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Concept of self – regulation in connection to executive functions and their development in children

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Abstract

This paper reviews the current knowledge of Self-regulation (SR) and its relationship to Executive functions (EFs) in children. SR represents activities to achieve goals in the context of human learning and socialization. SR integrates top-down (EFs) and bottom-up regulatory processes to control dominant impulses and to achieve optimal arousal levels. Effortful control (EC) is one of the top-down aspects of SR and conceptually overlaps with EFs because attentional and inhibitory control mechanisms are the central self-regulatory processes of both constructs.

The development of EFs has a significant impact on SR development and their developmental trajectories are similar. While basic biological factors at the temperament level are common to both, emotional aspects, e. g. motivation, occur in SR, but only in a part of EFs (Hot EFs).

The methods of measuring SR depend on the phenomenological level of the regulatory processes and the results may not inter-correlate. While correlations between SR and EFs measured at the behavioral level are present, they are unclear for performance tests. Performance assessments of SR and EFs often have only a weak correlation with behavioral rating scales, but coherent patterns can be identified. Complex understanding of regulatory functioning requires an integrative approach combining objective performance measures with subjective behavioral evaluations.

There are opportunities to improve SR during the lifetime. Evidence-based intervention programs are promising tools for therapeutic and preventive interventions. The profound understanding of SR with connections to other concepts such as EFs, EC, temperament and motivation can be a solid foundation for future research and may help to create more effective interventions in the following time.

Abbreviations:
Self-regulation (SR), Executive functions (EFs), Working memory (WM), Effortful control (EC), Inhibitory control (IC), Delay of gratification (DoG)

Self-regulation

Self-regulation (SR) can be viewed from several ***perspectives*** of different branches of psychology and, depending on this view, its conceptualization as a construct can also vary (Colombo *et al.* 2023; Robson *et al.* 2020; Xie & Li 2022). These processes are often studied from either a behavioral and temperamental approach or a cognitive-neurological approach (Liew 2011). SR is viewed differently by temperament researchers or school psychologists and may be viewed differently by psychologists from a cognitive, clinical or developmental perspective (e.g. life-span theory, relational developmental systems theory) (Liew 2011; McClelland *et al.* 2010). see Table 1.

Often, these SR processes are investigated either using a temperamental approach, derived from the knowledge of developmental psychology, or using a cognitive-neurological approach, originating on the knowledge of clinical and developmental neuropsychology (Liew 2011; McClelland *et al.* 2010).

Using the ***temperamental*** perspective, SR is based on the individual, biological differences in reactivity and regulation. While reactivity reflects the sensitivity and intensity of initial responses, SR involves attentional and inhibitory mechanisms that modulate these reactions. It is the ability to regulate the primary reaction that ultimately determines the level of functioning (Rothbart & Bates 2006). The temperament perspective emphasizes continuity in regulatory tendencies across situations (McClelland *et al.* 2010) and focuses on effortful control (EC) and executive attention as key elements of SR (Liew 2011).

A ***cognitive-neurological*** perspective tends to emphasize the situational aspects and variability of SR (McClelland *et al.* 2010) and focuses on EFs (Liew 2011). In the context of EFs, the focus is on cognitive processing aspects of SR and their link to the ability to plan, organize and complete tasks (Jacques & Marcovitch 2010).

Despite the different traditions of viewing SR, it is necessary to perceive EFs and EC processes as more than complementary in order to progress in the understanding of the roles of SR in development (Liew 2011).

In general, we can ***define*** SR as a multidimensional construct including emotions, cognition and behavior (McClelland *et al.* 2010; Schütz & Koglin 2023), and as a coherently integrated and hierarchically organized set of domain-specific control mechanisms (Blair & Raver 2012). These mechanisms are also the basis for the ability to regulate and coordinate components of emotion, cognition and behavior (Calkins 2007).

SR includes both top-down and bottom-up two-way regulatory processes (Nigg 2017) to exercise control over their dominant impulses (Robson *et al.* 2020). Top-down processes are primarily executive (e.g., inhibitory control, WM, attentional shifting), whereas bottom-up processes arise from automatic, affective, and motivational systems. SR refers to internal processes aimed at adapting the mental and physiological state to the context. It is therefore a deliberate attempt to modulate, modify or inhibit action and reaction in a more adaptive direction (Barkley 2004).

In terms of EFs (top-down processes), SR refers to the ability to control attention, emotion, and behavior in ways that support adaptive functioning, including the modulation of arousal and impulses. These processes are primarily concerned with controlling and regulating of one's own emotions (Eisenberg, Spinrad, *et al.* 2010; Mischel & Ayduk 2002) that is, with managing if, when, and how intensely emotions and related motivations or physiological states are experienced, as well as how they manifest in behavior (Eisenberg *et al.* 2007). It is important to note that even behaviors influenced by SR can create an environment or incentives that lead to new regulatory demands (Mayne & Ramsey 2001). SR processes include effortful perceptual management of stimuli and the manipulation of cognitions and emotion-related behaviors in general for the purpose of biological or social adaptation and/or achieving an explicit or implicit goal or goal state (Blair & Raver 2012; Eisenberg & Zhou 2016; Nigg 2017).

SR is characterized by processes or abilities to „determine a desired end state and to take action to move

Tab. 1. Linking the terminology of Self-regulation and other associated phenomena depending on the perspective on SR (McClelland *et al.* 2010)

Field of psychology	Terms related to Self-Regulation
Developmental psychology – studies of temperament	Effortful control and executive attention
Personality psychology	Ego control/resiliency
Clinical and developmental neuropsychology	Executive function
Cognitive psychology	Decision making
Educational psychology	Engagement
Educational and personality psychology	Motivation

toward it, while monitoring progress along the way" (Inzlicht *et al.* 2021, p. 320). However, the most comprehensive definition of SR is offered by Moilanen (2007, p. 835) as a process of "flexibly activating, monitoring, inhibiting, persevering and/or adapting one's behavior, attention, emotions and cognitive strategies in response to direction from internal cues, environmental stimuli and feedback from others, in an attempt to attain personally-relevant goals".

In order to capture the key aspects of SR, some authors postulated models of SR (Colombo *et al.* 2023). One of them is the ***Strength model*** of SR (Baumeister *et al.* 2018; Muraven & Baumeister 2000). It postulates three crucial factors necessary for successful SR: goals, motivation and sufficient capacity to resist these impulses and distractions— enabled by EFs (Hofmann *et al.* 2012). Despite scientific efforts, there is still much ambiguity in the definition of SR and the underlying associated constructs comprising SR (McClelland *et al.* 2010).

In terms of the definition of SR, it is useful to distinguish it from the construct of self-control. ***Self-control*** from a narrower, developmental, perspective is the ability of top-down coping to resist a stimulus-evoked response to execute a goal-relevant response (Diamond 2013). In a broader definition, based on a social perspective, it includes any intentional action that supports long-term adaptation (Fujita 2011) or any voluntary modification of responses (Baumeister *et al.* 2007) or voluntary self-governance (Duckworth & Kern 2011). Such a broader definition effectively simplifies self-control to the level of top-down processes of the SR. Nigg (2017) postulates that SR serves to link emotion with regulation when handling emotionally demanding tasks, while self-control serves to link cognition with control when handling cognitively demanding tasks. SR is a broader concept (Robson *et al.* 2020) referring to almost any self-selected and goal-directed behavior, while self-control is referring to overcoming salient but maladaptive impulses (Hofmann *et al.* 2012).

SR as a process that integrates emotions, cognition and behavioral aspects can be divided according to these areas. Cognition and emotion are integrated into the process of behavioral SR resulting in behavioral expression (McClelland *et al.* 2010). Nigg (2017) presents specific terms to designate ***SR of emotion***, ***action*** and ***cognition***.

Emotion regulation is often used to refer to the affective and emotional aspects of SR (Eisenberg & Sulik 2012). In this sense, it is regarded as a subdomain of self-regulation that focuses on how individuals monitor, modulate, and express their emotions, complementing attentional and behavioral regulatory processes. Cognitive SR is used in Cool regulatory processes involving conscious control of thoughts and behaviors, it is involved, for example, in planning, decision making, or problem solving (Zelazo & Müller 2002), whose origin and function belong to abstract or future-oriented events (McClelland *et al.* 2010). Cognition and emotion reflect two complementary, synergistic processes within the individual. Adaptive regulation involves the parallel coping of emotional cues with immediate salience and the alignment of cognitive resources to solve problems with prospective salience (McClelland *et al.* 2010).

