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# Exploring the Self-Regulation Universe

*Developmental Dynamics from Early Caregiving to  
Brain and Behaviour*

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### Abstract

Jónsdóttir, L. K. 2026. Exploring the Self-Regulation Universe. Developmental Dynamics from Early Caregiving to Brain and Behaviour. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Social Sciences* 242. 84 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-2776-1.

Childhood **self-regulation**, the ability to modulate behaviour, cognition, and emotion in service of adaptive behaviour and higher-order goals, is a robust predictor of important outcomes within childhood and beyond. Despite considerable research interest, the developmental pathways through which self-regulatory abilities emerge, interact, and relate to later outcomes are not fully understood. This thesis examines several of these pathways across three empirical studies, spanning multiple levels of analysis and developmental timepoints, with a focus on executive function (EF) and emotion regulation (ER). **Study I** investigated whether specific aspects of the early caregiving environment (maternal sensitivity and attachment security) predict self-regulation at age 6, and whether hot and cool EF in toddlerhood mediates these relationships. Contrary to hypotheses, no longitudinal associations were observed, raising important questions about whether the relationship between early caregiving and later self-regulation is more conditional, non-linear, or measurement-dependent than current models suggest. **Study II** examined whether inhibitory control in toddlerhood predicts internalizing and externalizing problems at age 9–10, and whether ER at age 6 mediates these pathways. No significant associations were found between early inhibitory control and later ER or internalizing or externalizing problems. However, general ER at age 6 predicted lower levels of both internalizing and externalizing problems, highlighting ER as a transdiagnostic, potentially modifiable factor in the development of childhood psychopathology. **Study III** examined developmental differences in choline concentration in the dorsal anterior cingulate cortex (dACC), a region implicated in error monitoring, action selection, and cognitive control, and its associations with cognitive control performance across children, adolescents, and adults. The association between dACC choline and cognitive control reversed direction across developmental stages (negative in children and positive in adults), suggesting that the neurobiological significance of this metabolite shifts fundamentally with development. Taken together, these findings reflect the conceptual and methodological complexity of studying self-regulation across development. While self-regulation remains a meaningful predictor of socioemotional outcomes, and neurobiological measures may offer meaningful insights into the development of cognitive control, transparent reporting of null findings reporting and continued refinement of theoretical and measurement approaches are necessary for advancing a cumulative science of self-regulation development.

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*To my parents, Jón Ingi and Harpa, for gently supporting my every  
endeavour, whether stupid or smart. (This was a smart one).*



# List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I. Jónsdóttir, L.K., Forslund, T., Frick, M.A., Frick, A., Heeman, E. J., & Brocki, K. C. (2024). A challenge to the expected: Lack of longitudinal associations between the early caregiving environment, executive functions in toddlerhood, and self-regulation at 6 years. *Developmental Science*, 27, e13526.
- II. Jónsdóttir, L. K., Frick, M. A., Frick, A., Heeman, E. J., & Brocki, K. C. (2026). Examining early inhibitory control and emotion regulation as predictors of childhood internalizing and externalizing problems: A longitudinal study. *JCPP Advances*, e70093.
- III. Jónsdóttir, L. K., Frick, A., Frick, M. A., Forsgren, M., Widegren, E., Gingnell, M., Weis, J., Heeman, E. J., & Brocki, K. C. (in preparation). Choline Concentration in the Dorsal Anterior Cingulate Cortex: Developmental Patterns and Associations with Cognitive Control.

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# Abbreviations

|          |  |
|----------|--|
| ABAS-II  | Adaptive Behaviour Assessment II         |
| BDS      | Backward Digit Span                      |
| CSF      | Cerebro Spinal Fluid                     |
| D-KEFS   | Delis-Kaplan Executive Function System   |
| dACC     | Dorsal Anterior Cingulate Cortex         |
| DCCS     | Dimensional Change Card Sorting task     |
| EF       | Executive function                       |
| EQ       | Emotion Questionnaire                    |
| ER       | Emotion regulation                       |
| EXT      | Externalizing problems                   |
| FDS      | Forward Digit Span                       |
| GM       | Grey Matter                              |
| HiTOP    | Hierarchical Taxonomy of Psychopathology |
| INT      | Internalizing Problems                   |
| MICE     | Multiple Imputation by Chained Equations |
| OSF      | Open Science Framework                   |
| PCA      | Principal Component Analysis             |
| PCC      | Posterior Parietal Cortex                |
| PFC      | Prefrontal Cortex                        |
| RDoC     | Research Domain Criteria                 |
| SDQ      | Strengths and Difficulties Questionnaire |
| SEM      | Structural Equation Model                |
| SNR      | Signal-to-Noise Ratio                    |
| SSP      | Strange Situation Procedure              |
| tCho     | Total Choline signal                     |
| tCr      | Total Creatine signal                    |
| TMT-B    | Trail Making Test B                      |
| WM       | White Matter                             |
| $\alpha$ | Alpha                                    |



# Introduction

*“What do you think your parents will say when I tell them you did this? Or even better, when I have to call and tell them you were seriously hurt?!”*

