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Self-regulatory abilities as predictors of scientific literacy among children in preschool and primary school years

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ABSTRACT

Previous evidence suggests that early self-regulation is related to the development of scientific literacy (SL) at preschool and primary school age. However, how (emotionally neutral) executive functions and the more emotion-related facets of self-regulation associate with early SL development remains largely unexplored. Drawing on data from 1,931 children and their parents from a German longitudinal cohort study, the study analysed various facets of self-regulation and unravelled their associations to early SL development at the ages of 5 to 7, while controlling for important child and family factors. The results indicated that inhibitory control and phonological working memory are related to SL at both ages. Furthermore, the effect of these facets on later SL remained significant even after controlling for earlier SL, while the effect of children's parent-reported effortful control on later SL at age 7 was completely mediated by earlier SL at age 5.

Educational relevance and implications statement

This research explores the associations between children's early self-regulation and the development of scientific literacy from preschool to primary school years. In particular, it considers both (emotionally neutral) executive functions (inhibitory control, cognitive flexibility and phonological working memory) as well as indicators of the more emotion-related facets of self-regulation (i.e., children's parent-reported effortful control and delay of gratification). We found inhibitory control and phonological working memory to significantly predict the development of scientific literacy (SL) in preschool and primary school years. Also, the parent-reported effortful control measure related to SL at age 5, but – contrary to inhibitory control and working memory – did not predict SL at the age of 7 when important controls were considered or changes in individual differences in SL were addressed. Furthermore, its effect was completely mediated by SL at the age of 5. Based on these results, intervention focusing on strengthening self-regulation and SL competences could be considered.

1. Introduction

Self-regulation represents "the internal and transitional processes that allow individuals to guide themselves in goal-directed activities" (Karoly, 1993, p. 25). They develop rapidly in preschool years (Kälin & Roebers, 2021) and become increasingly differentiated in the early school years (Schmidt et al., 2022). Despite different, partially overlapping conceptualizations and research traditions, integrated models of self-regulation comprise, among others, (emotionally neutral) executive functions (EF) as well as the more emotion-related facets of self-regulation (Jones et al., 2016). The (emotionally neutral) EF facet involve, among others, the cognitive processes (including inhibitory control, cognitive flexibility, and, e.g., verbal working memory) which modulate attention, control and goal-directed behaviour (Bailey & Jones, 2019). The more emotion-related facets of self-regulation are particularly addressed in research on effortful control (EC) rooted in temperament research (Rothbart et al., 2000) and in research on the delay of gratification (e.g., Jones et al., 2016; Mischel & Gilligan, 1964; Zelazo & Carlson, 2012), among others. These distinct yet unified facets of self-regulation are considered important for children's academic success (Frechette et al., 2021; Jones et al., 2016) which was also shown empirically, for example, in the domains of mathematics and reading in preschool and primary school age (Blair & Razza, 2007; Brock et al., 2009; Nakamichi et al., 2022; Willoughby et al., 2011). Furthermore, recent research suggests that early self-regulation is also relevant for developing scientific literacy (SL), for example for processes of scientific concept formation, hypothesis testing and revision (Gropen et al., 2011;

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Morgan et al., 2016; Saçkes et al., 2011; Vaughn et al., 2020). Yet, most studies – especially in the preschool (Anthony & Ogg, 2020; Bauer & Booth, 2019; Frechette et al., 2021; Fridman et al., 2020; Kim et al., 2021; Nayfeld et al., 2013) and primary school years (Anthony & Ogg, 2020; Kim et al., 2021; Morgan, Farkas, Wang, et al., 2019; Morgan, Farkas, Hillemeier, et al., 2019; Zaitchik et al., 2014) – have focused on the role of the (emotionally neutral) EF facets, leaving the association of the more emotion-related facets of self-regulation with SL largely unexplored. Given the importance of SL in recent research and the early emergence of individual differences in SL in preschool age (Kähler et al., 2020; Morgan et al., 2016), it is important to understand how various facets of self-regulation contribute to the early development of SL. Hence, the present study analyses the relevance of different facets of self-regulation in predicting SL development from preschool to primary school age, while controlling for important associated factors using data from a large-scale German longitudinal study (NEPS-SC1). It should be noted that children aged 5 still attend preschool in Germany, as compulsory education begins at the age of 6–7. While the majority of children in Germany (and in the present study: 85.43 % at age 3) attends preschool, they do not follow a specific curriculum and do not need to attain specific learning goals before formal schooling.

2. Scientific literacy

The relevance of scientific literacy (SL) has grown in recent years due to rapid advances in societies and technologies. SL enables children to cope with the changing world around them and to participate in the discourse of science (Chen et al., 2021). While SL evolves considerably over the childhood years, its roots are already evident among preschoolers (Morgan et al., 2016) and, thus, before formal schooling. Importantly, individual differences in SL levels at preschool age have been shown to continue into primary school (Kähler et al., 2020).

SL development in preschool entails the acquisition of knowledge of and about science. Knowledge of science (KOS) includes the more process-oriented facets of scientific reasoning, for example asking scientific questions, formulating hypotheses, designing experiments, observing and recording details (Lehrer & Schauble, 2006), whereas knowledge about science (KAS) involves the understanding of basic scientific concepts (Gelman, 2006; Kuhn, 2010; Lehrer & Schauble, 2006; Tolmie et al., 2016). Through KOS and KAS, a 5-year-old child can draw connections between theory and evidence by generating and testing simple hypotheses; for instance, he or she can verify whether the claim that a doll is in the cupboard is true or false (e.g., Duschl et al., 2007; Zimmerman, 2007) and draw connections between various physical mechanisms (e.g., gears need to make physical contact with one another to form a working system) or between physical mechanisms and the human body (e.g., the heart as a pump). Children continue to learn to accept or falsify claims (e.g., through self-directed experimental tasks) by drawing connections between objects also in primary school age. Yet, it is only after primary school that they proceed to more sophisticated phases of SL development which involve observing, recoding and evaluating evidence. In the primary school years, children may need some time before they start to make more formal generalizations across instances. E.g., they may make assumptions about gear function from playing with an eggbeater and inappropriately make a connection to the gear function of a bike (Lehrer & Schauble, 1998, as cited in Duschl et al., 2007, p. 97). Similarly, they may be unable to see the heart as interconnected tubes that enable nutrients to be transported to different parts of the body (Duschl et al., 2007, p. 99) and continue viewing it as a pump. These misconceptions need to be resolved with time, allowing the children to proceed towards more advanced levels of scientific reasoning/inquiry and concept formation. If they would persist into adolescence or adulthood, they would hamper their understanding of scientific mechanisms (Duschl et al., 2007).

Although the exact conceptualization of SL varies (Laugksch, 2000), most studies adhere to the basic idea of SL comprising of KOS and KAS. This conceptualization has been outlined in the Programme for International Student Assessment (Bybee et al., 2009) and by the American Association for the Advancement of Science (AAAS, 2009), and also forms the basis of the assessments in the German National Educational Panel Study (NEPS, Hahn et al., 2013). In these frameworks, the SL measures are applied to different content areas, for instance environment, health and technology (Hahn et al., 2013). In the NEPS-SC1, children's SL is assessed at the ages of 5 and 7, respectively, thus allowing an investigation of the effects of self-regulation and other influencing factors on their development from preschool to school age – which is of particular importance as early emerging individual differences in SL seem to set the stage for later developments.

