations and not acting impulsively or immoral/ unethically (Barkley 2001). The last division of inhibitory control within the dual view according to (Carlson & Wang 2007) indicates overlap of Hot and Cool EFs. The authors suggest 2 types of inhibition, ***delay inhibition*** as a Hot EF and ***conflict inhibition*** as a Cool EF (Peterson & Welsh 2014).

<u>*Hot executive functions*</u>

Hot EFs can be titled also as socio-emotional functions (Fernández García *et al.* 2021), that are activated in social situations with an affective context, due emotional characteristics of given situation, and motivational salience that activate an emotional response (Fernández García *et al.* 2021; Peterson & Welsh 2014). They involve affective, motivational, and reward-related processing (Dolcos & McCarthy 2006; Moriguchi 2022) in the direction of the social desirability of the environment (Vágnerová 2020). Due intentional regulation of emotions, Hot EFs modulate the approach-avoidance reaction (Moriguchi 2022) and thus allow us to reevaluate and decide whether to approach or avoid the stimulus (Semenov & Zelazo 2018). They are active while making decisions under risky or ambiguous conditions (Kerr & Zelazo 2004), when tension is created between immediate gratification and delayed reward (Peterson & Welsh 2014), while handling peer pressure, or learning from gains and losses, which is highly relevant in real-world contexts. That is why studies of Hot EFs emphasize the interaction of cognition and emotion in guiding behavior (Perone *et al.* 2018). Hot EFs are linked to emotional intelligence and to an individual's social success (Tsermentseli & Poland 2016). They are associated with prosocial behavior, positive relationships with others, mental health, but also with better coping strategies in adolescence (Kim *et al.* 2013; Ramos *et al.* 2023). In contrary, a low level of Hot EFs manifests itself in problematic behavior (Peterson & Welsh 2014; Tsermentseli & Poland 2016). Despite the fact that school success depends significantly less on Hot EFs than on Cool EFs, children who can better control their emotions and the resulting behavior perform better in school regardless of IQ (Vágnerová 2020).

There is still no clear and definitive agreement in the taxonomies of the functions that belong to this group. The most frequently listed skills here are ***delay of gratification, affective decision-making*** in situations of uncertainty, but we also include ***affective reversal learning*** (Fernández García *et al.* 2021; Zelazo & Carlson 2012), ***Theory of Mind*** (ToM) (Anderson *et al.* 2008; Tsermentseli & Poland 2016; Zelazo & Carlson 2012), and ***affective flexibility*** (Genet & Siemer 2011; Martins *et al.* 2020). Some authors also add ***self-regulation*** and ***emotional regulation***, the ability to navigate one's own emotional experience and to regulate the reactions they cause (Carlson & Wang 2007; Yang & Chen 2022), ***reward sensitivity***, the likeliness of risk modulation when the probabilities of outcomes change (Poon 2018). Moreover, other authors include constructs such as ***emotional intelligence*** or ***moral judgment*** (Anderson *et al.* 2008) while some perceive these abilities as being associated with, but not belonging to Hot EFs (Zelazo *et al.* 2005).

Delay of gratification is characterized as the reduction of the subjective value of a greater reward in the future as a consequence of the time that must be endured for the child to receive it (Peterson & Welsh 2014; Zelazo & Carlson 2012). It is the tendency to prefer a smaller reward earlier over a larger reward later in time (Kouklari *et al.* 2019; Poon 2018). It is related to capacity to endure a frustrating situation (Diamond 2013).

Affective decision making, also called reward/ punishment decision making, is a mental processing occurring on the selection of one or more possible options under risk where one employs both rational and emotional processes (Kouklari *et al.* 2019). It contains a form of tension when making decisions in uncertain situations (Fernández García *et al.* 2021).

Affective reversal learning is considered to be an ability to adjust/modify already learned associations between stimuli when the relationship between them changes, e. g. punishment for behavior that was rewarded in the past (Fernández García *et al.* 2021; Zelazo & Carlson 2012).