*I’m standing in one of the most beautiful places in Iceland, Stóruvöð, surrounded by green meadows and enormous boulders, with turquoise blue ponds scattered between them. I, a relatively inexperienced special education teacher, am yelling at the top of my lungs, utterly hopeless that I am in any way solving the problem. It is the school’s annual hiking day, and the tenth-grade students and teachers have made it halfway through the multiple-hour hike through Stóruvöð. Five of the 15-year-old boys in my care have taken a sharp turn away from the group, which was strictly forbidden, and managed to climb on top of one of the largest boulders in the area, with at least 15 meters of vertical drop down into rocky terrain. The boys are sitting there, dangling their legs from the edge, laughing at the tiny teacher panicking below. I am absolutely terrified. Fortunately, a more experienced teacher is close by, and through sheer gravitas and authority, she manages to get the boys down safely in time for the bus ride home. The joke, it seems, was getting old anyway.*

Moments like this, repeated across classrooms, playgrounds, and everyday life, illustrate the importance of a skill that is central to adaptive functioning in childhood and beyond: the ability to guide one's behaviour, emotions, and thinking in situations that demand restraint, flexibility, or foresight. In this thesis, I explore developmental aspects of these skills, which are collectively referred to as self-regulation. In a broad sense, self-regulation refers to the ability to adapt one's behaviour, cognition, and emotion to the situation at hand, that is, to regulate in line with a higher-order goal rather than act on immediate impulses (Inzlicht et al., 2021; Nigg, 2017). From this perspective, the boys on the boulder failed to regulate their behaviour. The immediate impulse to climb (and be cool in the eyes of their classmates) overrode the higher-order goal of staying safe (although the goal of being cool perhaps was more important to these teenagers in this instance...but that is a different

discussion!). I will let the reader judge my own regulatory performance in that situation.

Individual differences in self-regulation are associated with a wide range of important outcomes, both in childhood and beyond, including academic achievement, mental and physical health, adaptive behavior, criminality, personal finances, and substance abuse (Moffitt et al., 2011; Robson et al., 2020). While self-regulation abilities have been found to be highly heritable (Freis et al., 2022; Friedman et al., 2008; Willems et al., 2019), environmental factors also play an important role in their development (Bernier et al., 2012; Rhoades et al., 2011; Wu et al., 2021). Given its broad relevance for human functioning, self-regulation has attracted considerable research attention across developmental psychology, neuroscience, and clinical science.

Yet despite this interest, the field remains far from a complete picture. In a seminal paper on the self-regulation construct, Joel Nigg (2017) aptly described self-regulation research as a universe, which fits well with its multidimensional nature. Within this universe, different aspects of self-regulation can be organized along dimensions such as their level of granularity, their developmental patterns, and the timescale on which they operate. Self-regulation is therefore not a single, unified capacity, but a host of related abilities that may follow distinct developmental trajectories, rely on partially different biological mechanisms, and relate to outcomes in different ways (Nigg, 2017). While much has been learned about individual regions of this universe, large parts of it remain unexplored. How different regulatory abilities relate to each other across development, what shapes their emergence, and what their neural underpinnings look like across the full developmental span, are all questions that need further attention. The present thesis addresses several of these open questions, exploring different regions of the self-regulation universe across multiple levels of analysis and developmental timepoints.

## Defining self-regulation: conceptual landscape and key distinctions

While self-regulation may seem fairly straight-forward based on its definition, it is scientifically very complex. Indeed, self-regulation is most useful as an umbrella term for several different kinds of regulatory abilities we humans possess. Under self-regulation, we have constructs such as *executive function*, *emotion regulation*, *effortful control*, *behavioural inhibition*, *cognitive control*, and many others (Nigg, 2017). Each of these constructs represents different aspects of how individuals modulate thought, emotion, and action over time and across contexts, and is measured in its own specific way. Although these constructs are related, they are not interchangeable. Different aspects of

self-regulation may rely on partially distinct developmental pathways and biological mechanisms, and may therefore relate to outcomes in different ways. Building a knowledge base on how different self-regulatory abilities in childhood relate to future outcomes is therefore foundational for development of successful interventions, and for our understanding of childhood risk and resilience.

In this thesis, the focus is on executive function, a foundational aspect of self-regulation, and some of its different presentations. An additional self-regulatory ability, emotion regulation, will also be examined in association with executive function. These constructs will now be described in turn.

### **Executive function**

Executive function (EF; also referred to as cognitive control) can be described as a set of mental processes, which serve to allocate attention and guide behaviour in the service of adaptive goals (Diamond, 2013; Friedman & Miyake, 2017; Miyake et al., 2000). A particularly influential characterization describes EF as three separable yet interrelated core components; inhibitory control, working memory, and set-shifting (Miyake et al., 2000).

Among these core components of EF, inhibitory control, defined as the top-down ability to override a prepotent action or thought which is incompatible with a higher order cognitive goal (Anderson & Weaver, 2009; Hofmann et al., 2012; Nigg, 2017), has received particular attention as a predictor of a wide range of developmental outcomes. Inhibitory control emerges early and can be detected already in infancy (Holmboe et al., 2018), with individual differences becoming moderately stable and reliably measurable by 2 years of age (Broomell & Bell, 2022). The period between 3 and 5 years is marked by especially rapid improvement (Carlson, 2005; Garon et al., 2008, 2014; Wiebe et al., 2012), and early childhood represents a foundational window in which inhibitory control capacities are both highly plastic and predictive of future outcomes. Beyond its direct associations with later outcomes, inhibitory control has also been proposed to play a foundational role in the development of other aspects of self-regulation, most notably emotion regulation, by supporting the capacity to modulate attention and override maladaptive emotional responses (Bartholomew et al., 2021; Joormann, 2010; Pruessner et al., 2020). However, despite its theoretical importance, longitudinal evidence linking early inhibitory control to later emotion regulation and psychopathology outcomes remains limited, and the developmental mechanisms through which early inhibitory control shapes later self-regulatory abilities and psychopathology outcomes are not yet well understood.