3. Self-regulation

In understanding self-regulation, two research traditions are often highlighted: effortful control (EC) and executive functions (EF). EC is conceptualized in temperament research as the regulatory processes that modulate emotional, motor, and attentional reactivity (Rothbart, 1989; Rothbart et al., 2000). It includes facets such as inhibitory control, cognitive flexibility, and the ability to delay gratification (Jones et al., 2016). EF comprises of various cognitive facets, including inhibitory control, cognitive flexibility, and working memory (Miyake et al., 2000). Inhibitory control refers to the deliberate inhibition of dominant responses, while cognitive flexibility facilitates task switching (Miyake et al., 2000), and working memory involves the temporary maintenance and updating of information (Baddeley & Hitch, 1974). Although various models – covering a wide range of self-regulatory facets (partially rooted in different research traditions) – differ with respect to their conceptualization of the specific, more simple skills and the hypothesized more complex, higher-order abilities (e.g., Bailey & Jones, 2019, for discussion), most models differentiate somehow (Jones et al., 2016; Zelazo & Carlson, 2012) between (purely) cognitive facets of self-regulation (particularly addressed within EF research) and facets of self-regulation in (emotionally salient) motivationally relevant and everyday contexts (particularly addressed within EC research). For instance, the theoretical model by Jones et al. (2016) integrates the different yet related, research traditions of EF and EC research within a unified framework. However, despite the clear overlap between the facets of self-regulation conceptualized within EF and EC research, EF research is more focused on the cool facets of self-regulation assessed in emotionally neutral contexts (and less on emotionally salient contexts), while EC research is more focused on the hot or emotionally salient and everyday contexts (see Zhou et al., 2012, for an in-depth comparison). Focus on the hot facet, though theoretically acknowledged, is less frequently studied. Moreover, overlaps are evident in specific self-regulatory skills (such as inhibition, flexibility) between EF and EC as well as in the specificity of others, as, for instance, working memory is seen as specific to EF (purely cognitive facet), while delay of gratification is seen as specific to EC. From an empirical point of view, both, the research traditions on EF and EC have partially used the same measures (e.g., Go/No-Go tasks for inhibitory control/response inhibition; Zhou et al., 2012), but have also used different measures as EF research is more centred on behavioural measures (e.g., flanker task; Zhou et al., 2012), while EC research is rooted in temperament research and often includes report measures on everyday self-regulatory behaviour (e.g., CBQ; Rothbart et al., 2000) alongside performance-based tasks (e.g., Kochanska's multitask battery, delay task; Kälin & Roebers, 2021; Zhou et al., 2012).

While increasing literature supports the importance of an integrated view on self-regulation (Jones et al., 2016), the various distinctions between, e.g., cool (cognitive) and hot (emotional) EF (Zelazo & Carlson, 2012) or between EF and EC (as higher-level constructs) remain theoretically and empirically challenging. Therefore, in the following we will draw on a multi-faceted view of self-regulation considering both, i.e., emotionally neutral facets (particularly focused in EF research) as well as the more emotion-related facets (including measures derived from temperamentally rooted EC research) of self-regulation to study their relation to SL development. The emotionally neutral (EF) facets shall include inhibitory control, cognitive flexibility, and phonological working memory, while the more emotion-related facets will comprise a report measure on children's effortful control (derived from EC and temperament research, Putnam & Rothbart, 2006, see Jones et al., 2016) and a delay of gratification task derived from both the theoretical frameworks of Jones et al. (2016, EC component) and Zelazo and Carlson (2012; hot EF). Overall, these self-regulatory facets will be examined for their associations with specific academic achievements, particularly SL.

3.1. Self-regulation and academic achievement in preschool and primary school

Previous studies have mainly examined the associations of self-regulatory facets with academic domains such as mathematics and reading, revealing an association between the emotionally neutral (EF) facets and academic achievement, particularly in preschool (Brock et al., 2009; Willoughby et al., 2011) and primary school (Nakamichi et al., 2022). However, the role of the more emotion-related facets of self-regulation for academic achievement remains empirically unclear. For instance, some studies have found the more emotion-related facets of self-regulation to be insignificantly related to academic achievement in preschool (Brock et al., 2009; Willoughby et al., 2011), while others found them to be significantly associated to preschool (Blair & Razza, 2007) and primary school academic achievement (Nakamichi et al., 2022). In the following, we will briefly review the assumptions and results concerning the relation between various facets of self-regulation and early SL development among children.

3.2. Emotionally neutral executive functions (EF) and scientific literacy (SL) in preschool and primary school

As already outlined, the emotionally neutral (EF) facets of self-regulation may be particularly relevant for the early development of SL as they "help preschoolers develop basic habits of mind" and scientific reasoning abilities. In their theoretical framework, Gropen et al. (2011) specifically emphasizes the significance of the emotionally neutral (EF) facets for testing and revising hypotheses – a core scientific reasoning competence. They furthermore regard them as important in "representing and processing hierarchical rules, wherein a rule relates a means to an end" (Zelazo et al., 2003, as cited in Gropen et al., 2011). In particular, these facets enable children to create rules of higher complexity that they use to formulate and solve scientific problems (Zelazo et al., 2003). For instance, working memory helps children to maintain multiple facts in their mind, enabling them to test hypotheses (e.g., that dropping a stone from a height will result in it falling straight down). Inhibitory control helps children to test their hypotheses by enabling them to reflect on the difference between what they predicted (e.g., that dropping a feather from a height would result in it falling straight down like a stone) versus what they observe (that – contrary to the stone – the feather dropped from a height float in a circular motion). Without this, children would be guided by their immature beliefs and prior knowledge/theories, undermining any form of conceptual change and development (Piaget, 1974). Cognitive flexibility may continue contributing to the revision/confirmation of hypotheses as it enables children to reflect on the differences between rules or to consider multiple courses of action in the process of evaluation. For instance, children with advanced cognitive flexibility skills are able to change their incorrect predictions or in this case confirm their prediction (not all objects drop in the same manner; Gropen et al., 2011). Similarly, as these children reach primary school, they improve their ability to analyse problems and to perform in the scientific processes of hypothesis testing and revision that are integral to SL development. Recent theorizing has also pointed towards the significance of these facets for the acquisition of scientific concepts in SL development (Vaughn et al., 2020).

Empirical evidence supports these assumptions regarding the role of the emotionally neutral (EF) facets on SL development by showing that these facets predict SL in preschool age (Bauer & Booth, 2019; Frechette et al., 2021; Nayfeld et al., 2013; Zaitchik et al., 2014). For instance, a study by Nayfeld et al. (2013) found these facets to predict SL to a much greater extent than maths and vocabulary skills. Also, Morgan, Farkas, Hillemeier, et al. (2019) reported associations between those individual facets and academic achievement in science throughout primary school. Two further studies (Anthony & Ogg, 2020; Kim et al., 2021) documented a similar association, showing working memory and cognitive flexibility to be longitudinally associated with SL in preschool and primary school age. While these studies help reinforce the significance of the various emotionally neutral (EF) facets for SL development in preschool and primary school age, it should be noted that many of these studies analysed these associations using the same dataset (i.e. the ECLS:2011; Tourangeau et al., 2018). Hence, the present study is one of the first studies to analyse these associations using a different large-scale longitudinal dataset (NEPS; Blossfeld & Roßbach, 2019).

3.3. More emotion-related facets of self-regulation and scientific literacy in preschool and primary school age

One task that has been repeatedly used to capture the more emotion-related facets of self-regulation is the delay of gratification wait/delay task, indicating a facet of EC in the model of Jones et al. (2016) and of hot EF in the model of Zelazo and Carlson (2012). As already mentioned, another indicator is derived from temperament research (report measures on effortful control in everyday contexts, e.g., CBQ-subscale on effortful control; Rothbart et al., 2000). The significance of those measures (CBQ-effortful control measure and delay of gratification tasks) for SL has been highlighted particularly for the assimilation and accommodation of new information (Vaughn et al., 2020). Especially these facets of self-regulation have been pointed out as being important for changing a misconception (Vaughn et al., 2020). However, the role of the more emotion-related facets of self-regulation for SL remains largely unexplored among preschool and primary school children (Morgan et al., 2016). One study that examined this association found the delay of gratification (waiting before playing) and a gift wrap task (not to peak) to be non-significantly related to SL (Frechette et al., 2021). However, the study investigated a very specific sample of dual-language-learning preschoolers from low-income households. Given the lack of studies examining the more emotion-related facets of self-regulation to SL (together with the emotionally neutral (EF) facets) and the previous inconsistent findings on their effects on academic achievement in other domains, more studies are needed to clarify these associations, especially in preschool and primary school age.