ToM, also called metallization or social understanding, is a complex ability to think about the thoughts of others, especially their beliefs and desires (Fernández García *et al.* 2021). It is the ability to infer mental and emotional state, mental and emotion recognition, and false belief (Goldman 2012; Kouklari *et al.* 2017). It is a basis for prediction and anticipation, for mutual sharing of experiences with others (McDonald 2013; Zimmerman *et al.* 2016), for appropriate reactions in social interaction and in conformity with goals or intentions (Nonnenmacher *et al.* 2021). ToM includes two processes, process from an intrapersonal angle (reflecting on one's own thoughts and emotions) and an interpersonal angle (reflecting on the thoughts and emotions of others) (Westby & Robinson 2014). ToM includes several abilities. The first two levels are the critical aspect of ToM, the understanding of false beliefs, that enables the understanding that one's belief/representation of the world can contrast with reality (Kouklari *et al.* 2019). The first level is the ability to understand ***false beliefs of the first order***, the ability to understand one person's belief. The second level is the ability to understand ***the false beliefs of the second order***, the ability to understand a belief attributed to another person as well (Hollebrandse *et al.* 2014). The third level of ToM is the ***understanding of non-literal meaning*** like sarcasm, irony, lies, or lying in good intentions (white lie), persuasion, metaphors (Fernández García *et al.* 2021). Usually, contrary emotions, pretense, misunderstanding, figure of speech, appearance-reality, joke, double bluff, and forget are also investigated (O'Hare *et al.* 2009). The final fourth level is the understanding of the ***emotional state of another*** and the understanding of the concept of ***Faux pas*** which is an advanced ToM construct. It is the ability to recognize a flaw in a behavior or a remark in a social interaction that causes embarrassment or offense to the other (Korman *et al.* 2017).

Affective flexibility is an ability to flexibly switch between ways of processing emotional aspects of a stimulus or a situation (Jacques & Zelazo 2001; Malooly *et al.* 2013), to alternate between flexibly to attend to and to disengage from emotional material (Genet & Siemer 2011) due switching from focusing on the emotional content of a situation to a neutral interpretation to reduce the intensity of distressing emotion (Martins *et al.* 2020).

Emotional regulation refers to a range of voluntary and involuntary processes used to manage the occurrence, intensity, and duration of internal emotional states and physiological processes that occur in relationship to external events, for the purpose to respond appropriately in accord with the fulfillment of personal expectations and objectives. Adaptive emotion regulation includes flexible regulatory strategies (Gross 2014). The ability to flexibly alternate between different emotional perspectives (affective flexibility) is crucial for effective emotion regulation (Martins *et al.* 2020).

Hot and Cool EFs are interconnected and typically work together as a part of a more general adaptive function (Bechara 2004; Zelazo & Carlson 2012). The majority of real-life problems mostly evoke cognitive processing in the context of emotional reactions and they require interactions between both, cognitive and emotional operations (Qu & Zelazo 2007). Whether Hot or Cool EFs will be activated more, depends not only on the type of the problem, whether it is Hot or Cool, but also on its motivational significance (Zelazo & Cunningham 2007). The interconnection between Hot EFs and Cool EFs can be indicated through the ability to self-regulation, a construct that overlaps with executive functioning skills (Cool EF) (Diamond 2013; Jones *et al.* 2016). In emotionally loaded contexts may this ability relate to Cool EFs such as inhibitory control and cognitive flexibility. It occurs by higher priority task in order to stay focused, when tempting immediately rewarding alternative task appears. It requires inhibitory control, to suppress the desire for immediate rewards. In addition, an adaptive response to the frustration of not receiving some anticipated reward may require services of inhibitory control (Cool EF) to inhibit a frustrated response and cognitive flexibility (Cool EF) to reframe the situation (Kryza-Lacombe *et al.* 2021). Until now, it is not completely explored how results measured in Cool conditions relate to how one responds in Hot situations and how exactly Hot EFs and Cool EFs related and linked to each other.

Typical Development of EFs

The basic neurological structures corresponding to EFs may be identical regardless of the developmental phase. However, at a different child's age, these parts mature at different rates, through the processes of nerve myelination in the frontal lobe, especially during adolescence (Klingberg *et al.* 1999), which may represent a sensitive period for EFs functioning at this age (Poon 2018).

EFs develop throughout life. They first appear in childhood and their development continues until early adulthood (Anderson 2002). EFs may be a unified construct in early stages (Wiebe *et al.* 2011), then differentiate and specialize later on (Howard *et al.* 2015), creating separate Hot and Cool EFs (Miyake *et al.* 2000).

Overall, in typical development, Hot EFs exhibit fast development in the early years of age followed by age-related improvements across middle childhood and adolescence (Prencipe *et al.* 2011; Zelazo & Müller

2002). Cool EFs may undergo rapid advancement during early childhood, but Hot EFs may follow a more protracted developmental course (O'Toole *et al.* 2018). The development of Cool EFs is faster than Hot EFs. The improvement in Hot EFs performance appears to be achieved at an age when Cool EFs are already stable (Prencipe *et al.* 2011; Zelazo & Carlson 2012). Age-related improvements of Hot EFs not only seem to emerge later in time, but they are also more gradual than those of Cool EFs, which supports the theory of diverse development trajectories (Leshem *et al.* 2020; Prencipe *et al.* 2011; Welsh & Peterson 2014). The development of Cool EFs in children and adolescents improves linearly with age, while the developmental trajectory of Hot EFs has a non-linear, inverted "U" (bell) shape during this period, which may indicate a period of increased risk-taking tendencies in mid-adolescence (Poon 2018). Nevertheless, recent evidence indicates that the differentiation of EFs over development may have a more complex developmental trajectory and it is possible that the initially differentiated EFs undergo a period of integration later (Howard *et al.* 2015). Regardless of general developmental tendencies described above, the individual development of Cool and Hot EFs in children can vary. Children who score high in Cool EFs may not have well-developed Hot EFs and vice versa (Jursová Zacharová 2021).