An alternative view of EF invokes emotional and motivational context as a theoretical continuum, ranging from “*cool*” to “*hot*,” on which EF operates to regulate behaviour (Zelazo & Carlson, 2012; Zelazo & Miller, 2002). Cool EF is thought to be engaged in emotionally neutral contexts, which includes the majority of traditional, decontextualized, laboratory tasks measuring EF. Hot EF is thought to consist of skills used in situations that are motivationally and emotionally significant, and is further engaged in reappraising approach or avoidance of a salient stimulus (Zelazo, 2020). Evidence for a distinction between cool and hot EF at a behavioural level (Moriguchi, 2022; Perone et al., 2018; Zelazo, 2020; Zelazo & Müller, 2011), and a neural level (Happaney et al., 2004; Moriguchi, 2022; Nejati et al., 2018.; Perone et al., 2018), indicates that these could be differentially informative with respect to children's developmental outcomes, warranting their independent examination as predictors of later functioning. Nevertheless, relatively few studies have explicitly examined whether cool and hot EF are differentially predictive of children's outcomes, highlighting the need for research that models both constructs simultaneously.

### **Emotion regulation**

While definitions vary, ER can be broadly described as the ability to successfully modulate the intensity, duration, and quality of an affective state, experience, or response, in the service of a higher order cognitive goal (Eisenberg et al., 2007; Gross, 2015). ER is an aspect of self-regulation, that builds on and is supported by simpler regulatory processes. In this sense, ER theoretically represents a more complex layer of self-regulation, one that depends on foundational capacities such as inhibitory control to function effectively (Bartholomew et al., 2021; Joormann, 2010, 2019; Ochsner et al., 2012; Pruessner et al., 2020).

In infancy and early toddlerhood, successful ER relies heavily on caregiver-supported processes, with a gradual shift toward reliance on internal regulation strategies across toddlerhood and early childhood (Cole et al., 2004; Eisenberg & Spinrad, 2004). The transition into school-age is marked by especially rapid improvement in ER (Blandon et al., 2008; Murray et al., 2025; Noroña et al., 2018), as internal strategies become more sophisticated and increasingly child-directed (Kopp, 1989): a process that continues throughout later childhood and adolescence (Silvers, 2022).

Foundational self-regulation capacities, such as inhibitory control, may play an important role in shaping how ER develops over time (Bartholomew et al., 2021; Hughes et al., 2023; Pruessner et al., 2020), yet longitudinal

evidence on how early regulatory abilities contribute to the development of later ER remains limited.

ER has been described as a robust, transdiagnostic factor in childhood behavioural and emotional problems and psychopathology (Aldao et al., 2016; Beauchaine, 2015; Cavicchioli et al., 2023; Compas et al., 2017; Fernandez et al., 2016). ER is therefore a particularly important target for understanding the development of psychopathology more broadly, and as a potential mechanism through which earlier regulatory capacities influence later psychopathology.

How earlier, simpler self-regulatory capacities shape the emergence of more complex emotion regulatory skills across development, and how such associations may influence later socioemotional outcomes, therefore remains an open question.

While the complexity inherent in self-regulation research reflects the multidimensionality of the phenomenon itself, this comes with its challenges. The field has reached a point of both great promise, and significant confusion, with many constructs, many measures, and a lack of consensus on definitions (Baggetta & Alexander, 2016; Inzlicht et al., 2021; Nigg, 2017; Vink et al., 2020). One article referred to the state of affairs as “conceptual clutter and measurement mayhem” (Morrison & Grammer, 2016). Many self-regulation constructs overlap, but are often not modelled as such, and the developmental relationships between them remain poorly understood. Examining how distinct regulatory abilities relate to each other over time, rather than treating self-regulation as a single undifferentiated construct, is therefore an important step toward clarifying both the structure of self-regulation and its consequences for later development. In addition, progress in the field requires examining self-regulation at multiple levels of analysis. Self-regulation emerges from the interplay of neural, biological, and environmental factors, and no single method or level of analysis is sufficient to capture this complexity fully. Combining behavioural, longitudinal, and neurobiological approaches therefore offers a more complete picture of how self-regulation develops and what shapes it.

## Development of self-regulation – from simple to complex

One of the most fascinating aspects of self-regulation development is its timescale. While many basic cognitive and perceptual abilities reach maturity already in childhood, self-regulation continues to develop well into early adulthood. From the first months of life, the brain and body begin developing in ways that support the regulation of behaviour, cognition, and emotion. Rudimentary regulatory behaviours, such as tactile self-stimulation (e.g., hand-to-mouth behaviours) and attention regulation (diverting or sustaining attention), emerge during the first year and form the foundation for later development

(Hendry et al., 2016; Petersen & Posner, 2012; Wesarg-Menzel et al., 2023; Wu et al., 2021).