The integrative aspect of EFs allows children to control and regulate their behavior, remember instructions, be attentive/focused, and complete tasks (McClelland *et al.* 2010). Strong cognitive skills, more specifically the ability to direct attention effectively, can mitigate the negative effects of poor emotional regulation. The interaction between an emotion and the regulation of that emotion determines a child's level of adaptation (Rothbart & Bates 2006). Howse *et al.* (2003) found that behavioral regulation was a stronger predictor of academic achievement than emotion regulation, suggesting that even children with weaker emotional regulation could perform well if their behavioral regulation was strong. According to Blair & Razza (2007) behavioral regulation in children is a significant predictor of achievement and social outcomes prior to schooling. Children with strong emotional reactions who can regulate their subsequent behavior do better compared to individuals with little ability to regulate their behavior (Eisenberg *et al.* 2004; Rothbart & Bates 2006). Finally, authors in the field of SR argue for the integration of cognition and emotion, including how these processes manifest into regulated behavior and action (McClelland *et al.* 2010), thus, behavioral SR.

SR is an essential strategy for effectively coping with ***life change*** and thus predetermines how an individual develops and adapts to the changing world and the personal, interpersonal and social challenges that will emerge throughout life (McClelland *et al.* 2010).

SR skills are essential for a child's school readiness and future success (Dent & Koenka 2016). Individual differences in SR predict school success (Graziano *et al.* 2007), social skills, physical health, well-being, internalizing and externalizing problems, as well as risky behaviors and unemployment (Allan *et al.* 2014; Eisenberg *et al.* 2024; Eisenberg *et al.* 2010; Hails *et al.* 2019; Moffitt *et al.* 2011; Robson *et al.* 2020). Difficulties with SR are further associated with school failure, gambling, violence, addictions, delinquency, or depression (Baumeister & Vohs 2004; Santostefano 2010), as well as psychiatric disorders (Nigg 2017; Robson *et al.* 2020) while different aspects of SR may be related to different outcomes in different ways (Morris *et al.* 2014; Wakschlag *et al.* 2014). For an extensive review of SR as a predictor of future outcomes see a metaanalytic review of Robson *et al.* (2020).

Risk factors for SR can include ***sociodemographically disadvantaged*** environments. Children from low SES (low socioeconomic status) families or families belonging to ethical minorities in the country perform worse not only in academic achievement or school readiness but also in SR (Dearing *et al.* 2006;

Howse *et al.* 2003) and vice versa children who possess low SR were vulnerable to many risk factors (Lengua 2002). Another risk factor are ***stressors*** in early childhood. Most of a child's early experiences require immediate and intense parental responses. Examples of such stressors include inconsistent parenting styles, frequent changes in relational figures, intense and frequent violence, abuse or neglect, or stimulus deprivation (Morales & Guerra 2006). On the other hand, stressful situations require young children to spend a great deal of time managing their emotions, leaving little time for the intellectual exploration and learning that a calm and stimulating environment allows (McClelland *et al.* 2010). Early negative environmental influence (poverty, violence, unreliability) can create a set of emotional, cognitive, and behavioral strategies in children that, while they may be adaptive for that particular environment, are maladaptive in new, mainstream environments such as the school classroom (Fenneman & Frankenhuis 2020; McClelland *et al.* 2010; Wesarg-Menzel *et al.* 2023).

Children exposed to accumulated risk may have a more difficult time developing adaptive self-regulatory strategies (Masten *et al.* 2005). However, from a developmental plasticity perspective, there are opportunities for change and growth across the lifespan (Lerner 2006). Evidence-based programs exist to promote SR and social-emotional skills (Liew 2011).

Self-Regulation and its contextual incorporation

SR can be viewed from the perspective of broader regulation, in the context of intrinsic and extrinsic elements of ***regulation*** (Eisenberg & Spinrad 2004). SR is referred to as an intrinsic regulation, which includes regulation of self and by self, and emerges increasingly during development (Eisenberg & Zhou 2016). Extrinsic regulation includes regulation of others and regulation by others. It has an impact on SR, particularly in early life (Cox *et al.* 2010) and also throughout development and adulthood (Gross 2015). It includes socialization, which influences children's improvement of cognitive and emotional skills that they use in SR through social factors and through motivation and goals (Robson *et al.* 2020), which shape the willingness to enact SR (Wesarg-Menzel *et al.* 2023).

SR is developmentally important and aids in the integrative organization of its components (Palacios-Barrios & Hanson 2018). Most developmental theorists support separating SR organization into two categories: ***top-down*** and ***bottom-up*** processes (Evans 2008; Evans & Stanovich 2013; Nigg 2017), although Nigg (2017) noted that even top-down and bottom-up are not absolutely distinct processes.

Bottom-up mechanisms involve responses that are automatic and reactive, usually immediate, or stimulus driven. Top-down operations refer to strategic/deliberative processes, which deliberate and controlled thoughts or actions that are used for problem-solving, planning, future orientation, and preparation to achieve an anticipated goal (Nigg 2017), and may assist in regulating emotions and modulating behavior in response to contingencies (Blair & Raver 2012). This is also why top-down components are referred to as EFs (Barkley 2012; Zelazo *et al.* 2003). Higher-order, top-down EFs, which are the constituents of SR, influence and are influenced by bottom-up, less volitional aspects of SR (Blair & Dennis 2010). These bottom-up aspects of SR include more automatic, less effortful processes associated with stress physiology, emotional arousal, and attentional focusing (Blair & Raver 2012; Calkins & Fox 2002), as well as homeostatic and allostatic mechanisms in response to stress, challenge, or novel information (Nigg 2017).

To illustrate both types of processes, Palacios-Barrios and Hanson (2018) created a model from a neuroscience-based perspective providing initial information about how aspects of SR are formed in the brain (Palacios-Barrios & Hanson 2018). The authors offer

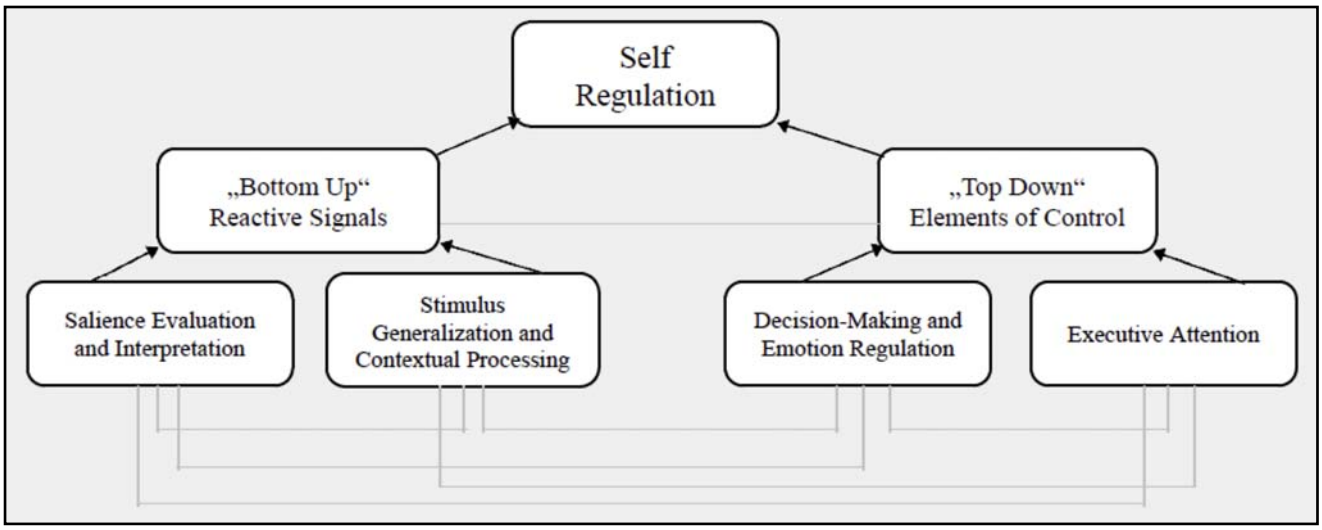

Fig. 1. Neurological view on top-down and bottom-up processes by SR. According to (Palacios-Barrios & Hanson 2018, p. 55)

a concept that originates from a focus on different brain circuits and divide the SR construct into top-down and bottom-up processes (Beauchaine *et al.* 2017; Casey 2015; Heatherton 2011), similar to the developmental approach. Considering the neurological model as well as theories of social information processing (Crick & Dodge 1994) and emotion regulation (Gross 2015), the authors described the following SR processes in Figure 1.