EFs development includes quantitative and qualitative changes in its different aspects. Nevertheless, the way in which such changes happen is still unknown in depth (Stelzer *et al.* 2014).

Development hot and cool EFs according the subcomponents

Infants (up to 1 year of age) already possess rudimentary EF skills (e. g. simple goal-directed activities) that are a precursor to later EFs (Cuevas *et al.* 2017). EFs share a common component of executive attention, a precursor to WM that develops first followed by the inhibitory control (Garon *et al.* 2008). After 4 years of age, EFs begin to differentiate more (Vágnerová 2020). Cognitive flexibility develops on the basis of WM and inhibitory control, therefore it occures much later in development (Diamond 2013) and it does not function fully until adolescence (Lee *et al.* 2013).

The ***updating*** ability improves significantly in the period between 10-11 years of age (Ludyga *et al.* 2019). Early Cool EFs may be associated with **inhibitory control** (O'Toole *et al.* 2020). Children exhibit steady improvement of inhibitory control between 3 and 6 years of age (Carlson *et al.* 2005). During early childhood, younger children fail to ***inhibit automatisms***, their natural tendency, whereas 5-years-old children already can (Moriguchi 2022). Inhibition of automatisms develops continuously during middle childhood (6-12 years of age), while at the end of middle childhood, around the age of 12, the inhibition of automatisms reaches final maturity level similar to adulthood (Symeonidou *et al.* 2016; Wilson *et al.* 2018). However, ***interference suppression*** develops even after 12 years of age (Fernández García *et al.* 2021), since, as a more complex type of inhibitory control, it involves a higher cognitive load.

Cognitive flexibility develops later on core fundaments of WM and inhibition (Diamond 2013), while ***set shifting*** can be flexible as early as around 3-3.5 years of age (Diamond 2005 2013; Zelazo 2006). Set-shifting significantly improves with age and progresses until the age of 12 years and, around this, it time also reaches full matureness (Wilson *et al.* 2018). Switching between rules is more difficult. Some authors argue essential enhancement of task switching in children aged 5-9 years (Hoyo *et al.* 2019) other propose the progress later, at the age of 10-11 years (Ludyga *et al.* 2019). However, there is a consensus that ***task switching*** improves during child development and declines by slowing down during aging (Kray 2006).

More studies are needed to clarify the course of Cool EFs subcomponents trajectories.

Basal **Hot EFs** are already present in early childhood (Grüneisen *et al.* 2023) and they improve. The first developmental improvements of Hot EFs have been observed since 4 years of age. Around this age and later, children can for the first time successfully favor the smaller of two rewards to the larger reward in the "Less is More" task which is linked to **emotional flexibility** (Carlson *et al.* 2005) and 4- and 5-year-olds have been found to outperform 3-year-olds on Hot gambling tasks (Hongwanishkul *et al.* 2005; Kerr & Zelazo 2004) connected with affective decision-making. There are indications, by measuring affective flexibility, that in development gender differences are present. Girls in preschool age (Visu-Petra *et al.* 2014), in middle childhood (Mocan *et al.* 2014), and preadolescence outperformed boys (Mărcuş *et al.* 2016).

Affective decision-making (Almy *et al.* 2018; Lensing & Elsner 2018) in ambiguous conditions achieves a significant improvement during middle childhood and continues the improvement even after reaching the age of 12. It has been found to be more gradual, with more noticeable changes showing up around 14- to 15 years of age (Prencipe *et al.* 2011).

The ability to **delay gratification** develops later and is not fully developed in early childhood (Mischel *et al.* 1989). 3-year-old children cannot apply function and resist while 4-year-olds have been found to outperform them (Carlson *et al.* 2015) and 6-year-old children can apply function and resist when they know that they will get a bigger reward later (Herrmann *et al.* 2015). During middle childhood, there is a significant improvement and continues developing (Steinbeis *et al.* 2016). At this age, children manage negative emotions better, resist failure, and are more persistent when they fail (Lensing & Elsner 2018; O'Toole *et al.* 2018; Prencipe *et al.* 2011). After reaching the age of 12 years, for a certain time, the delayed gratification has a tendency to decrease the perception of the value of a larger reward that involves a long waiting time (Fernández García *et al.* 2021). Further developmental progress is made in late adolescence and this process continues into adulthood (Prencipe *et al.* 2011).