These early capacities gradually become integrated into more complex effortful and automatic processes, in tandem with the development of attentional control, motor skills, and communication skills (Frick et al., 2017; Garon et al., 2014; Hendry et al., 2016; Wu et al., 2021). Across this process of hierarchical development, self-regulation shifts from being rooted in simple, largely involuntary behaviours dependent on external regulation provided by the caregiver, to becoming more complex, voluntary, and endogenous to the child (Wesarg-Menzel et al., 2023). Different self-regulatory abilities become integrated over time, enabling their use in increasingly complex and flexible ways. Importantly, this development is not linear. Different self-regulatory abilities mature at different ages, and rapid improvements are observed during specific windows of development (Best & Miller, 2010; Brocki & Bohlin, 2004). In addition, previous evidence from neuroscience and natural experiments (e.g. outcomes of early neglect of later adopted infants) indicates multiple sensitive periods in the development of self-regulation, during which environmental influences play a particularly important role in shaping these capacities (Larsen & Luna, 2018; Silvers, 2022; Thompson & Steinbeis, 2020).

The early caregiving environment is thought to serve as a particularly salient environmental factor, as it constitutes the primary social context in early life (Calkins et al., 2016; Samdan et al., 2020).

Two prominent regulatory aspects of the early caregiving environment are caregiver sensitivity and attachment security, which are theoretically distinct, yet highly related. While caregiver sensitivity refers to caregiver's ability to promptly and appropriately perceive, interpret and respond to their infant's signals (Ainsworth, 1969) attachment security refers to infant's expectancies regarding their caregiver's availability and responsiveness (Salter Ainsworth et al., 2015). Secure attachment should therefore, in theory, reflect a history of sensitive caregiving.

A core assumption of attachment theory is that the influence of attachment security in infancy has enduring effects on early socioemotional development (Weinfield et al., 2008). However, empirical evidence reveals complexities; the link between caregiver sensitivity and attachment security is only moderate (Bailey et al., 2007; Bigelow et al., 2010; Deans, 2018; Leerkes, 2011; Susman-Stillman et al., 1996), and while both predict later outcomes like executive function and social competence (Bernier et al., 2015; Cheng et al., 2018; Deans, 2018; Groh et al., 2014), these associations are sometimes weak or inconsistent (Belsky & Fearon, 2002; Fearon & Roisman, 2017; Forslund et al., 2020). Few studies examine both constructs simultaneously, though

limited evidence suggests attachment security may be a stronger predictor of self-regulation outcomes than caregiver sensitivity (Bernier et al., 2012; Kim et al., 2014; Leerkes & Wong, 2012). This raises important questions about which measure better captures early caregiving quality, and calls for more research on the mechanisms underlying their effects on child development.

Taken together, current theory and empirical evidence indicates that early development of simple self-regulatory abilities influences later, more complex self-regulation, and that the impact of environmental experience on this trajectory is not uniform across development, but is instead concentrated in sensitive periods during which the developing system is particularly responsive to external influences. One of these periods is infancy and early childhood, during which external regulation is increasingly internalized.

Despite broad agreement on the architecture of this developmental trajectory, several questions remain. It is unclear how aspects of the early caregiving environment shape the development of self-regulation, and through what mechanisms early regulatory capacities predict later, more complex forms of self-regulation. More broadly, the downstream consequences of this developmental pattern for socioemotional adjustment remain poorly understood.

## Self-regulation in socioemotional adjustment and psychopathology

In recent decades, child and adolescent mental health problems have become an increasing concern especially in the Western world, with research showing increased prevalence (Collishaw, 2015), earlier onset (Armitage et al., 2023), and worsening social, educational, and health outcomes (Sellers et al., 2019). Approximately 12% of Swedish children receive psychiatric care in a given year (Swedish National Board of Health and Welfare, 2024), which is similar to the global prevalence of mental disorders in children and adolescents (11.6%;(Kieling et al., 2024). While there is considerable debate on what the observed increase in prevalence indicates (Foulkes & Andrews, 2023; Timimi, 2025), increased attention is certainly being paid to child and adolescent mental health. Translating this attention into meaningful clinical progress requires understanding of the underlying mechanisms of psychopathology, which is essential for further development of treatments and interventions. Self-regulation represents one such mechanism, with robust evidence indicating that executive function and emotion regulation are important, transdiagnostic factors in psychopathology (Aldao et al., 2016; Cavicchioli et al., 2023; Halse et al., 2022; Yang et al., 2022), conferring risk across multiple forms of psychopathology rather than being specific to any single diagnosis. This aligns with contemporary frameworks such as the Hierarchical Taxonomy of

Psychopathology (HiTOP; (Kotov et al., 2017) and the Research Domain Criteria (RDoC; (Insel et al., 2010), both of which reconceptualize psychopathology as existing along continuous dimensions and emphasize the importance of identification of transdiagnostic mechanisms. Within HiTOP, internalizing problems (INT; e.g., worry, sadness, social withdrawal) and externalizing problems (EXT; e.g., impulsivity, defiance, aggression) represent broad dimensional spectra that underlie many distinct diagnoses, and are associated with concurrent and later maladjustment even in non-clinical samples (Fanti & Henrich, 2010; Kassing et al., 2019; Mason et al., 2004; Roza et al., 2003; Vergunst et al., 2023). Further study of the role of early self-regulation development in the emergence of INT and EXT symptoms therefore has the potential to elucidate specific targets for intervention, and knowing when distinct, early self-regulatory abilities become meaningfully associated with later outcomes can strengthen this knowledge even further. However, longitudinal research examining how specific, early self-regulatory abilities differentially predict INT and EXT remains limited, and the developmental pathways through which these associations unfold are not yet well understood.