SR in top-down processes includes (1) executive attention and (2) response evaluation and emotion regulation. In bottom-up processes, SR includes the following two aspects: 1) salience evaluation and interpretation and 2) stimulus generalization and contextual processing. SR processes are hierarchically organized, with top-down and bottom-up components adding to a larger construct of SR (Palacios-Barrios & Hanson 2018). Salience evaluation and interpretation – refers to the rapid detection of whether a stimulus is relevant, threatening, or rewarding. This process is linked to subcortical structures such as the amygdala and the insula. Stimulus generation and contextual processing involve the production of initial responses and their adjustment based on contextual information and prior experiences. This process is linked to hippocampus and related limbic-prefrontal pathways. Decision-making and emotional regulation are linked to the ventromedial prefrontal cortex and limbic structures, while executive attention represents the capacity to control and direct focus toward goals while ignoring distractions is linked to anterior cingulate cortex and the dorsolateral prefrontal cortex.

Nigg (2017) proposed a more ***hierarchically complex view*** of the different functions involved in SR, where different aspects of SR are hierarchically arranged in relation to granularity, development and time. Low-level components assemble into high-level components. The model includes the distinguishing of aspects by variation in specificity (or granularity), coverage, in temporal focus, and in developmental emergence during child's development, as described by Diamond (2013) where lower-level operations such as response inhibition and WM promote the emergence of more complex operations like higher order EFs (Nigg 2017).

Nigg adds a hierarchical integration of aspects of SR, in the context of their different timeframes (goals or conflicts) (Duckworth & Gross 2014; Verbruggen *et al.* 2014). Figure 2 illustrates this hierarchy. In terms of time, immediate and very short-term conflicts or goals require the involvement of EFs - response inhibition and WM. Immediate stimuli activate immediate bottom-up valuation mechanisms (valuation mechanisms of reward or cost). Their strength is counterbalanced by top-down operations such as response inhibition. Short-term goals are also supported by EFs (lower-order EFs), such as WM, which are subsumed under cognitive control. As the time span increases, additional operations are added to the SR process. Medium and longer timeframes include higher-order EFs (strategy and planning) in the context of preparing for future conflicts or challenges. The long-term future is largely the domain of higher-order EFs. Thus, the time perspective provides a complementary way of organizing "lower" and "higher" order constructs. Cognitive operations (e.g., lower- and higher-order EFs but also cognitive control) may be used for other purposes, but they represent top-down aspects of SR at the cognitive level (Nigg 2017).

Nigg (2017) adds temperament and individual personality characteristics to the model. Bottom-up SR is particularly active in optimizing immediate and short-term response. Discounting the effects of time (impulsivity vs. reflection) and the likelihood of a situation occurring (risk vs. certainty) reflects a different combination of bottom-up and top-down processes depending on the species and specific timeframes. Higher-order personality traits are related to the tendency to use short- and long-term strategies and describe the typical biases of an individual's responses (e.g. *appetitive approach-extraversion; cost-avoidance-neuroticism; exertion of top-down control-EC*).

As a result, Nigg (2017) further divides top-down processes into: a) basic processes that develop early and address immediate conflict signals such as cognitive control and EC, and b) complex cognitions and strategies for future conflict resolution, which is the regulatory application of complex aspects of EFs (functioning).

Increases in the complexity of the cognitive control structures underlying SR abilities enable the increase of complexity of solvable problems (Diamond 2013; Zelazo *et al.* 2003). More complex SR abilities integrate the coordination among many simpler SR abilities and can provide a longer-term solution to a wider range of SR problems (Garon *et al.* 2008). Reorienting attention by distress is a simple ability of regulating it, whereas reappraisal is a more complex ability which requires WM to simultaneously hold and evaluate multiple appraisals of what caused the distress, and attention shifting and inhibitory control to enable the transition from the original to the new appraisal (De France & Hollenstein 2022).

Elements of Self-regulation

SR consists of a dual system of ***impulsivity*** and ***effortful control***. Based on Diamond's model (2013) Figure 3, we show the division of SR into components of effortful control and elements of inhibition.

Developmental studies considering neurocognitive models have established the link between effortful control and executive attention (Rueda *et al.* 2005), with attentional focusing and inhibitory control as common elements between EC and EFs (Liew 2011).

According to Nigg (2017), components of SR can vary in their developmental assembly and functional time course. For an extensive review of SR abilities

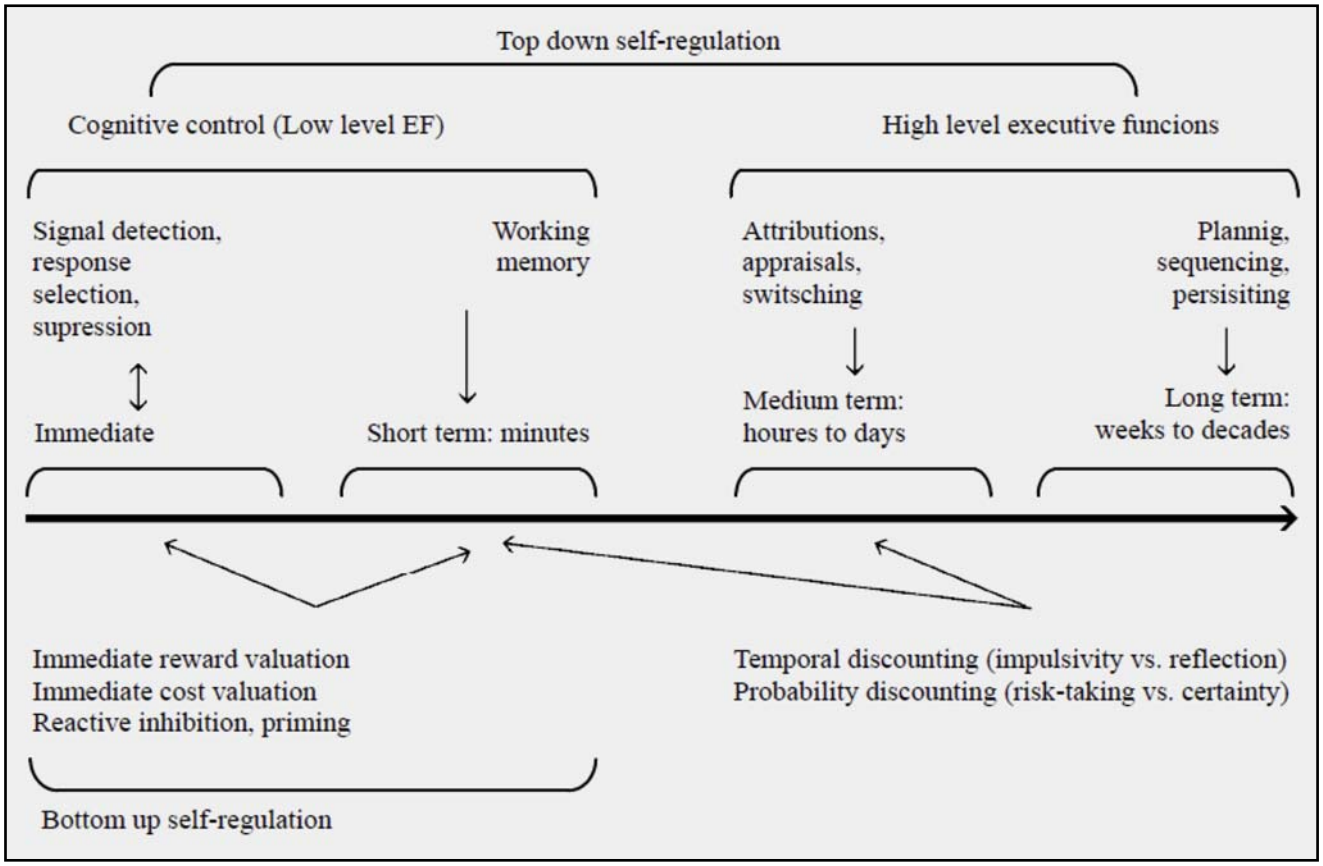

Fig. 2. Hierarchical model of top-down and bottom-up processes by SR (Nigg 2017, p. 375)

development see metaanalyses of Wesarg-Menzel *et al.* (2023).

Effortful control (EC) refers to an aspect of temperament (Rothbart & Bates 2006), although some authors are interpreting EC as a part of EFs (Diamond 2013; Fuster 2015) see Figure 3. EC is the innate ability to inhibit a dominant response or impulse to execute a subdominant response (Kochanska & Knaack 2003), i.e. the ability to regulate one's impulses and behavior, to motivate oneself towards a goal when there are conflicting desires, and to focus and shift attention easily (Atherton *et al.* 2020), thus is a predisposition for practicing SR (Diamond 2013). EC regulates emotional response, its constituent items include regulation of cognition and action as well (Nigg 2017).