ToM as multifaceted cognitive skill develops gradually. It starts with development in infancy and continues to improve throughout middle childhood and adolescence. As children grow older, they exhibit age-related performance gains and become able to solve more complex high-order ToM problems (e. g., emotion understanding) across middle and later childhood (Devine & Hughes 2013). The understanding of ***false beliefs of first-order*** develops during the early childhood. 4–5 years old children demonstrate understanding that others might hold and act on beliefs that are false and that appearance does not always correspond to reality (Andrews *et al.* 2003). Current research suggests the cut-off age of 3-4 years (Schug *et al.* 2016), other experts suggest up to 5 to 6 years (Chaplin & Norton 2015). On their basis, higher-order ToM gradually develop (Kouklari *et al.* 2019). The acquisition of more advanced ToM concepts is a later attainment (Wilson *et al.* 2018). Between 6 and 9 years of age, understanding of ***false beliefs of the second order*** develops. Later, the understandings of false beliefs of both orders stabilize (Hayward & Homer 2017). Performance on all concepts of ***understanding of non-literal meaning*** improved with age, mostly between the age of 7 and 12 years (Bock *et al.* 2015), but some concepts (persuasion, white lie, sarcasm, joke) proved difficult for the youngest children. Understanding of sarcasm and persuasion only develops around 10 years of age (Lecce *et al.* 2019) and this is where this ability begins to gradually stabilize, but there is no evidence of a ceiling effect in older children (Wilson *et al.* 2018). ***Understanding the emotional state of another person*** improves significantly between 6 and 12 years of age. Children develop recognition of emotions through facial expression at the age of 6 to 8 when the peak of this ability is reached, the ability does not develop significantly later on (Bulgarelli *et al.* 2015). On the contrary, the ability to understand how people control their negative emotions and their consequences does not develop at a younger school age. It probably only appears in adolescence (Brandone & Klimek 2018). Understanding ***Faux pas*** seems too demanding for childhood and probably much of adolescence. However, it is also possible that the used faux pas stories are not suitable for research in children of younger school age (Hayward & Homer 2017).

The development of **emotional regulation** connects and synchronizes with the development of other functions such as focused attention or understanding of the situation. These skills develop during early childhood (6-7 years of age). In that period, children already think less egocentrically thanks to which they already understand that different people in different situations can experience different emotions. They also begin to understand that in some situations it is more advantageous not to show their real emotions or to pretend other than the experienced ones. At the age of 9-10, children are able to regulate their emotional expressions if they are in not too stressful situations. At the age of 11-13, at the beginning of adolescence, there are overall changes in experience and thinking (Dennis 2010). Changes in the development of emotional regulation are related to the degree of maturation of EFs. At this age, brain areas associated with sensitivity to reward are more activated, while the brain activity of cognitive control decreases, which can be reflected in more impulsive behavior (Kryza-Lacombe *et al.* 2021; Sabatier *et al.* 2017).

The development of Hot and Cool EFs occurs mostly unintentionally in children within the framework of natural interaction with the social environment and fulfillment of its requirements. Both types of EFs, Hot and Cool, can be successfully stimulated in children at the age of 4 with regular intentional activities (Pellizzoni *et al.* 2021).

Atypical development in EFs

Difficulties in EFs can be considered trans diagnostic indicators of atypical development in children. Adverse childhood experiences (e. g. complications in prenatal stage or while being born, childhood illness or injuries) and stress can disturb the development of neural systems and EF skills and increase the risk for general features of broad range of psychopathological conditions (Malloy-Diniz *et al.* 2017; Zelazo 2020). Dysfunction in Hot and Cool EFs may result in different psychopathologies and neurodevelopmental outcomes (Anderson 2002; Sonuga-Barke 2003). Their clinical expressions generally include disruption in both Hot and Cool EFs, such as impairment in delay gratification, verbal and behavioral disinhibition, and the inability to anticipate consequences (Zelazo & Carlson 2012). EFs disorders in children arise in a variety of situations at different ages at different levels of disability complexity. The distinction between Cool and Hot can be helpful to characterize comorbidities within diagnostic categories and heterogeneities within them in children with atypical development (Zelazo 2020).