The protracted development of self-regulation, coupled with its importance for socioemotional adjustment and psychopathology, raises questions about its underlying mechanisms, that behavioural data alone may not be able to answer. Moving beyond the behavioural level and examining neural substrates of self-regulation across development further adds to our understanding of how self-regulatory abilities are refined from childhood into adulthood, and what drives this refinement.

## Neural substrates of cognitive control across development

The prefrontal cortex (PFC) has long been identified as the primary neural substrate of cognitive control (Diamond, 2002; Fuster, 2002; Kolk & Rakic, 2022; Miller & Cohen, 2001). The PFC is one of the last brain regions to reach full maturity (Casey et al., 2005; Diamond, 2002), with ongoing structural, functional, and neurochemical changes observable from infancy to early adulthood (Caballero et al., 2016; Fiske & Holmboe, 2019).

This protracted development of the PFC maps onto the extended time period of self-regulation development, with a wealth of literature demonstrating developmental associations between the two (Chevalier et al., 2019; Diamond, 2002; Fiske & Holmboe, 2019; Fiske et al., 2025; Ravindranath et al., 2022).

A consistent finding in the cognitive neuroscience literature is that cognitive control does not reside within the PFC alone, but is supported by large-scale functional brain networks. These networks are composed of different regions in the brain that show temporally synchronized patterns of neural activity (Menon

& D'Esposito, 2022). Across development, organization and connectivity within these networks undergo substantial changes, with increased myelination of pathways, and structural and functional changes within connected regions (Fiske & Holmboe, 2019; Oldham & Fornito, 2019). This means that while the PFC is a foundational region, many areas of the brain are of interest when it comes to studying the development of cognitive control. One of these areas is the dorsal part of the anterior cingulate cortex (dACC). While the exact description of the role of the dACC in human functioning is still debated (Holroyd & Yeung, 2012; Shenhav et al., 2016; Touroutoglou et al., 2020; Vassena et al., 2017), previous evidence shows that the dACC is an important hub in several brain networks related to cognitive control (Menon & D'Esposito, 2022; van den Heuvel & Sporns, 2013), with connections to cortical and subcortical structures, and has on its own been implicated in several distinct self-regulatory abilities, such as error monitoring, and reward-based decision making (Touroutoglou et al., 2020). Increased understanding of the developmental integrity of the dACC is therefore central to elucidating the neural mechanisms by which cognitive control is refined across development.

In addition to studies on structural and functional neuroimaging, recent work has begun examining neurochemical mechanisms underlying cognitive control development (Larsen et al., 2022; Zhang et al., 2024). However, neurochemicals fundamental to neural signalling and structural integrity remain largely unexplored. One such candidate is choline, a metabolite involved in cholinergic neurotransmission, methylation for epigenetic regulation, and the synthesis of phospholipids essential for dendritic growth, synapse formation, and myelination (Bekdash, 2019; Wang et al., 2017). These processes are all particularly active during periods of structural and functional remodelling, suggesting that choline concentration in the dACC might be indirectly associated with cognitive control development. In fact, there is ample evidence from animal research (Derbyshire & Obeid, 2020; Gámiz & Gallo, 2021; McCann et al., 2006), and some indications from human research (Gould et al., 2025; Obeid et al., 2022), of the involvement of choline in higher-order cognition. Given choline's role in the structural and functional processes active during dACC maturation, and evidence linking cholinergic integrity in the ACC to executive function in adults, there is reason to further examine age-related patterns and individual differences in dACC choline and their associations with cognitive control development.

# Aims of the thesis

The overarching aim of this thesis is to explore the self-regulation universe across multiple levels of analysis, developmental timepoints, and levels of granularity. Three studies were conducted, each with a focus on slightly different aspects of the self-regulation universe, but all with the common goal of deepening our understanding of how self-regulation develops and what it predicts.

Specifically, the aims of the three studies were:

Study I: To examine whether caregiver sensitivity and attachment security in early childhood predict self-regulation at age 6, and whether this association is mediated by hot and/or cool self-regulation at age 4.

Study II: To examine whether inhibitory control at age 4 predicts internalizing and externalizing problems at ages 9–10, and whether this association is mediated by emotion regulation at age 6.

Study III: To examine the association between choline concentrations in the dACC and cognitive control in childhood, adolescence, and adulthood, and whether this association differs across developmental stages.

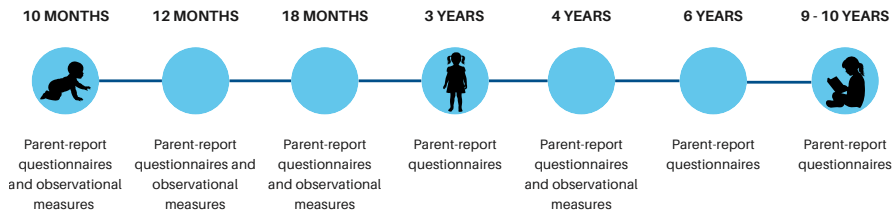
# Methods

## Participants

### Study I and II

All participants in Study I and Study II were part of the EFFECT study, a longitudinal, multi-method project on the development of self-regulation (Frick et al., 2019, 2017; Heeman et al., 2024, 2025; Jónsdóttir et al., 2024, 2026). The sample was recruited from the local birth registry in Uppsala, Sweden, between August 2013 and June 2014. Families in the area, with newborns, received a general letter of recruitment from Uppsala Child- and BabyLab. The response rate was 30%. 146 of the interested caregivers were contacted a few weeks before their infants turned 10 months old. Initial exclusion criteria were atypical development, preterm birth (child was born before 37 weeks gestational age;  $n = 2$ ), and parents not speaking Swedish with the child ( $n = 6$ ). In addition to exclusion based on predetermined criteria, further initial attrition was caused by the following; participation declined due to having moved out of the region ( $n = 2$ ), or the project being too time-consuming ( $n = 10$ ). Initial exclusion and attrition resulted in a sample of 126 infants and their families.