EC refers to voluntary control over activation or inhibition of behaviors through attentional (***shifting*** and ***focusing***) and inhibitory control mechanisms (Eisenberg *et al.* 2010; Lengua *et al.* 2008; Liew 2011). EC involves following abilities to regulate dominant impulses (***inhibitory control***), to focus and shift attention when needed (***attentional control***), and to activate to pursue goals when there are competing desires (***activational control***) (Rothbart & Bates 2006), or to perform an action when there is a tendency to avoid (Evans & Rothbart 2007). Some of the EFs abilities involved in EC involve not only top-down regulatory processes: inhibitory control, attentional control (Eisenberg *et al.* 2024) similar to cognitive processes such as EFs (Pallini *et al.* 2018), but also motivational processes (i.e., activational control, goal attainment, persistence) similar to broader SR traits (Atherton *et al.* 2020).

According to Diamond (2016) EC is a predisposition to manage SR easily versus finding SR challenging. If SR is too strong, spontaneity may be absent.

Positive outcomes are associated with stronger EC (Kochanska *et al.* 2000; Rothbart & Bates 2006). EC involves deliberately overcoming what an individual wants to do in order to do what they ought to do (McClelland *et al.* 2010), that is why a stronger EC is a social advantage that is associated with stronger internalization of rules, a greater likelihood of responding positively even in the face of disappointment, and lower levels of aggression (Kochanska & Knaack 2003; Simonds *et al.* 2007).

EC and ***EFs*** conceptually overlap in part because attentional and inhibitory control mechanisms are central SR processes for both constructs (Liew 2011). EC is among the top-down aspects of SR, and, at the trait level, represents many of the cognitive control aspects of EFs, in particular executive attention (Nigg 2017). It has been suggested that the executive attention network underlies EC and that both networks predict emotion regulation in social situations (Simonds *et al.* 2007). The functions associated with ***executive attention*** overlap with the more general notion of EFs in

childhood, which includes WM, planning, switching, and inhibitory control (Welch 2001). All these capacities, together with the regulatory functions of the attentional systems seem likely to underlie EC (Rothbart & Rueda 2005; Rueda *et al.* 2004). Moreover executive attention has been described as an overt manifestation of EC (Rothbart & Posner 2005), which is related to cognitive or executive regulatory processes (McClelland *et al.* 2010). EC can therefore also be seen as somewhat equivalent to the efficiency of executive attention (Rothbart & Rueda 2005). EC, although stemming from executive attention, also adds other abilities as it develops (Rothbart 2011).

According to Nigg (2017), EC at the cognitive level maps onto cognitive control, i.e., the basic controlled operations that underlie complex cognition. Thus, in the context of SR, ***cognitive control*** may be synonymous with EC.

Inhibition and Impulsivity. According to Diamond's model (Diamond 2013, 2016) **elements of inhibitory control (IC) are important components of** SR, specifically, ***response inhibition*** – inhibition at the level of behavior (self-control and discipline) and inhibition at the level of attention (part of interference control) – ***inhibition at the level of attention*** (selective or focused attention) ***attentional inhibition***. ***Executive attention*** is a complete synonym with attentional inhibitory control (Diamond 2016).

Attentional inhibition represents ignoring competing stimuli to allow focus on goal-relevant information. In this sense, it is closely related to interference control and to executive attention. However, this top-down function is controversial; computational models suggest that inhibition may not be necessary to focus attention, as simple deactivation of competing signals may suffice. Although attention is not typically used in this way, it can also be inhibited by bottom-up signals (e.g., anxiety signals that divert attention away from the immediate stimulus and towards another stimulus) (Nigg 2017).

Executive attention is used to overcome attention to competing stimuli and to focus attention on stimuli relevant to the target. It is a form of top-down attention, similar to endogenous attention and focused attention (Nigg 2017). It is part of a cool EF - inhibitory control (Posner & DiGirolamo 1998; Rueda *et al.* 2005). Executive attention refers to the regulation of top-down attention (Diamond 2013).

Response Inhibition is a top-down ability to deliberately or effortfully inhibit the elicited behavior in order to keep the behavior moving toward a goal. It is a component of EC and EFs (Nigg 2000; Simpson *et al.* 2012). Response inhibition refers to the avoidance or interruption of a response-regardless of discounting, the strength of the stimulus, or the context of the decision (Aron *et al.* 2004; Simpson *et al.* 2012). It is closely related to inhibition switch, in which one action is replaced by another. It is an early developing component of top-down aspects of SR (Diamond 2013). Inhibition is closely connected with impulsivity (Tan & Lumeng 2018) and response inhibition is a component of impulsivity as well as a component of compul-

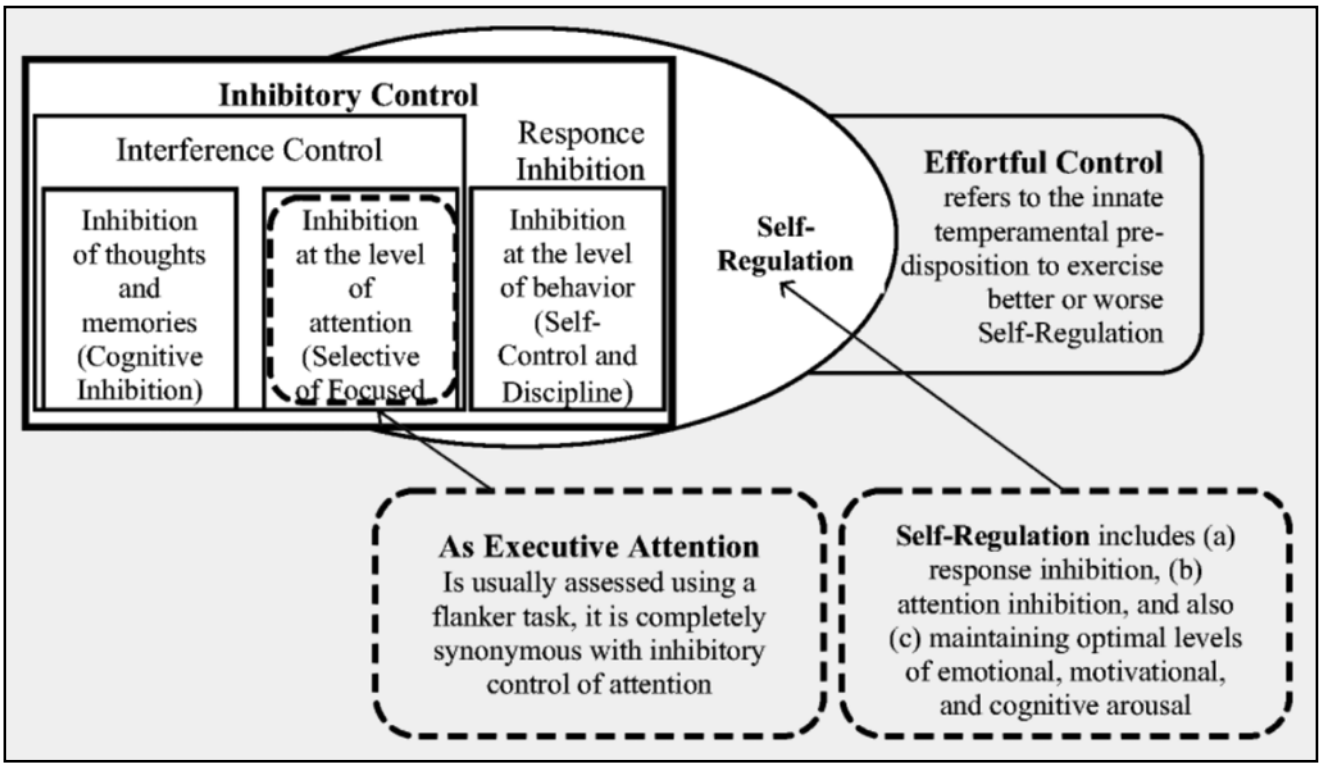

Fig. 3. Components of SR according to Diamond. According to (Diamond 2016, p. 16)

sivity. In the case of cue-activated automatic behavior, disinhibition and impulsivity are the same. Other cases of impulsivity include discounting of delayed rewards and are not reducible to disinhibition. In spite of that, response inhibition is often incorrectly confused with impulsivity (Nigg 2017).