4. Covariates

To evaluate the contribution of self-regulatory facets (between ages 3–5) to the development of SL (at and between ages 5 and 7), certain family and individual characteristics should be used as controls. These include (a) negative affectivity (reflecting anger reactivity, mood instability or strong negative emotions) and (b) surgency (reflecting high activity level, high-intensity pleasure seeking, low shyness and high impulsivity), as these reactive facets of temperament have been found to be negatively interrelated with EC and academic achievement (Nasvytienė & Lazdauskas, 2021). Other factors such as (c) non-verbal cognitive functioning and (d) receptive vocabulary are included as these indicators of the fluid and verbal facet of intelligence could influence children's EF abilities, SL performance and academic achievement (Blair & Razza, 2007; Frechette et al., 2021). Furthermore, children's (e) home interaction language also plays a role, as the self-regulatory and SL performance of children growing up with more than one language and with less advanced majority-language skills may differ to those of monolingual children (Frechette et al., 2021); (f) socio-economic background (SES) is also considered as children growing up in families with a low SES may have EF deficits and lower opportunities to indulge in SL (Frechette et al., 2021; Nayfeld et al., 2013); (g) and lastly, children's gender is included as the self-regulatory performance and SL of boys and girls may differ (Kähler et al., 2020).

5. Current study

This study considers children's early self-regulatory abilities (at ages 3–5 years) and their contribution to children developing SL in preschool (age 5) and primary school (age 7) respectively. In addition, when analysing the effects of self-regulation on later SL (at age 7), we considered children's earlier levels of SL (which may predict later SL; Dole & Sinatra, 1998; Saçkes et al., 2011), thereby addressing the effects of the self-regulatory facets on changes in interindividual differences of SL from preschool to early primary school age. To test for the specificity of the predicted relations, the study controlled for relevant child-related (e.g., nonverbal cognitive functioning) and family-related factors (e.g., SES) that might underly the predictive relations between self-regulation and SL. Additionally, we also separately considered the specific role of the emotionally neutral (EF) and the more emotion-related facets of self-regulation for SL (as an exploratory analysis) in the preschool (age 5) and primary school years (age 7). Finally, the direct and indirect contribution of self-regulatory facets to SL development at the ages of 5 to 7 were analysed to determine whether early self-regulatory facets impact SL at the age of 7 only via SL at the age of 5 or also directly (implying an effect on individual progress). While we expected the emotionally neutral (EF) facets of phonological working memory, inhibitory control, and cognitive flexibility to significantly predict SL at both ages, our hypotheses regarding the effects of the more emotion-related facets, i.e. the CBQ-effortful control measure and delay of gratification task, were less clear. Although theoretical assumptions indicate that effects of these self-regulatory facets could be expected, supporting empirical evidence is lacking or contradictory. Thus, our study remains exploratory regarding the relationships between the more emotion-related facets of self-regulation and early SL development. Furthermore, the investigation of the direct and indirect (via earlier SL differences) contribution of various self-regulatory facets to SL development was also exploratory. While past studies examined this association for academic/mathematical achievement (Backer-Grøndahl et al., 2019; Gashaj et al., 2019), the relations for SL development have so far not been examined.

6. Methods

6.1. Participants

We used data from the newborn cohort (NEPS-SC1) of the ongoing German National Educational Panel Study (NEPS; Blossfeld & Roßbach, 2019; NEPS Network, 2021). This longitudinal study has been conducted on a representatively drawn sample of 3481 children and their families, recruited between February and July 2012 in Germany (Weinert et al., 2016; Würbach et al., 2016; demographics of full sample in Appendix A). We utilized data from measurement wave 4 conducted in 2015 when the children were about 3 years old (T1). Furthermore, three additional time points across the next four years were included (Table 1), with a total of 1931 children participating in the SL measure when they were 7 years old (T4). For this study, we used data collected when the children were 3, 4, 5 and 7 years old (Würbach et al., 2016). Data of the measurement point at age 6 were not included, as none of the study variables were assessed at this time point. All measures (see Appendix B) were assessed in children's homes, and the individual tests were administered using a tablet computer. As this study used approved secondary data, an additional ethics or review board approval was not required.

6.2. Measures

6.2.1. Emotionally neutral executive functions (EF) facets of self-regulation

Phonological working memory (as an indicator of working memory; T1): This was measured using a digit span task adapted from the German version of the "Kaufman Assessment Battery for Children" (K-ABC; internal consistency: 0.86; Melchers & Preuß, 2009), when the children were 3 years old. The children were individually presented with sequences of digits in an auditory format and asked to immediately reproduce each sequence of numbers correctly. The number of digits kept increasing. A maximum of 15 items (with a stopping rule) was administered. The child's score comprised the number of correctly reproduced sequences (actual range in the study 0–15).

Inhibitory control (T2) was tested using a child-adapted version of Eriksen's flanker task (Eriksen & Eriksen, 1974). The task has a high test-retest reliability and interclass correlation of 0.92 (Bauer & Zelazo, 2014). The task involved introducing the children to fishes and asking them to indicate the direction of the fish in the centre of the display by pressing a corresponding button. In the congruent items, all fishes had the same orientation (< < < < <), whereas in the incongruent items the direction of the fishes on the outside and of the fish in the centre (< < > < <) differed. The tablet was connected to a reaction time keyboard which measured the accuracy and reaction time of the responses. The children were instructed to concentrate on the middle fish and to press the button corresponding to the direction of the fish as fast as possible. To do the task correctly, they had to ignore the direction of the outer fishes in the incongruent (< < > < <) items. Before starting the test phase of this flanker "focus centre" task, up to three practice sessions were conducted. In each practice session, children completing five of the seven practice items reached the test phase. The task's test phase comprised 30 items including 20 congruent and 10 incongruent items. For this study, the proportion of correct responses (ranging from 0.0 to 1.0) on the incongruent trials of the task (Oeri & Roebers, 2022) was used to determine the children's inhibitory control abilities.

Cognitive Flexibility (T2): This was assessed using a switching task

Table 1
Overview of the assessed variables across time points.

	Waves			
	Wave 4 (T1)	Wave 5 (T2)	Wave 6 (T3)	Wave 8 (T4)
Age	3 years	4 years	5 years	7 years
Assessed variables	Phonological working memory, Delay of gratification, Effortful control (parent-report)	Inhibitory control, Cognitive flexibility,	Scientific literacy (SL),	Scientific literacy (SL)
	All control variables (including negative affectivity and surgency)	Effortful control (parent-report) Control variables (negative affectivity and surgency)	effortful control (parent-report) Control variables (negative affectivity and surgency)	

Note. TI = Time point.

(second part of the flanker's task) but with a rule change (Eriksen & Eriksen, 1974; Oeri & Roebers, 2022). Hence, instead of focusing on the middle fish, the children were now asked to switch their focus on the outer fishes and to indicate their direction. In the incongruent trials (< < > < <), the children now had to ignore the direction of the middle fish when indicating the direction of the outer fishes by pressing the respective response button. Before the task's test phase, a practice session was conducted with three items. Similarly, the task was administered only to children who had passed the first task for inhibitory control in the first or second practice session. The task's test phase comprised 16 items including eight congruent and eight incongruent items. The proportion of correct responses (ranging from 0.0 to 1.0) in the incongruent trials of this task was used to determine children's cognitive flexibility.