Deficits in the Hot and Cool EFs categories can be seen in different diagnoses such as attention deficit hyperactivity disorder (ADHD) (Petrovic & Castellanos 2016; Stern *et al.* 2017), autistic spectrum disorder (ASD) (Johnston *et al.* 2019; Rašková *et al.* 2022; Zimmerman *et al.* 2016), learning disabilities (Toll *et al.* 2011), antisocial personality disorder (Ogilvie *et al.* 2011), conduct disorder (CD) (Rubia 2011), developmental coordination disorder, fetal alcohol syndrome (FAS), obsessive-compulsive disorder (OCD) (Pietrefesa & Evans 2007), depression (Nelson *et al.* 2018), anxiety (Shi *et al.* 2019), but also as the consequences of premature birth (Lee *et al.* 2022), as the consequences of psychotic syndromes in at-risk youth, as well as the consequences of traumatic brain damage (Zelazo 2020) or post-traumatic stress disorder PTSD (Olff *et al.* 2014), or obesogenic eating (Tan & Lumeng 2018). These disorders are known to affect either Hot or Cool EFs at the neural level, these disorders nevertheless seem to exhibit both components at the clinical and behavioral level proposing interdependency (Leshem *et al.* 2020).

For example, children in preschool age with ADHD have difficulties in the area of inhibition (Schoemaker *et al.* 2012), children with Down syndrome have problems mainly in the domains of WM and planning (Daunhauer *et al.* 2014), preterm children have deficits in WM and emotional control (Dzambo *et al.* 2018), moreover attention problems may occur as well (Talge *et al.* 2010) without a finite cut-off point at which children are spared from potential long-term neurodevelopmental effects of PT birth (Hodel *et al.* 2016), autistic children have problems with planning and WM (Memisevic *et al.* 2023), and children with ADHD have difficulties in the area of inhibition (Schoemaker *et al.* 2012).

Research indicates that EF skills can be cultivated through scaffolded training and are a promising target for therapeutic and preventive intervention. Intervention efficacy can be enhanced by mitigating disruptive bottom-up influences such as stress, training both Hot and Cool EF skills, and adding a reflective, metacognitive component to promote transfer of trained skills (Zelazo 2020).

ADHD in children

ADHD (Attention-deficit/hyperactivity disorder) is one of the most wide-spread neurodevelopmental disorders, characterised by presence of symptoms of inattentiveness and hyperactivity, affecting approximately 5 to 8% of children worldwide (Cheesman *et al.* 2022; Jangmo *et al.* 2019). ADHD is predominately diagnosed in boys, in approximate ratio (girls/boys) from 1:2 to 1:10 (Mowlem *et al.* 2019).

Causes of ADHD are associated with various structural and functional changes in CNS, namely abnormalities in neurotransmitter regulations, notably dopamine and norepinephrine, but also other neurotransmitters meditating their effects through G protein coupled receptors (GPRCs) (Del Campo *et al.* 2011; Ptacek *et al.* 2009). Typical for individuals with ADHD are also differences in structural development, and functional activation of various brain regions, such as prefrontal cortex, basal ganglia, anterior cingulate cortex, and cerebellum (Faraone *et al.* 2015; Gehricke *et al.* 2017). According to neuroimaging studies, ADHD individuals tend to have underactivated frontostriatal circuts, frontoparietal network and ventral tegmental area and lowered activation in reward associated brain network compared to neurotypicals (Faraone *et al.* 2015). ADHD is also associated with dysregulation of default-mode network (DMN) and cognitive control network, with lower functional connectivity within both (Faraone *et al.* 2015). Development of changes in structural and functional networks and brain regions can be explained by polygenetic risk factors (Faraone & Larsson 2019). Despite strong genetic link, there are various environmental factors that could contribute to development of ADHD or can negatively impact severity of the

Tab. 2. Syptoms of executive dysfunction in ADHA

a) **Problems in cognitive and affective control**, regulations deficits of arousal and calmness, problems with concentration, planning and organising and problems with guidance (Schreiber *et al.* 2014; Schuch *et al.* 2015).
b) **Difficulties in attention and control**, such as dysregulated ability to sustain and control attention, being easily distracted therefore making mistakes, having poor concentration of attention, short attention span, deficits in flexibility of attention, having problems with selective attention and inability to regulate one's own behaviour (Lemiere *et al.* 2010).
c) **Low inhibition control**; difficulties with inhibition of inappropriate reaction (Çelik *et al.* 2023).
d) **Deficits in attention switching**; for diagnosed individuals, it's much harder (and takes longer) to switch tasks, possibly due to problems in inhibition control (Rauch *et al.* 2012).
e) **Poor planning and organising skills**; due to increased impulsivity, and tendency to act impulsively (McCormack & Atance 2011).
f) **Problems with delayed gratification**; due to difficulties in organising and planning and impulsive nature of ADHD, individuals prefer to take immediate rewards instead of focusing on long term rewards, requiring sustained effort (Geissler *et al.* 2014; Martinelli *et al.* 2017).
g) **Deficits in working memory**; problems with tasks requiring memorizing and using instructions, deficits in visuo-spatial memory (Alloway *et al.* 2010; Gomez *et al.* 2016).
h) **Deficits in time estimation**; individuals with ADHD tend to think activity took longer/or, they tend to underestimate time necessary for completing task due to problems defficits in working memory (Walg *et al.* 2017; Weissenberger *et al.* 2019).
i) **Problems with comprehension of complex verbal assignments** as an consequence of deficits in working memory and ability to hold sustained focus when reading, tend to lead to limited ability to understand verbal commands (Wassenberg *et al.* 2010).

disorder such as, smoking during pregnancy, psychosocial stress during pregnancy and preterm childbirth (Soheilipour *et al.* 2020; Tole *et al.* 2019).