Impulsivity is a rapid, unplanned response that occurs without adequate reflection on consequences, even when a later, goal-relevant rewarding response is available. It can be adaptive or maladaptive depending on the context and the degree of inflexibility when the context changes. It is mediated by bottom-up processes (e.g. spontaneous reward appreciation/or discounting) and top-down processes (e.g. bias from previous goals; response inhibition). The second meaning of impulsivity is a non-reflective choice or preference for an immediate rewarding response (motivational decision-making style), e.g. where immediate reward is the priority. In this case, impulsivity is more than just disinhibition, because it also reflects (implicit and explicit) consideration of immediate and delayed reward. It is modulated by both processes: bottom-up by reward valuation (part of the motivational system) and top-down by goal-related bias. In particular, the immediacy of the reward, not just its earlier acquisition, is what elicits a different response system (Mitchell *et al.* 2015). Impulsivity in this context depends on mental calculations involving the factor of time (Nigg 2017).

Development of Self-regulation

The development of SR is a dynamic, multilevel and interactive process throughout life. SR develops in critical periods from early childhood to adulthood (Nigg 2017) with the most significant growth in the early to middle years of childhood (Raffaelli *et al.* 2005). Each person is an active agent in the development of their SR (McClelland *et al.* 2010). In general, early SR is characterized by external regulation by others, and later develops into internalized SR (Kopp 1991). Development of SR has a non-linear trajectory and takes place gradually, through a hierarchical, cascading process. Low-level abilities integrate into more complex abilities in accordance with the development of physical and neurological systems and the gradual internalization of control during childhood (Cox *et al.* 2010; Masten & Cicchetti 2010).

SR skills develop rapidly in toddlers and preschoolers (Rothbart & Bates 2006). Early indicators of rudimentary SR or precursors of EC are identified already in young children (Eisenberg & Sulik 2012).

Children's ***cognitive development*** has a significant impact on their SR (McClelland *et al.* 2010). Improvements in the complexity and coordination of EFs enable children to solve more complex SR problems (Wesarg-Menzel *et al.* 2023). Aspects of EFs that are also part of or related to EC improve in ***infants and preschoolers*** (Garon *et al.* 2008). Infants can sustain attention by 8 to 10 months of age (Kochanska *et al.* 1998, 2000) and by 9 to 18 months of age, attention becomes more voluntary (Ruff & Rothbart 2001). Furthermore, attentional switching and behavioral inhibition improve in toddlers by 30 months and reach high levels of accuracy around 36 to 38 months (Posner & Rothbart 1998).

Inhibitory control of behavior typically emerges from 24 to 36 months of age (Gerardi-Caulton 2000) with a marked increase in performance (EC) between 22 and 33 months of age and EC being higher in girls. Whereas better EC at 22 months was associated with greater anger regulation and at 33 months with more regulated anger and joy and with stronger restraint (Kochanska *et al.* 2000). The ability to inhibit behavior in response to one stimulus and activate behavior in response to another stimulus improves between 3 and 4 years of age (Jones *et al.* 2003). Similarly, from 2 to 4 years of age, the time during which children can wait for a reward increases (Carlson *et al.* 2005; Li-Grining 2007).

In the late ***preschool and early school-age*** (3.5 – 7 years of age), there is further improvement in EC and EFs (Carlson *et al.* 2005; Diamond *et al.* 1997). EC continues to improve throughout the school years and at a slower rate into adulthood (Crone *et al.* 2006; Leon-Carrion *et al.* 2004). SR processes also develop during ***adolescence*** (Eisenberg & Sulik 2012), but may take different forms or include different processes compared to SR during childhood transitions. Asynchronous, non-linear development in various aspects of SR, is moderated by the context of emotions (Casey 2015; Cohen *et al.* 2016), but also by stage of formal operations in adolescence (12-15 years) (Bronson 2001). This process includes intentionality and emotion (Fox & Riconscente 2008; Piaget 1968). When children enter the stage of formal operations, they are increasingly able to deliberately control their thoughts and actions, organize and systematically solve problems (Gestsdottir & Lerner 2008). They develop not only planning skills but also their higher-order cognitive processes, which are involved in assessing important life dilemmas. Goal-seeking and motivation become increasingly important during adolescence (Gestsdottir & Lerner 2008).

The influence of several ***biological*** (temperament) and ***environmental factors*** (family, teachers, peers) even including home physical environment (Bagais & Pati 2023), and affects the development of SR from infancy (McClelland *et al.* 2010). One of the biological factors influencing the development of SR is ***temperament***. Temperament affects the way emotions are expressed, but also the way one interprets the emotions and behavior of others. The way a child expresses his emotions and behavior causes different reactions from parents. Parents' reactions to the child's behavior play a role in the formation of attachment. Secure attachment is an important predictor of SR (Calkins 2004).

In childhood, SR begins to develop in the family environment, even though infants and toddlers are able to learn emotion regulation also through peer interactions (Pahigiannis & Glos 2020). In the early and

preschool years, parents play a significant role in shaping the development of SR by creating a supportive environment that provides opportunities for decision-making and practicing SR. During adolescence, parental influence becomes less direct and adolescents themselves play a more active role in their own decision-making and SR (McClelland *et al.* 2010) due self-selection of peers and contexts (Wesarg-Menzel *et al.* 2023).

The ***preschool*** environment is one of the first environments in which children are exposed to peers and a structured environment in which they are required to self-regulate (Phillips *et al.* 2006). In the preschool-age (3-6 years of age), there are also many changes that facilitate the development of SR (Blair 2002). SR is important for achieving success in ***kindergarten*** but also throughout ***elementary school*** (Howse *et al.* 2003; McClelland *et al.* 2006). Considerable variability has been found in the SR skills of children entering kindergarten (Lin *et al.* 2003). Specific aspects of SR (attention, WM, and inhibitory control) are necessary for children to develop positive behaviors in the classroom context (McClelland *et al.* 2010).

Measurement of Self-Regulation

The way SR is measured depends on the phenomenological level of regulatory processes from internal (biological/physiological) to external (social behavior). We can measure one level, but also multiple processes at the same time. Studies (Gross & Levenson 1993) point to the fact that regulation at one phenomenological level (behavioral - facial expression) may affect regulation at another level (physiological). Thus, the measurement of SR may vary not only from level to level but also from the way internal and external processes are captured (McClelland *et al.* 2010).

SR is mainly inferred from data collected from the child, observations of the child and from third parties commenting on the child's SR (parent/guardian, teacher) (Block 2008). The different measurement options are clearly represented by the ***multidimensional approach*** to measuring SR (McClelland *et al.* 2010). It is based on three dimensions of conceptual viewing SR (Figure 4). The first dimension represents what is being measured. It is depicted on the Y-axis (ascending) as a typification of SR from a phenomenological perspective. The second dimension on the X (horizontal) axis expresses the context of the environment where the measurement took place. The third dimension corresponds to the procedure of how the SR is measured and is represented in windows of different intensities of grey. The white windows show the data obtained directly from the individual (child), the light grey ones