6.2.2. More emotion-related facets of self-regulation

CBQ-effortful control (T1, T2 and T3): This indicator was assessed through parent-report using a very short German version of the Child Behavioural Questionnaire (CBQ-VSF; Putnam & Rothbart, 2006) when children were aged 3, 4 and 5. Parents rated the items on six-point Likert scales, ranging from “does not apply at all” to “completely applies” (Appendix B). The scale included items such as “is concentrated while painting or drawing” and “gets carried away if viewing picture books” at measurement points T1, T2 and T3. The correlations across the three measurement points for this measure (0.47–0.52) were moderate. The reliability of this measure at T1 (α = 0.26), T2 (α = 0.38) and T3 (α = 0.30) respectively were low. In order to increase the reliability of this measure it was averaged across the individual items and waves (α = 0.74).

Delay of gratification (T1): The ability of 3-year-old children to delay gratification was measured using a waiting paradigm (Mischel & Gilligan, 1964). The child was presented with a big and a small wrapped gift, and a USB button was placed between the gifts. The child could either wait for an unknown amount of time (maximum 181 s) to receive the big gift or press the button to receive the small gift instantly. The child's decision to wait or not wait (0 = *did not wait* and 1 = *waited*) was used as a measure of delay of gratification.

6.2.3. Scientific literacy (SL; T3 and T4)

Children's SL was first assessed when they were 5 years old. The framework and context-related elements used in the NEPS were developed based on various studies. They assess both knowledge of science (KOS) and knowledge about science (KAS). Measurement of KOS (13 items) comprised content-related components such as matter, development, interactions, and systems; measurement of KAS (seven items) included process-related components such as scientific inquiry and scientific reasoning. Both KOS and KAS were assessed in three scientific contexts – health, the environment and technology – using one, ten, and nine items respectively. The child was exposed to the test items virtually in a science and technology game, guided by a little dragon named “Nepsi”. The dragon introduced the 17 picture items and four multiple-choice answers for each of the items, instructing the child to choose one of the options. Additionally, the child was asked to provide answers to three true-false items shown successively. Overall, the test comprised 20 items (Appendices C and D; Hahn et al., 2014), and the WLE score was used as a measure for the analysis (ranging from 2.96-4.88; scaled using item response theory; Hahn et al., 2013; Hahn, 2019, 2021). The reliability of the measure was sufficient (EAP/PV reliability = 0.673; weighted likelihood estimators or WLE reliability = 0.639; Hahn, 2019).

In the NEPS, SL was measured again when the children were 7 years old. The test was constructed based on the same competence model as at the age of 5 but adjusted for age. Through an anchor-item design, the data could be linked across the age-adapted versions. The reliability of the WLE estimator was again acceptable (EAP/PV reliability = 0.695; weighted likelihood estimators or WLE reliability = 0.670; Hahn, 2021; actual range: 4.91–3.70).

6.2.4. Control variables

Negative affectivity and surgency (T1, T2, T3): These reactive temperament facets were assessed using the same very short German version of the Child Behavioural Questionnaire (CBQ-VSF; Putnam & Rothbart, 2006) as for the parent-report on effortful control when the children were 3, 4 and 5 years old. The parents rated the three items of each scale on a six-point Likert scale, ranging from “does not apply at all” to “completely applies” (Appendix B for items used). The correlations across the three measurement points for negative affectivity (0.48–0.57) and surgency (0.56–0.63) were moderate. The reliability of negative affectivity at T1 (α =0.56), T2 (α = 0.62) and T3 (α = 0.57) and of surgency at T1 (α = 0.48), T2 (α = 0.54) and T3 (α = 0.56) respectively were relatively low. To improve the measure's reliability, it was averaged across individual items and waves for negative affectivity (α = 0.76) and surgency (α = 0.81).

Non-verbal cognitive functioning (T1): As an indicator of basic nonverbal cognitive functioning, the subtest “Categorization” of the Snijders-Oomen nonverbal intelligence test (SON-R 2 1/2–7; Tellegen et al., 2007) was administered in the NEPS via a tablet computer. The subtest requires children to understand abstract connections between two or more objects for a total of 15 test items. The first seven items presented the children with a certain characteristic that they should use to sort out four or six cards. The next nine items (one practice item, eight test items) presented the child with three pictures with a common characteristic, and the child was instructed to pick two more pictures with the same characteristic from a selection of five or more cards. The test followed a learning format, which involved providing the child with feedback on whether the answer was correct or not after each item. The test ended as soon as three mistakes were registered. In this study, the weighted likelihood estimator (WLE) actually ranging from (4.05–6.09) was used as a measure for this construct.

Receptive vocabulary (T1): Children's receptive vocabulary was assessed using a German version of the Peabody Picture Vocabulary Test (PPVT-4; internal consistency as reported by the test authors: α = 0.97; Dunn & Dunn, 2007; Lenhard et al., 2015). The child was instructed to select one picture out of four options matching an auditory presented word. Before the test, a practice session with a minimum of two and a maximum of four practice items was conducted. Children who solved at least two items out of the four were allowed to move on to the test phase. The test included 228 items with 19 sets (with increasing levels of difficulty), each comprising 12 items. The test phase began with Set 1 and continued until the child had made more than seven mistakes in a set. The sum score of correctly solved items (actually ranging from 0 to 121) was used in this study.

Home interaction language (T1) was assessed in the parent interview (1 = *only German*, 2 = *mostly German, but sometimes also another language*, 3 = *mostly another language but sometimes also German*, 4 = *only another language*) and recoded for categories 2–4 as 0 = *language other than German* (23.5 %) and category 1 as 1 = *only German* (76.5 %) for this study.

Socio-economic status (SES; T1): The SES of the family was measured using the Highest International Socioeconomic Index (HISEI; Ganzeboom et al., 1992). The index is based on ISCO-2008 coding, which hierarchizes an individual's last occupational status based on his or her education and his or her average earning in that occupation. The variables were re-coded to generate the highest ISEI score of the two parents (ranging from 13.87 to 88.9).

Gender (T1): The gender of the child was reported by the parents and coded as 0 = *male* (49.9 %) and 1 = *female* (50.1 %).

7. Data analytic plan

7.1. Descriptive analyses and interrelations between predictors

To examine the associations between the early facets of self-regulation (from ages 3 to 5), correlational analyses were computed (see Appendix E). The correlations were relatively low within and between the emotionally neutral (EF) and the more emotion-related facets of self-regulation (ranging between $r =$ 15–0.13).

Furthermore, when considering whether the facets of self-regulation could be treated as a one or two-dimensional construct, two confirmatory factor analyses (CFA) were conducted, but the fit indices for both models were very low and the indicator of cognitive flexibility did not fit either a one- or a two-dimensional construct (Appendices F). Given these results, an exploratory factor analysis (EFA) was additionally conducted to explore the underlying structure of the various self-regulatory facets. The facets were found to load on a two-factor model (Appendix G). However, only phonological working memory (0.49) exceeded the loading criterion of 0.40 for the first, and only inhibitory control (0.52) for the second factor. None of the other variables met the minimum loading criterion of 0.40 in the rotated factor loadings (promax and varimax; Stevens, 2009). Hence, the results of the CFA and EFA indicated that the facets should be treated separately in the main analyses (i.e., when analysing their association with SL at ages 5 and 7, respectively; see below). Yet, to explore the specific predictive role of the emotionally neutral (EF) and the more emotion-related facets of self-regulation, we additionally considered these facets separately as predictors of SL (as an explorative analysis, see below).