The study had 7 waves of data collection, with the latest data collection taking place in 2023 (see Figure 1 for the study's timeline). For Study I, data from waves 1, 2, 4, and 5 were analysed. For Study II, data from waves 5, 6, and 7 were analysed. For Study I and Study II, participants who provided data at fewer than two timepoints were excluded. In Study I, two additional participants were excluded from the analyses due to atypical development, resulting in a final sample of 108 infants. In Study II, a final sample of 94 participants provided data on at least two of the study's timepoints.



**Figure 1.** A timeline of data collection within the EFFECT project, and broad description of data collected

### Missing data and multiple imputation

As is the case for most longitudinal studies, especially those involving children, there was variation in sample size between waves of data collection. Both permanent and temporary attrition was observed, meaning that while there was some data loss due to participants dropping out of the study, some participants also returned to the study after having missed one or more waves of data collection. In addition, there was variation in sample size for each task or questionnaire within the waves, due to various factors, such as fatigue and experimenter error. In Study I and Study II, missing data was addressed using multiple imputation by chained equations (MICE). With this method, we estimate a person's missing datapoint based on their own observed data, as well as the rest of the sample. Regression models are fitted using participants with observed values (using all variables or an appropriate selection), and multiple plausible values for the missing ones are drawn (Azur et al., 2011). Multiple completed datasets are therefore created, reflecting the uncertainty in the estimations of missing values. Analyses are then run individually on each of the multiple datasets, and results of these analyses are pooled. In Study I and Study II, pooling was done using software packages that rely on Rubin's rules (Rubin, 1987), where the point estimate is the average of estimates across the different datasets, and the standard error reflects both the within-analysis sampling error and the difference in estimates between different datasets. Correspondence checks are of high importance when using imputation methods such as MICE, to ensure adequate correspondence of the original data and the imputed data. Several useful methods of comparison are available. In Study I and II, visualizations and summaries of variable distributions were compared for imputed and non-imputed data, and correspondence was deemed satisfactory (visualizations and/or summaries were included in appendices with the published articles).

### Study III

All participants in Study III were part of the FEAR project, a cross-sectional, multi-method study on neural and psychological aspects of fear conditioning in three different age groups; children, adolescents, and adults (Widegren et al., 2024, 2025). The original dataset contains structural and functional MRI data, data from behavioural and eye-tracking tasks, and various questionnaires measuring psychological variables and general background factors.

Participants were recruited from ongoing longitudinal studies at the Department of Psychology, Uppsala University, as well as through online advertisements, between September 2019 and June 2022. For the purposes of the original project, the participants were initially recruited based on age into three distinct age groups; children (6 - 9 years old), adolescents (13 - 17 years old), and adults (30 - 40 years old). The inclusion criterion was belonging to one of these age groups. Exclusion criteria were the following; hearing impairment, uncorrected visual impairment, presence or history of a severe psychiatric problem, somatic conditions, or neurological conditions, atypical development, ongoing pharmacological treatment, pregnancy, menopause, and contraindications for MRI scanning. When either contacted by recruiter, or after responding to an advertisement for participation, potential participants, and, in the case of children or adolescents, their parents, were provided with a link to a webpage containing more information about the study. Participants who agreed to take part completed an online consent form and a screening questionnaire covering the exclusion criteria. If the responses to the questionnaire indicated eligibility for participation, adult participants were contacted by phone and underwent the Mini International Neuropsychiatric Interview (MINI; Sheehan et al., 2010) by phone with a trained clinician. Eligible adolescent and child participants completed the MINI-KID interview by phone conducted by a trained clinician.

Exclusion and initial attrition resulted in a total of 148 eligible participants (53 children, 41 adolescents, and 54 adults). After additional attrition during the study ( $n = 20$ ), participants with missing data on the cognitive control measures ( $n = 2$ ; 1 child, 1 adolescent), or missing or technically invalid MRS data ( $n = 22$ ; 12 children, 2 adolescents, 6 adults), were excluded from the analysis. The final analytical sample ( $n = 106$ ), with complete MRS and cognitive control performance data, consisted of 23 children (15 females, 65%, 8 males, 35%), 38 adolescents (21 females 55%, 17 males, 45%), and 45 adults (22 females, 49%, 23 males, 51%).

## Procedures

### Study I and II

Data for Study I and II comes from different waves of data collection within the EFFECT project (see Figure 1). For Study I, data from waves 1, 2, 4, and 5 were analysed. For Study II, data from waves 5, 6, and 7 were analysed. At waves 1, 2, and 5, participating parent/child dyads visited the laboratory facilities at Uppsala University. During these visits, the children and their parents participated in a series of structured and semi-structured tasks. Each visit lasted approximately 2 hours. At waves 4, 6, and 7, parents responded to an online questionnaire containing several scales. Caregivers provided written, informed consent for their own and their child's participation. Participation was reimbursed with gift cards at each timepoint of data collection (worth 200 SEK).