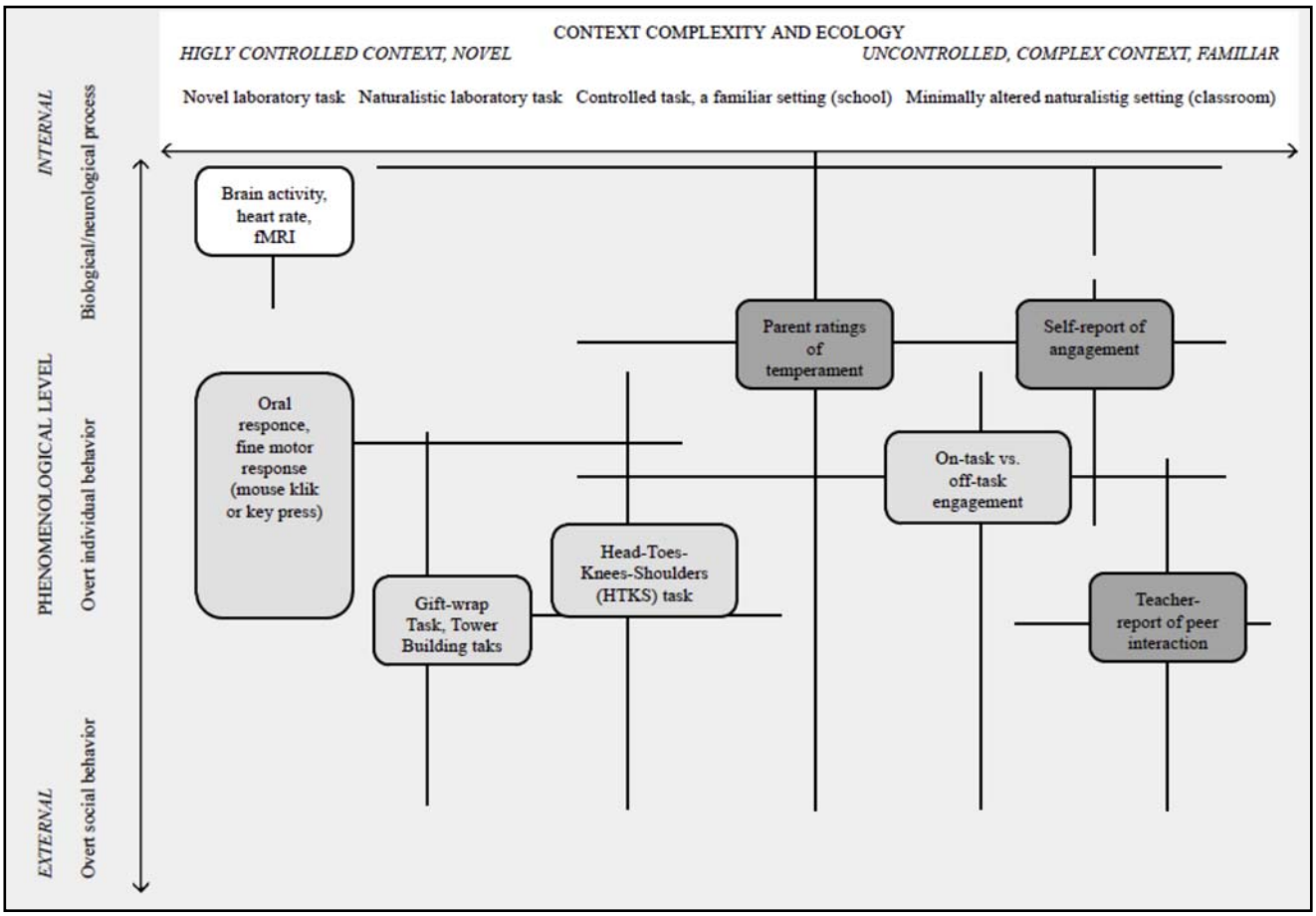

Fig. 4. Dimensional approach of measurement of SR (McClelland et al. 2010, p. 532)

depict the observed report. Figure 4 shows also the "whiskers", which illustrate the variability of the instruments at the phenomenological levels they measure and in the settings in which they are relevant. Measurement instruments with longer "whiskers" implicitly or explicitly measure SR across multiple dimensions of phenomenological level and/or context. On the left, the methods are situated in highly controlled and novel laboratory contexts (e.g., fMRI, structured tasks). On the right, the methods reflect complex context, such as everyday familiar settings. Vertical axis represents phenomenological level: from down - overt social and individual behavior to top - inner biological and neurological processes.

A relatively newer method, the Experience Sampling Method (***ESM***), helps to understand moment-to-moment regulatory decisions in everyday life (Shernoff *et al.* 2003). Another trend in interactional measurement of SR is the Head-Toes-Knees-Shoulders game (***HTKS***), which measures the regulation of overt behavior and also activates attention, WM, and inhibitory control (Cameron Ponitz *et al.* 2008). A simpler version of the Head-Toes Task (***HTT***) has also been used (Wanless *et al.* 2011).

The most advanced type of intrinsic measurement of SR is at the level of physiological and neurological processes (McClelland *et al.* 2010). These typically involve the **autonomic nervous system (ANS)** and its parasympathetic branch, as well as central nervous system indicators. Measures such as **heart rate variability (HRV)** and **respiratory sinus arrhythmia (RSA)** are widely used as non-invasive markers of parasympathetic nervous system (PNS) activity (Porges *et al.* 1994). RSA, which reflects vagal modulation of the heart via the vagus nerve (Porges 2007), is often interpreted as an index of self-regulatory capacity. When measured at baseline, RSA indicates dispositional levels of parasympathetic activity (El-Sheikh 2005).

In addition to autonomic markers, **event-related brain potentials (ERPs)** provide insight into the neural dynamics of self-regulation. For instance, the **P300 component** - a positive deflection in the ERP waveform has been associated with attentional allocation and the updating of WM.

Although psychophysiological variables provide a different view of regulation than other methods, it is not clear yet to what extent psychophysiological responses reflect the processes involved in emotion regulation. Physiological responses often use a combination of reactivity and regulation. However, there are multiple ways in which people regulate their emotions (Gross 1998) including cognitive strategies (e.g., distraction) and response modulation (e.g., attempting to control behavioral responses), and these may differ in which physiological responses are associated with them (Eisenberg & Sulik 2012).

In the interpretation of the results, it is also important to consider the context of the measurement, as well as the individual characteristics of the children interacting with the context. For example, a child's gender may predict SR in some types of contexts. Boys are more successful on information processing speed tasks compared to girls (Brocki & Bohlin 2004), and in contrast, girls are more successful at SR at school and at home compared to boys (Vitaro *et al.* 2005). The influence of cultural context is also important. Asian children outperform Western children in the strength of inhibitory control (Oh & Lewis 2008; Sabbagh *et al.* 2006) as an important aspect of SR. Any observation needs to account for observer bias and subsequent inter-observer differences (Mashburn *et al.* 2006), but also for the possibility that internal processes of SR are not manifest in the child's immediate behavior (Fredricks *et al.* 2004). It may be most useful to use data from a variety of measurement sources: parents and teachers, self-assessments, and direct measures to best capture SR across multiple phenomenological levels and contextual dimensions (McClelland *et al.* 2010).

Link between EFs and Self-regulation

While SR tends to be defined as a broader concept (Blair 2016; Blair & Dennis 2010) due to its implications for situational functioning in the real world (Bronson 2001), EFs are generally viewed as the primary cognitive processes contributing to an individual's SR (Barkley 1997). Nonetheless, how closely the constructs of EFs and SR are linked is not clearly defined (Garon 2016).

Most theories of EFs primarily view ***top-down*** aspects of SR (Diamond 2013; Miyake *et al.* 2000; Zelazo & Carlson 2012; Košíková *et al.* 2024). Miyake's *et al.* model of EFs (Miyake & Friedman 2012) contains partially dissociable components, but they share a common underlying process. The authors focused on three Cool EFs that primarily involve top-down regulation: WM updating, response inhibition, and shifting. These Cool EFs support important mechanisms in an individual's self-regulatory goal pursuits (Hofmann *et al.* 2012) see Table 2

WM, traditionally viewed as a 'cool' cognitive concept, may be implicated in the regulation of 'hot' processes such as unwanted emotional experiences, desires, and cravings (Hofmann *et al.* 2012). But these need not be only Cool EFs processes. Casey (2015) noted that computationally, emotion is another type of information on which top-down cognition operates.

However, some authors refer EFs to any type of regulation that is adaptive to the individual, including ***bottom-up*** mechanisms such as activation and arousal (Tucker *et al.* 1995). Similar models of EFs, that include Hot processes and divide EFs into ***Hot and Cool EFs*** emphasize bottom-up regulation (Zelazo & Cunningham 2007). Hot EF is top-down processing (including regulation) of emotional or incentive signals (Zelazo & Carlson 2012; Zelazo & Müller 2002). It is ambiguous whether it has any different meaning than top-down SR of emotion - but it serves to emphasize

Tab. 2. Connection between EFs and SR mechanisms (Hofmann *et al.* 2012, p. 175)

EFs	SR mechanisms
WM updating	• Active representation of self-regulatory goals and standards. • Top-down control of attention toward goal-relevant information and away from attention-grabbing stimuli. • Shielding of goals and standards from interference. • Suppression of ruminative thoughts. • (Down-) regulation of unwanted affect, desires, and cravings.
Behavioral inhibition	• Active inhibition of prepotent impulses and habitual, 'mindless' behaviors.
Task-switching (Cognitive control)	• Flexible switching between different means subserving the same (self-regulatory) goal ('means-shifting'). • Switching between multiple goals ('goal-shifting/balancing').

that EFs are involved in regulating emotion. Cool EF is top-down processing (including regulation) of salient information signals that have minimal incentive and/or emotional intensity (Nigg 2017).

As another example of bottom-up processes Garon (2016) points to reflective thinking as central to EFs, and the process of iterative reprocessing, which allows lower-level representations to be reworked into more abstract representations. Higher levels of processing are thus dependent on the lower level processes that take place bottom up. Blair (2016) distinguishes between bottom-up regulatory processes and top-down effortful processes whereby those bottom-up processes are relevant to the regulation of top-down processes (Blair 2016; Garon 2016), where SR involves both types of processes and EFs involve only top-down regulatory processes (Garon 2016).