7.2. Regression analyses

To analyse the role of the self-regulatory facets to SL at ages 5 and 7 respectively, two models were conducted – one without and one with the inclusion of control variables. Furthermore, a third model also included SL at the age of 5 when predicting children's SL at the age of 7 to examine the effects of the self-regulatory facets on SL development (i.e., their effect on the changes of individual differences in SL between 5 and 7 years of age). In doing so we also controlled for all other variables possibly relevant to differences in SL at the age of 5 and possibly still for SL at the age of 7.

In addition to the overall regression models, we conducted (as an exploratory analysis), a set of regression models, wherein (i) the predictive relationships of only the emotionally neutral (EF) facets of self-regulation (i.e., phonological working memory, inhibitory control, and cognitive flexibility) to SL (at ages 5 and 7) were analysed. Similarly, another model (ii) included only the more emotion-related facets of self-regulation (CBQ-effortful control and delay of gratification) and their association to SL at these ages. This allowed us to additionally investigate the predictive role of these facets without the inclusion of the emotionally neutral (EF) facets on SL and vice versa (at ages 5 and 7). Before performing the analyses, we accounted for missing data (Table 2) using multiple imputations by chained equations (MICE; White et al., 2011). We included the main and control variables from our analysis model in the imputation model and created m = 50 imputation datasets (Hondralis & Himbert, 2018; Raghunathan et al., 2001; White et al., 2011). All these analyses were conducted using Stata 17 software. The regression analyses were performed using the mi estimate and mibeta, fisherz Stata command (for standardized coefficients), which is in line with Rubin's combining rules for multiple imputation (Rubin, 1987, 1988).

7.3. Structural equation modelling (SEM) on direct and indirect effects of the facets of self-regulation on SL

To specifically test direct and indirect effects of the self-regulatory facets on SL, we additionally implemented structural equation modelling (SEM) using the Mplus 7 statistical software and tested whether the specific self-regulatory facets related to SL at the age of 7 only indirectly via SL at the age of 5 or also directly, thus pointing to an effect on SL changes between the ages of 5 and 7 (Muthén et al., 2017). We only included the self-regulatory facets that had shown significant effects on SL in the regression analyses and modelled them (as well as children's SL at the ages of 5 and 7) as manifest variables. While the first model estimated the direct and indirect relationships between the study variables, a second model tested whether the interrelationships remained stable when controlling for the effects of the control variables. Missing data were handled using the full information maximum likelihood method (FIML). It should be noted that the model fit could not be assessed by the goodness-of-fit indicators (CFI- Bentler, 1990; TLI-Tucker & Lewis, 1973; RMESA-Browne & Cudeck, 1992) because the models were identified/saturated models (CFI = 1.0, TLI = 1.0, RMSEA = 0.00, SRMR = 0.00); however the standardized estimates of the relationships were reported (Figs. 1 and 2).

8. Results

8.1. Descriptive statistics and correlations among predictor and outcome variables

The descriptive statistics for all study variables are presented in

Table 2
Descriptive analysis for all study variables (N = 1931).

Variable	*Obs*	*Mean (SD)*	*Range*	*Scale*
Self-regulatory facets (3–5 years)				
(1) Phonological working memory (3 y)	961	3.30 (2.34)	0–10	Sum score
(2) Inhibitory Control (4 y)	1338	0.72 (0.26)	0–1	% Correct
(3) Cognitive Flexibility (4 y)	1243	0.53 (0.31)	0–1	% Correct
(4) CBQ- Effortful Control (3–5 y)	1570	4.37 (0.81)	1.22–6	Average score
(5) Delay of gratification (3 y)	1717	0.77 (0.41)	0–1	Dichotomous
Scientific Literacy (5&7 years)				
(6) SL (5 y)	1748	0.03 (0.97)	2.96–4.88	Weighted likelihood estimator
(7) SL (7 y)	1931	0.00 (0.97)	4.91–3.70	Weighted likelihood estimator
Control variables (3–5 years)				
(8) Negative Affectivity (CBQ, 3–5 y)	1569	3.30 (0.92)	0.22–6	Average score
(9) Surgency (CBQ, 3–5 y)	1569	4.24 (0.88)	0.77–6	Average score
(10) Non-verbal cognitive functioning (3 y)	1744	0.25 (2.48)	4.05–6.09	Weighted likelihood estimator
(11) Receptive Vocabulary (3 y)	1429	48.38 (27.92)	0–121	Sum score
(12) Home Interaction Language (3 y)	1815	0.76 (0.42)	0–1	Dichotomous
(13) SES (HISEI; 3 y)	1458	61.50 (20.29)	13.87–88.9	Continuous
(14) Gender (male/female; 3 y)	1845	0.50 (0.5)	0–1	Dichotomous

Note. SL = Scientific literacy, SES = Socio-economic status, HISEI = Highest International Socioeconomic Index, CBQ = very short German version of the Child Behavioural Questionnaire (CBQ-VSF; Putnam & Rothbart, 2006).

Table 3
Correlations between the predictor and outcome variables.

Predictor variables	Outcome variables	
	Scientific Literacy (age 5)	Scientific Literacy (age 7)
Self-regulatory facets (3–5 years)		
(1) Phonological working memory (3 y)	**0.21***	**0.26***
(2) Inhibitory Control (4 y)	**0.18***	**0.21***
(3) Cognitive Flexibility (4 y)	0.01	0.01
(4) Delay of gratification (3 y)	0.07	0.00
(5) CBQ- Effortful Control (3–5 y)	**0.13***	**0.10***
Control Variables (3–5 years)		
(6) Negative Affectivity (CBQ, 3–5 y)	**−0.07***	**−0.08***
(7) Surgency (CBQ, 3–5 y)	**−0.07***	**−0.08***
(8) Scientific Literacy (5 y)	–	**0.57***
(9) Non-verbal cognitive functioning (3 y)	**0.25***	**0.28***
(10) Receptive Vocabulary (3 y)	**0.41***	**0.39***
(11) Home Interaction Language (3 y)	**0.26***	**0.20***
(12) SES (HISEI, 3 y)	**0.22***	**0.28***
(13) Gender (male/female, 3 y)	0.04	**−0.17***

Note. SES = Socio-economic status, HISEI = Highest International Socioeconomic Index, CBQ = very short German version of the Child Behavioural Questionnaire (CBQ-VSF; Putnam & Rothbart, 2006).
* $p < .05$.

Table 2, and the correlations between predictor and outcome variables are listed in Table 3 (Appendix H, for interrelations between all study variables). SL at the age of 5 was significantly associated with most of the self-regulatory facets, i.e. phonological working memory, inhibitory control and CBQ-effortful control, as well as with most of the control variables, except for cognitive flexibility, delay of gratification and gender. Most of the correlations were positive, while, as expected (Nasvytienė & Lazdauskas, 2021), the reactive temperamental variables of negative affectivity and surgency correlated negatively with SL.

The correlations between phonological working memory, inhibitory control and CBQ-effortful control were also significant for SL measured at the age of 7. However, no significant correlations were found between cognitive flexibility or delay of gratification and SL at the age of 7.

8.2. Regression analyses

8.2.1. Self-regulation and scientific literacy at the age of 5

The results of the regression analyses are shown in Table 4a. In model 1a, the self-regulatory facets explained 9 % of the variance and the inclusion of control variables in model 1b accounted for an additional 15 % of variance. Hence, in total, 25 % of variance was explained.

Regarding the individual contribution of the self-regulatory facets, in model 1a, the CBQ-effortful control, phonological working memory and inhibitory control measures were significantly related to SL. However, no effects were found for delay of gratification and cognitive flexibility. In the conditional model (1b) similar associations were found. Furthermore, all control variables, except gender, were found to being significantly related to SL; yet the overall pattern of effects of the self-regulatory facets on SL remained robust with some reduction of ß-weights.