Although clinical manifestation of ADHD on individual level can vary, globally there are differences between typical clinical manifestation in boys and girls, with boys' symptoms being more from the impulsive/hyperactive cluster and with girls typically displaying more internalised symptoms and difficulties affecting attention (Skogli *et al.* 2013). One of the reasons why boys are diagnosed at a younger age and in a greater number is the more noticeable manifestation of ADHD signs (Mowlem *et al.* 2019). Other reasons include ability of developing better coping strategies in girls, i.e. girls being more effective in hiding symptoms (Young *et al.* 2020). ADHD symptoms are usually present from early childhood, with mean age to conclude the diagnosis being 6 years old (Rocco *et al.* 2021; Visser *et al.* 2014).

According to clinical manifestation of the symptoms there are 3 main subtypes of ADHD, depending on more pronounced manifestation: a) Predominantly inattentive presentation (ADHD-PI or ADHD I), if enough symptoms of inattention, but not hyperactivity-impulsivity, are present, b) Predominantly hyperactive-impulsive presentation (ADHD-PH or ADHD-HI), if enough symptoms of hyperactivity-impulsivity but not inattention are present, c) combined presentation (ADHD-C), if enough symptoms of both criteria inattention and hyperactivity-impulsivity are present (American Psychiatric Association 2022).

Executive function in ADHD

Children with ADHD, compared to their neurotypical peers tend to show problems in all core EFs, with most notable deficits in working memory, response inhibition and task switching and in higher order EFs, manifested throughout deficits in ability to plan and organize, hold sustained attention and self regulate (Çelik *et al.* 2023; Gomez *et al.* 2016; McCormack & Atance 2011). More detailed description of various EF deficits typical for ADHD presentation is provided in Table 2.

Comorbidities and comparison of EFs dysfunction in ADHD with other neurodevelopmental disorders

More than two thirds of individuals with ADHD have psychiatric **comorbidities**, with more than 50% of individuals with ADHD being also diagnosed with Oppositional Defiant Disorder (ODD), 40% attachment disorder and 25% having comorbid anxiety disorder. More than 40% individuals with ADHD are also affected by learning disabilities (Gomez *et al.* 2016; Mahone & Denckla 2017).

Most notable difference in executive functioning between ADHD and ODD has been demonstrated thorough different results in Iowa gambling test (IGT), which is used to measure reward-related decision-making and Hot EF. IGT was developed to simulate real life decision making under uncertain conditions (Bechara *et al.* 1994). In IGT, the individual is instructed to make 100 choices with reward (getting fictional money, for choosing specific card), or risk of loosing them, with condition of increased risk when choosing increased reward choices (Groen *et al.* 2013). ADHD individuals tend to risk more than healthy controls, and individuals with ODD tend to risk more than people with ADHD, even when correcting for ADHD symptoms. Thus, EF of reward related decision making (Hot EF) seems to be affected irrespective of ADHD status in ODD, leading to worsened reward-related EFs in combined ADHD with ODD (Hobson *et al.* 2011). Similar results have also been demonstrated in different studies by using different risk and reward-related decision methods, such as balloon analogue risk task (BART) (Humphreys & Lee 2011).

There are marked differences in EFs typical for ADHD, and other neurodevelopmental disorders, such as specific learning disability (LD) and autism spectrum disorder (ASD) (Ahuja *et al.* 2013; Antshel & Russo 2019; Mayes *et al.* 2000).

EFs in children with LD, but without ADHD tend to be less affected, whereas LD combined with ADHD intensifies both learning difficulties and executive dysfunction (El Wafa *et al.* 2020; Mayes *et al.* 2000). Specifically, both in ADHD and LD group, time management EF, problem solving (self-organisation) EF are affected at similar level, whereas self-restraint EF (inhibition), self-motivation EF and emotional regulation EF are more affected in ADHD, than in LD alone. In case of combined ADHD+LD, all executive function domains are affected at a much greater degree (El Wafa *et al.* 2020).