Looking at SR through the differentiation of EFs in Hot and Cool EFs represented by ***Garson's model*** (2016) Figure 5, the Hot and Cool regulatory processes that serve SR, manifest some similarities and differences (Garon 2016): 1.) The first similarity is that both Hot and Cool EFs contain both top-down and bottom-up processes. The Hot EFs in this model are Delay of Gratification (DoG) and advantageous decision making (ADM), while the Cool EFs are WM, set shifting and response inhibition. Hot bottom-up regulatory processes are, for example, "formation of a stimulus-value set" or "formation of a response-value set" and Cool bottom-up regulatory processes are "formation of an attention set" and "formation of a response/response set" are typically not considered EFs (Garon 2016). 2.) The second similarity is conflict regulation. Hot EFs tasks involve resolving conflicts related to motivation, whereas Cool EFs tasks involve resolving conflicts related to cognition, behavioral responses, or both (Garon *et al.* 2008). 3.) A third similarity involves the dependence of both types of EFs on representations in long-term memory (see Figure. 5), each, however, relies on a different kind of representation.

On the other hand, within SR processes, differences between Hot and Cool EFs can also be outlined. Cool EFs use stable long-term memory but although the WM (Cool EF) may be involved in activating and strengthening associations in long-term memory (Blumenfeld & Ranganath 2007), they do not alter these long-term representations. In contrast, the representations used by Hot EFs are more plastic (Damasio 1994). Hot EFs are actively involved in learning and creating new value-based representations (Murray *et al.* 2015; Pujara *et al.* 2016). The use of this type of plastic representation allows for faster and more variable responses to environmental changes (Garon 2016).

The second difference between Hot and Cool EFs is their position in the EFs processing hierarchy (Zelazo 2015).

In Figure 5, Cool EFs are positioned at a higher level than Hot EFs. As a result of this arrangement, networks of Hot and Cool EFs can participate in solving the problems of Hot EFs. Whereby the degree of their involvement varies depending on the type of task (Garon 2016).

Aspects of Hot EFs are a significant part of the SR. Also in the past, behavior in "hot" contexts has been predominantly studied in terms of SR, a construct that overlaps with executive functioning (Kryza-Lacombe *et al.* 2021) building on the concept of the continuum of Hot and Cool EFs (Zelazo & Carlson 2012; Zelazo & Müller 2002). It is not surprising that inhibitory control (IC) that was originally exclusively part of Cool EFs can now be characterized as either "hot" or "cool" (Lui *et al.* 2021). Hot IC serves in more emotionally salient contexts (Zelazo & Carlson 2012), such as the ability to resist temptation (e.g., delay of gratification or following a prohibition given by an adult). Hot IC has previously been linked to regulatory behaviors, such as the ability to self-soothe and modulate emotional arousal (Kochanska *et al.* 2000; Rothbart *et al.* 2006). Thus, SR may be viewed as having a notably strong "hot" IC component (Di Norcia *et al.* 2015; Kim *et al.* 2013).

Current theoretical discussions continually further explore the conceptual overlap between constructs such as SR, Hot EFs and EC (Welsh & Peterson 2014). Moreover, EFs measures, developed in cognitive psychology, contribute to SR outcomes in theoretically meaningful ways as predictor, as process moderator, or as process mediator (Hofmann *et al.* 2012).

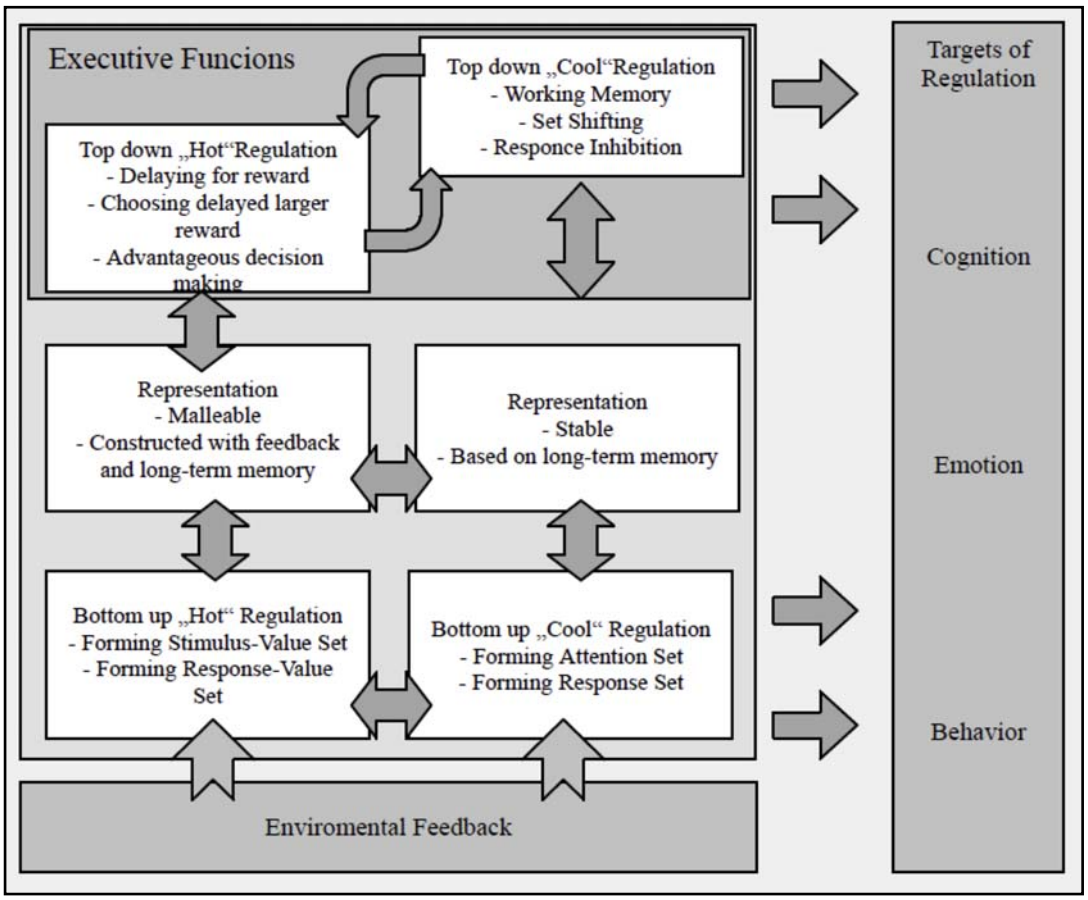

Fig. 5. Model of Hot and Cool EFs in top-down and bottom-up processes of SR (Garon 2016, p. 71)

Development of EFs and Self-regulation

The development of ***Cool EFs*** accelerates faster than that of ***Hot EFs***. The enhancement in performance of Hot EFs seems to be achieved at an age when Cool EFs are already stable (Prencipe *et al.* 2011; Zelazo & Carlson 2012). Age-related improvements in Hot EFs not only appear to occur later, but are also more moderate than those in Cool EFs, supporting the theory of different developmental 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, whereas the developmental trajectory of Hot EFs has a non-linear, inverted "U" - bell shape during this period (Poon 2018). The current findings provide further evidence of a Hot-Cool distinction in EFs in middle childhood (6-12 years of age), suggesting that these constructs should be investigated separately when assessing EFs (Wilson *et al.* 2022).

In standard development, the foundations of Cool ***EFs*** are being laid by the age of three years. In this age, these executive abilities are named the „general executive processes" and refer to a single undifferentiated skill (Wiebe *et al.* 2008). After the 3rd year of life, qualitative changes occur. After the 4th year of age, EFs begin to differentiate more into inhibition and WM (Jurado & Rosselli 2007). At the end of the preschool-age, EFs differentiate into three basic interrelated processes: inhibition, WM and cognitive flexibility (Isquith *et al.* 2004). The largest progress in shifting, inhibition, and selective attention was observed between the age of 8 and 10 years with a plateau in performance between 10 and 12 years (Klimkeit *et al.* 2004).

Children's cognitive development has a significant impact on their ***SR development*** (McClelland *et al.* 2010). It is understandable from the essence of the basic components of SR consisting of EC and inhibition. SR is usually assessed using measures that integrate ***inhibitory control***, ***executive attention***, and ***WM*** (McClelland *et al.* 2007), but naturally also through ***EC*** (Eisenberg & Sulik 2012). ***EC*** contains components of EFs as ***shifting, focusing, inhibitory control*** (Eisenberg, Spinrad, *et al.* 2010; Lengua *et al.* 2008) and ***attentional control*** (Rothbart & Bates 2006). ***Executive attention*** is related to cognitive or executive regulatory processes (McClelland *et al.* 2010) and has also been described as an overt manifestation of EC (Rothbart & Posner 2005), EC can therefore also be seen as somewhat equivalent to the efficiency of executive attention (Rothbart & Rueda 2005). Clearly EC and ***EFs*** conceptually overlap in part because attentional and inhibitory control mechanisms are central SR processes for both constructs (Liew 2011).