When only including the (i) more emotion-related and (ii) emotionally neutral (EF) facets of self-regulation, similar results prevailed (Table 4b). In (i) model 1.1a only the CBQ-effortful control measure significantly predicted SL and (ii) in model 1.2a phonological working memory and inhibitory control significantly predicted SL with nearly the same ß-weights as in the model considering all self-regulatory facets simultaneously.

Table 4a
Regression analysis: self-regulatory facets and scientific literacy at age 5.

	Scientific Literacy (age 5)			
	Model 1a		Model 1b	
	β	SE	β	SE
(1) CBQ-effortful control (3–5 y)	0.09***	0.03	0.04*	0.02
(2) Delay of gratification – does apply (3 y)	0.00	0.06	0.00	0.05
(3) Phonological working memory (3 y)	0.19***	0.01	0.06*	0.01
(4) Inhibitory Control (4 y)	0.17***	0.11	0.10**	0.10
(5) Cognitive Flexibility (4 y)	0.03	0.10	0.01	0.09
(6) Negative Affectivity (CBQ, 3–5 y)			0.00	0.02
(7) Surgency (CBQ, 3–5 y)			0.01	0.02
(8) Non-verbal cognitive functioning (3 y)			0.09***	0.01
(9) Receptive Vocabulary (3 y)			0.31***	0.00
(10) Home Interaction Language – only German (3 y)			0.07**	0.02
(11) SES (HISEI, 3 y)			0.16***	0.00
(12) Gender (female, 3 y)			0.00	0.04
R^2		0.09		0.25
ΔR^2				0.15
F for change in R^2				56.76***

Note: Delay of gratification: does apply = the child waited for the bigger gift, SES = Socio-economic status, HISEI = Highest International Socioeconomic Index.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

8.2.2. Self-regulation and scientific literacy at the age of 7

In model 2a (Table 5a), the self-regulatory facets predicted 12 % of the variance in SL. In model 2b, the control variables contributed another 15 % of explained variance. Finally, the inclusion of SL at the age of 5 (Model 2c) explained another 15 % of variance. In total, 43 % of variance was explained.

In model 2a, CBQ- effortful control, phonological working memory and inhibitory control showed significant contributions. The contribution of delay of gratification and cognitive flexibility were found to be insignificant. Upon inclusion of the control variables in model 2b, only the effects of phonological working memory and inhibitory control remained significant, while the effects of cognitive flexibility and CBQ-effortful control became insignificant.

Finally, in model 2c (including SL at age 5 additionally), the self-regulatory facets of phonological working memory and inhibitory control remained significant. Furthermore, SL at the age of 5 proved to be the best predictor of SL at the age of 7, suggesting considerable stability of interindividual differences in SL over time.

When only including the (i) more emotion-related self-regulatory facets (in Table 5b), the CBQ-effortful control and the delay of gratification measures were significantly related to later SL (model 2.1a).

Table 4b
Regression analysis including the more emotion-related and the emotionally neutral (EF) facets of self-regulation to SL at age 5.

	Model 1.1a		Model 1.2a	
	β	SE		
(1) CBQ-Effortful control (3–5 y)	0.13***	0.03		
(2) Delay of gratification – does apply (3 y)	0.03	0.06		
(3) Phonological working memory (3 y)			0.20***	0.01
(4) Inhibitory Control (4 y)			0.18***	0.10
(5) Cognitive Flexibility (4 y)			0.03	0.09
R^2		0.01		0.08

Note. Delay of gratification: does apply = the child waited for the bigger gift, SES = Socio-economic status, HISEI = Highest International Socioeconomic Index.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 5a
Regression analysis: self-regulatory facets and scientific literacy at age 7.

	Scientific Literacy (age 7)					
	Model 2a		Model 2b		Model 2c	
	β	SE	β	SE	β	SE
(1) CBQ- Effortful Control (3–5 y)	0.06*	0.03	0.03	0.03	0.01	0.02
(2) Delay of gratification – does apply (3 y)	0.01	0.06	0.02	0.05	0.01	0.04
(3) Phonological working memory (3 y)	0.25***	0.01	0.12***	0.01	0.09**	0.01
(4) Inhibitory Control (4 y)	0.19***	0.10	0.12***	0.09	0.07**	0.08
(5) Cognitive Flexibility (4 y)	0.03	0.09	0.00	0.09	0.00	0.07
(6) Negative Affectivity (CBQ, 3–5 y)			0.01	0.02	0.01	0.19
(7) Surgency (CBQ, 3–5 y)			0.04*	0.02	0.03	0.02
(8) Non-verbal cognitive functioning (3 y)			0.14***	0.01	0.11***	0.01
(9) Receptive Vocabulary (3 y)			0.24***	0.00	0.11***	0.00
(10) Home Interaction Language – only German (3 y)			0.05*	0.02	0.02	0.02
(11) SES (HISEI, 3 y)			0.21***	0.00	0.14***	0.00
(12) Gender (female, 3 y)			0.13***	0.04	0.13***	0.04
(13) Scientific Literacy (5 y)					0.43***	0.02
R^2		0.12		0.28		0.43
ΔR^2		.		0.15		0.15
F for change in R^2				68.87***		384.72***

Note: Delay of gratification: does apply = child waited for bigger gift, SES = Socio-economic status, HISEI = Highest International Socioeconomic Index.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 5b
Regression analysis including the more emotion-related and the emotionally neutral (EF) facets of self-regulation to SL at age 7.

	Model 2.1a		Model 2.2a	
	β	SE		
(1) CBQ- Effortful Control (3–5 y)	0.10***	0.03		
(2) Delay of gratification – does apply (3 y)	0.05*	0.06		
(3) Phonological working memory (3 y)			0.26***	0.01
(4) Inhibitory Control (4 y)			0.19***	0.10
(5) Cognitive Flexibility (4 y)			0.03	0.09
R^2		0.01		0.12

Note. Does apply = child waited for bigger gift, SES = Socio-economic status, HISEI = Highest International Socioeconomic Index.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

However, when including the effects of other facets (as also reported in Table 5a) only CBQ-effortful control remained a significant predictor of later SL.

When including only (ii) the emotionally neutral (EF) facets of self-regulation in model 2.2a, phonological working memory and inhibitory control remained significant predictors of SL and, again, cognitive flexibility was found to be insignificantly associated with SL at age 7.

Further robustness checks revealed similar associations between the self-regulatory facets and children's SL at the ages of 5 and 7, respectively (Appendix I) when comparing the imputed data with the non-imputed data as well as when including only children who performed 70 % and above correctly on the congruent items of the flanker task measuring inhibitory control (Appendix J). This was done as low performance on the congruent items might indicate overall inattentiveness to the task or a lack of understanding the task (Bialystok, 2011). To test whether the inclusion of the CBQ measures at age 5 may have affected our results (see Mitchell & Maxwell, 2013), we compared the results of the presented models with other models using the CBQ scales either aggregated only across age 3 and 4 or at 3 years of age (thereby realising a sequential longitudinal design; Mitchell & Maxwell, 2013; see Appendices M and N). In both cases, the CBQ-effortful control measure predicted SL at age 5 and the combined measure (ages 3 and 4) predicted SL also at age 7. However, all effects lost their significance when the controls were added to the models. As the ß-weights were relatively close to the ones in the reported regression models and in the SEM analysis (see appendix O), there is no indication that effects were overestimated by the partial cross-sectional overlap between this predictor and the first SL measurement.

8.3. Structural equation modelling

To further explore the effects of self-regulation on later SL, we computed two structural equation models (one with and one without control variables) which explicitly specified a direct path of the self-regulatory facets on later SL as well as an indirect path of these facets on SL at the age of 7 via SL at age 5.