### Study III

Participants responded to online questionnaires (adults and adolescents completed self-report questionnaires, parents of participating children completed parent-report questionnaires), and took part in two in-person visits. During the first visit, participants completed a series of cognitive tasks in addition to a fear acquisition and extinction paradigm. During the second visit, participants underwent MRI scanning at Uppsala University hospital. In addition to the MRS sequence used for analysis in Study III, the scanning protocol included functional and structural imaging sequences. Total scan time was approximately 40 minutes. Adult participants and caregivers of children and adolescents participating in the study provided written informed consent, and informed assent was obtained from participating children and adolescents. Participation was reimbursed with a gift card (worth 850 SEK).

## Measures and analyses

### Study I – II

#### **Maternal Sensitivity Scales**

The Maternal Sensitivity Scales (Ainsworth, 1969) were used to code a semi-structured play session. The scales address a mother's ability to perceive, accurately interpret, and respond promptly and appropriately to the infant's signals.

The 26-minute semi-structured play session was divided into 6 blocks of different lengths, with each block placing a different level of demand on the mother.

In the first block (3 mins), the mother was asked to fill out a form, and the experimenter left the room to fetch some toys for the infant, leaving the mother to divide her attention between filling in the form and the infant, with no toys in the room. In the second block (3 mins), the experimenter brought a set of toys and again left the room, while the mother was still filling out forms. In the third block (7 mins), the experimenter brought a new set of toys, and the mother was instructed to play with the infant as she would do at home. In the fourth block (4 mins), the experimenter brought a children's book for the mother and infant to read and explore. In the fifth block (4 mins), the experimenter brought a toy, assumed to be difficult for an infant this age to master, for the mother and child to play with. In the sixth block (5 mins), the mother and infant were left to play without toys.

Criterion-related validity has been established for the scales with other measures of maternal sensitivity. Video recordings of the sessions were coded as a whole on a 9-point scale of the mother's responses, ranging from 1 = *highly insensitive*, to 9 = *highly sensitive*. A set of 25 randomly selected cases was coded by two independent raters, and inter-rater reliability was ICC = 0.74.

### **Strange Situation Procedure**

At 12 months, the standard Strange Situation Procedure (SSP) (Salter Ainsworth et al., 2015) was performed to assess infant-caregiver attachment security. The SSP aims to activate the attachment system using mild stressors, including an unfamiliar ("strange") environment, a stranger, and two brief separations from the caregiver. The procedure took place in a room that contained the following: a floor rug, a set of toys, two chairs, and two magazines.

Between episodes, the mother and the researchers monitored the infant through a live video feed, and instructions were provided to the mother.

Eight video-recorded episodes of the procedure were performed as follows: 1) the mother and infant were introduced to the room. The mother was instructed to place the infant on the rug, bring the toys to the infant's attention, and then have a seat and read a magazine. 2) the mother sat quietly in the chair and read for 3 minutes, and responded naturally to the infant as needed. 3) a stranger (trained researcher) entered the room. The stranger proceeded to read quietly for 1 minute, then communicate with the mother for 1 minute, and lastly engage with the infant for 1 minute. 4) the first separation took place. The mother left the room, leaving the infant with the stranger for a maximum of 3 minutes. The stranger would calm the child if needed, and then sit quietly and read, while responding naturally to the infant as needed. 5) the first reunion took place. As the mother entered the room, the stranger left, and the

mother proceeded to engage with the infant for a maximum of 3 minutes. 6) a second separation took place. The mother now left the room, leaving the infant alone for a maximum of 6 minutes. 7) the infant was reunited with the stranger. The stranger entered the room and interacted shortly with the baby, calming the child as needed. The stranger then sat down to read quietly and responded naturally to the infant for a maximum of 3 minutes. 8) the second reunion between mother and infant took place.

A certified coder classified each child in one of four attachment categories based on the infant's responses: secure, avoidant-insecure, resistant-insecure, and disorganized.

Attachment security was recoded into a dichotomous variable (0 = insecure, 1 = secure), with insecure comprising the avoidant, resistant, and disorganized classifications. In terms of reliability of this categorization, inter-rater agreement on attachment secure/insecure classification over 25 random cases was excellent (92% agreement, Cohen's unweighted  $k = .86$ , 95% CI, .67–1). The choice of using a two-factor approach was made for two main reasons. First, we had no hypotheses concerning differential effects related to certain subcategories of insecure attachment. Second, based on the sample size of the study, we would most likely have observed a lack of power for analysis based on the different subcategories of insecure attachment.

### **Day/Night Stroop task**

At 4 years, inhibitory control (here, an indicator of cool EF) was measured using the Day/Night Stroop task (Gerstadt et al., 1994). In this task, the child was shown pictures of a sun and a moon on a computer screen, and the experimenter discussed with the child how the sun shines during the day, and the moon shines at night. Next, the child was asked to play an “opposite game”; say “night” when shown a picture of a sun, and “day” when shown a picture of a moon. Previous research indicates that this task captures individual differences in 4-year-olds, with convergent validity between verbal and manual versions of this task (Montgomery & Koeltzow, 2010), and adequate test-retest reliability (albeit in a slightly different version) when used with children in the same age range as the current study (Thorell & Wählstedt, 2006). In total, 12 pictures were presented in a fixed order for 2.5 s each, with 2.5 s pauses between picture presentation. The child's first answer was recorded. Possible scores ranged from 0–12 correct answers.