The above context suggests that the ***developmental trajectories of EFs and SR*** are similar. The question remains whether the developmental trajectory of SR

follows the developmental trajectory of EFs. We assume that when EFs and SR are investigated on a behavioral basis the two variables will correlate. The likely reasons for this are environmental influences and the desire to behave in a socially appropriate/desirable manner (Hofmann *et al.* 2012; Liew 2011).

On the other hand, when using performance tests, the correlation is not clear. The results obtained in performance tests for EFs show low correlations with the results from behavioral rating (Hagen *et al.* 2016; Pino Muñoz & Arán Filippetti 2021) and similar to SR (Nigg 2017). A laboratory-based observations, computerized reaction time and accuracy tasks, and rating scales have weak intercorrelations (McAuley *et al.* 2010), although coherent patterns can be identified (Duckworth & Kern 2011).

Link between EFs and Self-regulation in context of motivation and temperament

To examine the overlap and possible differences between SR and EFs entirely, some other significant constructs influencing SR and EFs have to be taken into account, namely motivation and temperament.

SR can be regarded as a broader regulatory framework that not only includes cognitive mechanisms typically associated with EFs, but also extends into motivational and emotional domains. While EFs are instrumental in describing the cognitive structure of self-control - such as WM, inhibitory processes, and cognitive flexibility - these functions do not sufficiently address the ***motivational forces*** or environmental contingencies that influence regulatory behavior in real-world settings. For instance, Eberhart *et al.* (2024) observed that children demonstrated more consistent self-regulatory behavior during child-led activities than in teacher-directed ones, highlighting the influence of situational autonomy and context.

Similarly, Wesarg-Menzel *et al.* (2023) emphasize that cognitive assessments alone cannot fully capture children's adaptive functioning. Though EFs represent essential cognitive skills, they do not explain how these are selectively activated in emotionally salient or socially complex scenarios. In response to this limitation, Wesarg-Menzel and colleagues proposed a dual-pathway model of SR development: one emphasizing adult scaffolding (the Ability Pathway), and the other focusing on children's internal motivational states and goal orientation (the Goals and Motivation Pathway). This approach underlines the need to conceptualize SR as a construct that, while related to EFs, includes distinct motivational and contextual dimensions.

The role of motivation is especially critical in this distinction. Whereas EFs refer to what individuals are capable of doing from a cognitive standpoint, SR accounts for why - and under which circumstances - those capabilities are enacted. Duckworth *et al.* (2019) articulate this by framing motivation not as an auxiliary factor but as a central mechanism that initiates, sustains, and directs regulatory behavior in alignment with personally meaningful goals.

On the other hand, there is a common biological basis for SR and EFs. As we stated before, EC is an element connecting EFs, SR and ***temperament***. Temperament is a neurophysiological construct which can be defined as constitutionally based individual differences in reactivity and regulation (Rothbart *et al.* 2001). Reactivity is supported by ANS, which contributes to physiological arousal and responsivity, while regulation reflects higher-order processes that enable modulation of this reactivity (e.g., shifting attention away from a frustrating stimulus; Eggers 2023). Thus, ANS activity forms an important biological substrate of temperament, but temperament as a construct extends beyond autonomic processes to include central neural mechanisms (CNS) involved in attention and emotion regulation.

Temperament manifests itself in the area of the activation level, at the vegetative level, in reactions to various stimuli, in emotional experience, attention and influences the reactivity of emotionality, motor skills, attention, and SR (Simonds *et al.* 2007), thus naturally determines the likely style of response to stimuli (Procházka 2016). Temperament is relatively consistent across situations (from infancy to early school-age) (Kopala-Sibley *et al.* 2018; Procházka 2016; Rothbart & Bates 2006). As a construct, temperament contains executive attention (Cool EF), SR, and an emotional affective component (Hot component).

Temperament mediates emotional regulation through the ability to suppress or activate behavior based on the evaluation of the situation (Procházka 2016) and influences how SR develops (Duckworth *et al.* 2013; Mittal *et al.* 2013). The most frequently examined temperament component in relation to SR is EC (Rothbart & Bates 2006). Research shows that considering potential interactions between temperament and EFs can help to predict a broad categories of psychological problems in middle childhood (Wilson *et al.* 2022).

Conclusion

The concept of Self-regulation (SR) is very broad. SR is a construct that can be viewed from several ***perspectives*** in different fields of psychology. Depending on the perspective, the concept of SR varies. In this paper we focus on temperamental and cognitive-neurological perspective.

SR is ***defined*** as a multidimensional construct that includes emotions, cognition and behavior (McClelland *et al.* 2010; Schütz & Koglin 2023), and as a coherently integrated and hierarchically organized set of domain-specific control mechanisms (Blair & Raver 2012). SR integrates top-down and bottom-up regulatory processes (Nigg 2017) to control dominant impulses (Robson *et al.* 2020). SR is an essential strategy for effectively coping with life changes and thus predetermines

how an individual develops and adapts to the changing world and the personal, interpersonal and social challenges that will emerge throughout life (McClelland *et al.* 2010).

We present SR using the model of a ***dual system*** of impulsivity and effortful control (EC). Impulsivity is a nonreflective stimulus-driven action (Nigg 2017). EC is the inherent ability to inhibit a dominant response or the impulse to execute a subdominant response (Kochanska & Knaack 2003), and is one of the top-down aspects of SR, and represents many of the cognitive control aspects of EFs, especially executive attention (Nigg 2017). This conceptual overlap arises because attentional and inhibitory control are central to both SR and EFs (Liew 2011).

The ***development*** of SR is influenced by many biological (temperamental) and environmental factors that arise during the development of children. Naturally, the development of EFs in children (Hot and Cool) has a significant impact on their SR development (McClelland *et al.* 2010). While cognitive growth is essential, SR is also deeply rooted in the social and environmental context in which a child grows up. Recent research by Howard *et al.* (2021) provides compelling evidence of a reciprocal relationship between EFs and SR, suggesting that these capacities not only develop together but also influence one another across early childhood.

Risk factors for SR can include socio-demographic disadvantaged environments (Dearing *et al.* 2006; Howse *et al.* 2003) and stress factors, such as inconsistent parenting styles, frequent changes in relational figures, intense and frequent violence, abuse or neglect, or stimulus deprivation (Morales & Guerra 2006). Children with accumulated risks may have difficulties developing adaptive self-regulatory strategies (Masten *et al.* 2005)

Measuring SR requires consideration of regulatory processes operating on multiple levels, from internal biological and neurological mechanisms to externally observable behaviors. However, studies have shown that performance-based assessments of SR and EFs often correlate only weakly with behavioral rating scales (Hagen *et al.* 2016; Nigg 2017; Pino Muñoz & Arán Filippetti 2021). A similar pattern emerges across different methodologies: lab-based observations, computerized tasks, and rating instruments typically exhibit limited intercorrelation, despite some consistent findings (Duckworth & Kern 2011; McAuley *et al.* 2010). These discrepancies suggest that various assessment tools may tap into distinct, context-specific facets of SR and EFs. As such, a comprehensive understanding of regulatory functioning requires an integrative approach - one that combines both objective performance measures and subjective behavioral evaluations across settings.

One of the key challenges in conceptualizing ***SR*** lies in its considerable ***overlap with EFs***. Although both constructs have common biological basis in ***temperament*** and share several underlying processes - particularly attentional control and inhibition - it remains useful to distinguish them, particularly in developmental contexts. This separation provides greater clarity in understanding the unique pathways through which SR and EFs contribute to behavioral regulation over time.

Since SR is a broader concept than EFs, it includes ***motivational*** aspects in addition to cognitive structures. Motivation activates the child's self-regulatory abilities in emotionally significant situations and in the fulfillment of important goals.

This ***review summarizes*** the broad knowledge about the construct of SR, its processes, contextual interactions between top-down and bottom-up processes, elements, development and measurement, as well as connections with EFs and their mutual developmental trajectories and possible ways of measuring them. SR is an integrating construct containing not only the elements of EFs (Hot and Cool), motivation, but also the elements of temperament. These relationships and mutual overlaps of constructs can lead to the exploration of new connections and clarification of the contours of the concepts. In this way, we would like to contribute to the discussion on the relationship and interconnection of developmental trajectories of SR and EFs also in the context of other key phenomena such as motivation or temperament. Naturally, knowledge about the processes and development of SR allows to extend the possibilities and effectiveness of early intervention elements for the development of SR. It is an opportunity for science to be translated into practice, which can hopefully help to improve children's quality of life.

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All authors express their consent with publication of the article.

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