For this analysis, we only considered the facets that were revealed to be significant predictors in the regression analyses. This includes the facets of phonological working memory, inhibitory control, and the CBQ-effortful control measure.

Fig. 1 shows the results with the standardized estimates ($p < .05$). Phonological working memory, inhibitory control, and the CBQ-effortful control measure showed significant effects on SL at the age of 5; each of the self-regulatory facets had significant indirect effects on SL at the age of 7 via SL at the age of 5 (Appendices K and L for the estimates of the indirect effects). Furthermore, phonological working memory and inhibitory control had additional significant direct effects on SL at the age of 7, while the CBQ-effortful control measure showed no significant direct effect. Upon inclusion of all control variable (Fig. 2), all resulting associations were similarly significant.

9. Discussion

The present study draws on models of self-regulation (Jones et al., 2016; Zelazo & Carlson, 2012) and examines emotionally neutral (EF) facets (phonological working memory, inhibitory control and cognitive flexibility) as well as more emotion-related facets of self- regulation (CBQ-effortful control and delay of gratification) as potential predictors of SL from preschool to primary school years.

As hypothesized, the regression results show the self-regulatory facets of phonological working memory and inhibitory control to be significantly related to SL at ages 5 and 7 as well as to SL development between age 5 and 7 (i.e., to the change of individual differences). Furthermore, the CBQ-effortful control measure was also related to SL at both ages but did not reach significance for later SL at age 7 when the

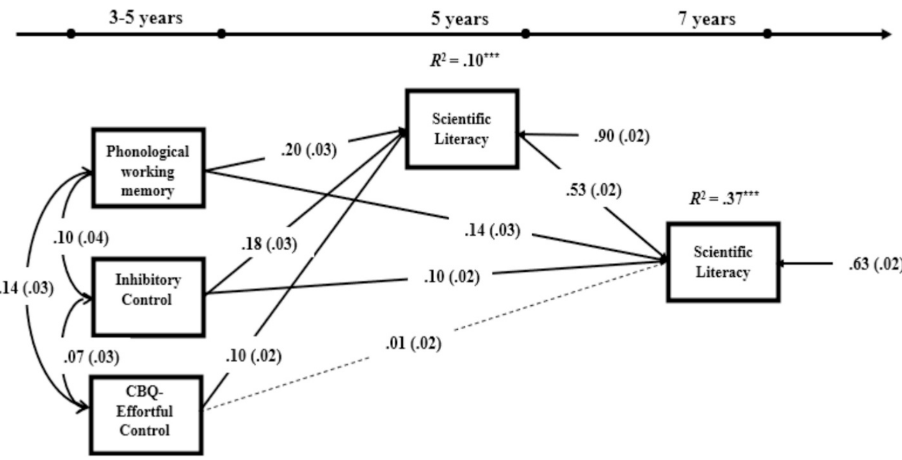

Fig. 1. Significant standardized results of model 1 (without controls; $p < .05$).
Note. $N = 1931$; CFI = 1.00, TLI = 1.00, RMSEA = 0.00, SRMR = 0.00.

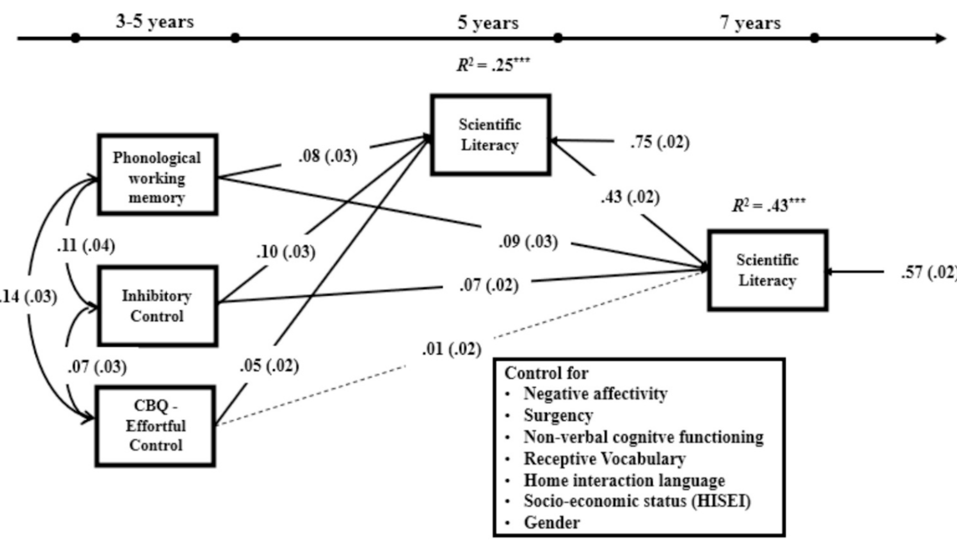

Fig. 2. Significant standardized results of model 2 (with controls; $p < .05$).
Note. $N = 1931$; CFI = 1.00, TLI = 1.00, RMSEA = 0.00, SRMR = 0.00.

controls were included in the model. In addition, when considering the direct and indirect effects of these self-regulatory facets (SEM analysis) on SL development, phonological working memory and inhibitory control were directly and indirectly related to SL at ages 5 and 7, whereas CBQ-effortful control was only indirectly (via SL at age 5) related to SL at age 7. The indicators of cognitive flexibility and delay of gratification remained insignificant throughout the analyses.

Thus, while we did find significant relations of early self-regulation to SL development – even when controlling for important confounding child and family factors, this did not hold true for all facets included in the study. Concerning the exploratory investigation of the (potentially different) role of the emotionally neutral (EF) and the more emotion-related facets of self-regulation to SL, this differentiation neither showed up in the structural relations between the facets of self-regulation included in the study, nor did it covary with the observed effects or non-effects of the individual facets of self-regulation on SL. Furthermore, considering those facets separately did not change the overall pattern of results. Therefore, the results on the different facets of self-regulation will be discussed separately in the following.

Relations between individual facets of self-regulation and SL. As expected, our results support the assumption that phonological working memory as well as inhibitory control contribute significantly to SL development. This has been hypothesized based on theoretical (Gropen et al., 2011) and empirical reasons (e.g., Frechette et al., 2021; Morgan, Farkas, Wang, et al., 2019; Morgan, Farkas, Hillemeier, et al., 2019; using ECLS data). Yet, our results extent previous findings to another large-scale dataset and country as well as to other indicators of self-regulation. In particular, other studies predominantly used measures on the central executive of working memory showing a longitudinal association to SL in preschool (e.g., Frechette et al., 2021) and primary school years (Zaitchik et al., 2014) as well as between these ages (Kim et al., 2021). Our study showed similar pattern of results for phonological working memory and inhibitory control. This suggests that better inhibitory control and phonological working memory may help children to develop scientific competences in childhood that set the stage for later developments. In particular, even when controlling for important child and family factors (see below), these associations remain robust.

However, contrary to our expectations and existing empirical evidence (e.g. Anthony & Ogg, 2020; Frechette et al., 2021), our indicator of cognitive flexibility was not associated with SL at the ages of 5 and 7, respectively. This discrepant finding could be due to different reasons. On the one hand, effects might depend on the age-range under study. For instance, while Gropen et al. (2011) find 4-year-olds to be able to perform well on cognitive flexibility tasks, other scholars argue that cognitive flexibility skills may not be differentiated from working memory and inhibitory control at age 4 (Garon et al., 2008) and that these skills may develop later, for instance around the age of 5. On the other hand, past studies predominantly administered the dimensional change card sort task (DCCS; Zelazo, 2006) to capture cognitive flexibility in preschool children (Gropen et al., 2011). While the switching flanker task (2nd part of the flanker task) used in this study has been successfully employed as an indicator of flexibility/switching in some studies (e.g., Gashaj et al., 2019; Oeri & Roebers, 2022), overall, the flanker's task is predominantly employed as a measure of inhibitory control (Bauer & Zelazo, 2014; Oeri et al., 2018; i.e. the 1st part of the flanker, also used in our study). Hence, it is an open question whether our results are due to this specific indicator (or other reasons, see above) and/or whether the switching flanker task measures a different skill than the DCCS task.