Executive functioning could be also affected by specific learning disability, with each LD having unique EFs dysfunction profile compared to ADHD (Kibby *et al.* 2021). Specifically, in developmental dyscalculia (DD), using methods such as Attention Network Test (ANT), there seems to be a greater deficit in alerting effect in developmental dyscalculia, which indicates different underlying mechanisms of executive dysfunction between ADHD and DD (Askenazi & Henik 2010). ADHD and developmental dyslexia (DD), are often found in comorbidity, but level of executive function of reading fluency (measured through oral reading tests), seem to be best predictor of presence of DD, irrespective of presence of other ADHD symptoms (Al Dahhan *et al.* 2022).

Although executive dysfunction symptoms in people with ADHD and autism spectrum disorder (ASD) tend to overlap, there are significant differences between these two diagnoses, specifically, ADHD individuals tend to struggle most clearly in inhibition tasks; due to impaired ability to withhold a pre-potent response and have problems with planning and problem solving. Individuals with ASD have most profound deficits in cognitive flexibility, requiring rapid switching between multiple perspectives (Antshel & Russo 2019). Furthermore, age related improvements in EFs are less clear for individuals with ADHD than ASD and task performance correlate positively with parent reports in communication abilities and negatively with hyperactivity for individuals with ASD, but not for those with ADHD (Antshel & Russo 2019; Happé *et al.* 2006).

Diagnostics of ADHD and measurement of EFs in ADHD

Except for anamnestic interview and clinical observations, there are tools in disposal for professionals in mental health to use for early and more precise ADHD diagnostics (Peterson *et al.* 2024). Most commonly used tools are: a) Parent ratings of presence of ADHD symptoms; CBCL (Child Behavior Checklist) (Biederman *et al.* 2021); b) Teacher ratings; Pelham Rating Scale (SNAP-IV) (Swanson *et al.* 2001); c) Youth self-reports; The Dominic Interactive for Adolescents-Revised (DIA-R) (Bergeron *et al.* 2017); d) Combined rating scales; Computerised adaptive tests (CATs) (Gibbons *et al.* 2020). Despite all commonly used diagnostic tools, with altered executive functioning being one of the core ADHD symptoms, tools measuring levels of EF provide options for precise additional diagnostics (Holmes *et al.* 2010).

In common clinical setting neuropsychological tests such as continuous performance tests (CPTs), and other methods such as structured interview are widely used (Davidson *et al.* 2016; Peterson *et al.* 2024; Toplak *et al.* 2008).

One of the most comprehensive diagnostic tools for measuring presence of executive dysfunction not only in ADHD children and adolescents is BRIEF-2 (Behavior Rating Inventory of Executive Functions 2); an executive function questionnaire for parents and teachers at school-age children with most notable features such as being able to provide multiple perspective (both answers from parents and teachers are collected), having specific normative gender and age-based data and having nonoverlapping scales, statistically derived scale measures of different behaviours (such as ability to control impulses, modulate responses and keeping track of behaviour on others) (Dodzik 2017). The structure of the BRIEF-2 is based on theories that outline a hierarchical organization of EF (Baddeley 2012).

BRIEF-2 consist of behavioural regulation scales (inhibit, shift and emotional control) and metacognition scales (initiate, working memory, plan/organize, organisation of materials and monitor) (Gioia *et al.* 2002). For preschool children, BRIEF-P, an assessment tool, designed for children aged between 2 and 5 years, is available, with questions specifically tailored for understanding of young children consisting of reports of observed behaviour in everyday situations, providing conceptualized picture of child's executive skills (Bausela-Herreras *et al.* 2023; Sherman & Brooks 2010).

In BRIEF results, adolescents and children with ADHD demonstrate higher scores indicating more pronounced deficits in EFs than neurotypical individuals, with ADHD group showing notable differences, most particularly in working memory (WN), plan/organise (PlanOrg) and inhibit subscales (Davidson *et al.* 2016; Toplak *et al.* 2008).

There are also different profiles in BRIEF-2 results, depending on ADHD type (Gioia *et al.* 2002). Although children from all 3 ADHD subtype groups tend to be scored higher in behavioural rating index (BRI), emotion regulation index (ERI) and cognitive regulation index (CRI) scales compared with healthy controls, there are pronounced differences in scores between subtypes. Children with ADHD-I receive higher ratings in cognitive regulation index scores most notably in working memory and plan/organize subscales, than children with ADHD-PH, but with less severe behavioural dysregulation. On the on the contrary, children with predominantly impulsive type (ADHD-PH) tend to receive higher ratings in behaviour rating index, with more pronounced scores in inhibit subscale. In combined presentation (ADHD-C) both ratings in BRI and CRI scales are substantially elevated (Gioia *et al.* 2002; Hendrickson & McCrimmon 2019; Jacobson *et al.* 2020).