With respect to the exploratory analysis on the CBQ-effortful control measure (Rothbart, 1989) our results are in line with the findings of other studies examining its relation to maths and vocabulary achievement in preschool years (Blair & Razza, 2007) and extent them to SL. They hint towards an association between this regulatory facet of temperament and the scientific processes of conceptual and analytical development at age 5 (Morgan et al., 2016; Vaughn et al., 2020). However, as the association between CBQ-effortful control and SL at the age of 7 was insignificant (when controls were included), the developmental association of this measure across age could not be determined. In particular, the relation to SL at age 7 was completely mediated by SL at age 5 (see Figs. 1 and 2). This might suggest that this facet of self-regulation is particularly important in the very early phases of SL development but less for the development between age 5 and 7. However, this assumption needs further research with more extended scales on children's effortful control.

Contrary to the CBQ-effortful control measure, the delay of gratification task was insignificantly related to SL throughout childhood. This finding is in line with studies wherein children's ability to wait and receive a bigger gift later rather than immediately receiving a smaller gift was insignificantly associated with academic achievement in preschool and primary school (Brock et al., 2009; Willoughby et al., 2011). These results also partially align with the study by Frechette et al. (2021) who found one of the delay tasks – a gift wrap task (at age 5) – to be insignificantly related to SL at age 5 which was attributed to its highly skewed distribution. In our study, 78 % of 3-year-olds waited for the larger gift, already showing delay skills at this young age, with a small and insignificant correlation with SL ($r = 0.07/0.00$). However, the association between delay of gratification and SL might show up, if, for example, the delay of gratification task would have been implemented with longer waiting times that might lead to more pronounced individual differences in task performance. Furthermore, differences in assessment types could have influenced the results, as the delay of gratification task was measured using a performance based task, while CBQ-effortful control was assessed via a parent-report measure (Zhou et al., 2012).

With respect to *the control variables*, our results hint to the assumption that the more reactive facets of child temperament, i.e. negative affectivity and surgency, are not as relevant as CBQ-effortful control with respect to their relation to SL. In the regression analyses, both were not associated to SL and controlling for these variables did not change the overall results. This finding is compatible with those reported in a meta-analysis by Nasvytienė and Lazdauskas (2021) who found only small negative effect sizes between negative affectivity and three academic variables (i.e. maths, reading and general). Similarly, the size of the effect of surgency on academic achievement was close to zero and non-significant in the meta-analysis. As expected, most of the other control variables included in the study – receptive vocabulary, nonverbal cognitive functioning and SES – were significantly associated with both SL at ages 5 and 7 as well as with some facets of self-regulation, particularly with phonological working memory, inhibitory control and CBQ-effortful control. Thus, controlling for these potentially confounding factors is highly important when studying the relation between self-regulation skills and SL. The fact that the main pattern of results hardly changed when these controls were included, underlines the robustness and specificity of the relations shown.

Mediating relations. When analysing the direct and indirect effects between facets of self-regulation (i.e., phonological working memory, inhibitory control, and CBQ-effortful control) on SL at ages 5 and 7, the results extent existing studies conducted in the context of mathematical achievement (e.g., Backer-Grøndahl et al., 2019; Gashaj et al., 2019). While we find a direct as well as an indirect effect (via SL at age 5) of phonological working memory and inhibitory control on later SL, the CBQ-effortful control measure only shows an indirect effect on later SL (via SL at age 5). Together with the regression results, this hints, to the assumption that effortful control might be particularly relevant in the early phases of SL development (Edossa et al., 2018). However, this does not necessarily hold true for all emotion-related facets of self-regulation. In fact, Backer-Grøndahl et al. (2019) found performance in a gift wrap task in the preschool years to be directly and indirectly related to academic achievement (maths and reading) at 6 and 7 years, respectively. Yet, our delay of gratification measure was neither directly nor indirectly related to SL (see above). Thus, this points towards the need to uncover the relation between more emotion-related facets of self-regulation and how they may relate to academic achievement (particularly SL).

Overall, this study builds on previous research by corroborating earlier findings and expanding our understanding of how different facets of self-regulation contribute to SL development from preschool to primary school age. It is one of the first studies to analyse their associations with SL within a large longitudinal sample and to include multiple important confounding child and family factors thereby documenting the robustness of effects.

9.1. Limitations of the study

However, our study also has limitations. For instance, the direct measures of self-regulation in the NEPS-SC1 dataset were not conducted uniformly across the ages of 3 to 5 (see Table 1). As a consequence, the developmental improvements in the various facets of self-regulation (between ages 3–5 and later on) and their relation to SL development could not be analysed in this study. Similarly, the CBQ measures – comprising effortful control, negative affectivity and surgency – did not allow for determination of potential age-related changes as the temperament facets were assessed with a very short instrument (VFS-CBQ; Putnam & Rothbart, 2006). Only three out of the twelve items of the instrument (per dimension) were used in the NEPS assessments due to time constraints. Although these items were carefully selected based on pre-studies (Bayer et al., 2015), the reliability of such short scales is limited. Therefore, we decided to aggregate the scores across ages 3, 4 and 5 to increase reliability (see results for robustness checks). However, future studies should investigate more-item scales of these facets longitudinally in their relation to SL development. Furthermore, in our study there was only one indicator for each facet of self-regulation due to time restrictions; this could be improved in future studies by including more tasks for each facet. For instance, the backward digit span task and the backward corsi block test (Fanari et al., 2019) could be used as further indicators of working memory (as these tasks require mental manipulation of verbal and visual-spatial information) to investigate whether other facets of working memory impact even more on SL development (Anthony & Ogg, 2020). Similarly, response inhibition tasks such as Go/No-go and cognitive flexibility tasks such as the DCCS could be included to test if the results are specific to the indicator or the theoretically supposed facet of self-regulation. Given that the delay of gratification task lacks developmental sensitivity, including additional direct tasks measuring the same facet could be beneficial. Furthermore, delay of gratification and CBQ-effortful control were measured using different assessment methods. Future studies could benefit from using comparable assessment approaches (i.e., either performance or report based) when assessing the relations between emotion-related facets and SL development. Finally, we could not include any indicators of the learning environments except overall family SES; thus, future studies could also control for preschool and/or school-related factors such as SL stimulation/training, quality of education and quality of the student-teacher relationship (Gropen et al., 2011) as these programs support children's ability to reflect and revise their scientific investigations e.g., either through collaborative learning or conducting training programs for teachers helping them have extended interactions about scientific processes.

10. Conclusion

Despite these limitations, the findings of this study contribute to the literature by demonstrating a positive relation between early facets of self-regulation such as phonological working memory and inhibitory control and SL development from preschool to primary school age (ages 5 and 7). Furthermore, the CBQ-effortful control measure was also significantly associated with SL performance at age 5 even when controlling for other influential child and family factors. While these relationships cannot be interpreted as causal, future studies could examine these associations further. In particular, intervention studies might help to show whether improving self-regulation could lead to advanced SL development. Interventions focused on strengthening self-regulatory abilities in preschool might be especially beneficial to SL development as they may teach children to think critically in the context of scientific inquiry (Gropen et al., 2011) and because the stage for later developments in school seem to be set already in preschool age.

CRediT authorship contribution statement

Aashna Doshi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Sabine Weinert:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Manja Attig:** Writing – review & editing, Methodology.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lindif.2024.102515.

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