In BRIEF-2, well documented differences in children with typical profile for ADHD, ASD and learning disabilities have also been observed. Typical manifestation of executive dysfunction of children and adolescents with learning disabilities resemble ADHD-I profile, but at a much lower scale. Children with ASD, tended to peak at shift scale, with much higher scores than any aforementioned groups (Gioia *et al.* 2002).

In neuropsychological measurements, such as Rey-Osterrieth Complex Figure (ROCF), psychometric tool using two-dimensional line drawing requiring visuomotor representation, that measures spatial planning, organisational skills, long-term figural memory and grapho-motor abilities children and adolescents with ADHD tend to perform poorly compared to their neurotypical peers. Most profound differences are in the number of remembered details, configured accuracy, planning, preservation and neatness. Deficits in selective attention and working memory are thought to be contributing factors to weaker performance in ROCF in ADHD group (Sami *et al.* 2004; Schreiber *et al.* 1999).

Children with ADHD also have difficulties in inhibition of reactions, demonstrated by performance in various tasks measuring EFs, such as Stop Task (Logan *et al.* 1997), that requires child to respond rapidly (either react or non-react to presented stimuli), and measures response inhibition, with both *ADHD-C* and *ADHD-I* groups having more inhibitory failures (Adams *et al.* 2008). There are also heterogeneous

EF profiles demonstrated in intragroup differences, in widely used methods such as The Trial Making Task (subtest of Halstead-Reitan Neuropsychological Battery) requiring participant to trace letters and numbers as quickly as possible without errors, with this method being able to provide a measure of speed and set-shifting ability (Bowie & Harvey 2006). Poor set-shifting/speed has been proposed to be present at significantly greater level in individuals with hyperactive-impusive (*ADHD-HI*) presentation and the results in EF measuring tasks correlated with poor academic performance (Roberts *et al.* 2017).

Using methods such as IQ tests (WISC-R), tests measuring higher order problem solving (ToLDx) tests measuring abstract reasoning, cognitive flexibility, problem solving and set shifting (WCST), verbal fluency measures and tests for selective attention (Stroop test) and working memory (WISC-R digit span), ADHD-I subtype is associated with significantly better performance in verbal working memory and verbal category shifting in comparison with ADHD-C, yet there seem to be no significant differences in terms of inhibition, set shifting, planning and overall cognitive flexibility between two groups, with both groups showing substantial deficits compared to neurotypical controls (Bahcivan Saydam *et al.* 2015).

Conclusion

Researchers have been dealing with the topic of EFs and their exploration for quite a long time. Thanks to this, we know a lot about EFs, but there is also a lot that is waiting to be clarified and connected to the context of the functioning of the minds of children and adolescents, and their behavior. The area of Cool EFs is well-researched, as evidenced by many presented models, while the taxonomy of Hot EFs is not yet definitively unified and comprehensive, similarly to the description of mutual iteration of Hot and Cool EFs and their overlap.

The typical development of Cool and Hot EFs does not follow a single developmental trajectory. The development of Cool EFs in children and adolescents improves linearly with age, while the developmental trajectory of Hot EFs has a non-linear, inverted "U" (bell) shape which may have impact on behavioral manifestation (Poon 2018).

On the other hand genetics, adverse childhood experiences (pre-, peri- and postnatal) and stress can interfere with the development of neural systems linked to EFs and increase the risk of a broad range of neurodevelopmental and psychopathological conditions (Malloy-Diniz *et al.* 2017; Zelazo 2020). Dysfunction in Hot and Cool EFs may occur in connection with a lot of them.

ADHD is characterized primarily by deterioration in the cognitive area of inhibition – suppression of prepotent responses (Cool EF) and secondary by deterioration in reward-related functions - delayed gratification (Hot EF) (Pauli-Pott *et al.* 2019; Zelazo & Müller 2002), but other difficulties in EFs can be manifested as well. Differences in EFs typical for ADHD and other neurodevelopmental disorders have been found. Also, ADHD may be associated with comorbidities that also impact the EFs. Usually, these dysfuntions of EFs can be measured with tools for early and more precise ADHD diagnostics i.e., BRIEF or ROCF. Results of research indicate that EF skills can be cultivated and fortified through scaffolded training due therapeutic and preventive intervention by a practitioner (Zelazo 2020).

The review extensively presented EFs as functions representing a separate and very robust research category of processes, which are given considerable attention in the scientific community. However, EFs are functionally part of many other forms of behavior, integrated into other psychological processes (Procházka *et al.* 2021), which opens up new areas for further research in the future. Similarly, there is a strong link connecting the knowledge on the essence of EFs progress and development in helping interventions. Deepening the knowledge on models and subtypes of EFs and typical and atypical neuropsychological development can provide up-to-date information to practitioners enabling more effective interventions. The common goal of both disciplines, researchers and practitioners, should remain to improve the quality of life of children with EFs deficits and their families.

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