### **Beads-task**

At 4 years, working memory (here, an indicator of cool EF) was assessed using the Beads task. This task originates from the Stanford-Binet Intelligence Scales (Thorndike, 1986), and is now commonly used as an EF measure,

particularly tapping working memory (Hughes & Ensor, 2005). Within the Stanford-Binet IV, the task is a reliable and valid measure of non-verbal reasoning (McCallum & Whitaker, 2004). In our slightly modified version of the task, the child was presented with a set of 12 wooden beads in three different colors and in four different shapes, along with a photograph of the beads. In a first familiarization trial, the child was asked to identify the beads on the table matching ones the experimenter pointed to on the photograph. In a second familiarization trial, the child was asked to memorize the look of a bead laid out by the experimenter (the bead was presented for 2 s, and then removed from view). The child was then immediately shown the photograph and asked to point out the correct bead. After these familiarization trials, six test trials resembling the second familiarization trial, but increasing in difficulty, took place in the following manner: Trials 1 and 2: One bead presented for 2 s and then removed from view. Trials 3 and 4: Two beads presented for 3 s. Trials 5 and 6: Three beads presented for 3 s. In all trials, the beads were removed from view after presentation, and the child was immediately presented with the photograph and asked to identify the correct beads. Correctly identifying a bead resulted in a score of 1. Possible scores ranged from 0 to 12 correct answers.

### **Dimensional change card sorting task (DCCS)**

At 4 years, set shifting (here, an indicator of cool EF) was measured using the Dimensional change card sorting task (DCCS; Zelazo, 2006). Two boxes were presented to the child, one with a picture of a red rabbit and the other with a picture of a blue boat. This task had two conditions; pre-switch and post-switch. The pre-switch trials were performed in the following manner: The child was asked to play the “shape game,” that is, to sort cards with pictures of rabbits or boats into boxes with a congruent picture, irrespective of colour (one box featured a picture of a blue boat, the other a picture of a red rabbit). The cards were presented in a semi-randomized order, so no more than two cards of the same shape were presented in a row. Feedback was provided during the pre-switch trials. When the child has sorted the cards correctly five times in a row, the pre-switch condition was complete. For the post-switch trials, the experimenter now instructed the child to play the “colour-game,” that is, to sort the cards according to their colour. The experimenter repeated the instructions before handing the child the first card. Cards were labelled as they were passed to the child, for example “this is a red rabbit.” Eight cards (one blue boat, one red rabbit, three red boats, and three blue rabbits) were presented in a semi-randomized order (no more than two of the same colour in a row). There is evidence of good test-retest reliability of this task with

children of this age (Beck et al., 2011; Müller et al., 2012). Performance on DCCS in toddlerhood has been shown to increase with age, and the task has been shown to capture individual differences in 4-year-olds (Carlson, 2005; Doebel & Zelazo, 2015). Score was based on the number of correctly sorted cards in the post-switch condition. Two cards in the post-switch trial were to be sorted congruently to the “shape-game” in the pre-switch trial, meaning a score of 2 might have indicated a persevering sorting strategy. Possible scores ranged from 0 to 8.

### **Snack delay task**

At 4 years, delay of gratification (here, an indicator of hot EF) was measured using the snack delay task (Carlson, 2005; Kochanska et al., 2000). The child was presented with two bowls containing the preferred snack (as chosen by their parent), one bowl contained two treats and the other contained 10 treats. The child was then asked to choose which bowl they preferred (as expected, all children preferred the bowl containing 10 treats). The child was informed they could have the bowl of their choosing if they remained in their seat and waited until the experimenter returned to the room. The child was provided with the option to ring a bell for the experimenter to return immediately, and then receive the bowl they did not prefer (containing two treats). The experimenter then left the room for 3 min unless the child rang the bell. There is evidence of the original version of this task having criterion-related validity (Spinrad et al., 2007), and short-term test-retest reliability (Floyd & Kirby, 2001). Scores were based on the number of seconds the child remained in the room without ringing the bell. Possible scores ranged from 0 to 180.

### **Wrapped gift task**

At 4 years, delay of gratification / behavioural inhibition (here, an indicator of hot EF) was measured using the wrapped gift task (Kochanska et al., 2000). A wrapped gift was presented to the child, after which the experimenter announced they had forgotten the decorative bow for the gift. The child was asked to stay seated and not to touch the gift until the experimenter returned with the bow. The experimenter then left the room and returned after 90 s. At least one previous study found evidence of this task having criterion-related validity (Spinrad et al., 2007). Scores were based on the number of seconds the child refrained from touching the attractive gift (indicated by coding a video recording), with possible scores ranging from 0 to 90.

### **Adaptive Behaviour Assessment II (ABAS-II)**

Personal and interpersonal self-regulation were assessed at 6 years, using the two subscales Self-Direction Skills and Social Adaptive Skills, of the Swedish

version of the parent report questionnaire ABAS-II (Oakland & Harrison, 2008). The ABAS-II measures adaptive behaviour ability, according to a conceptual foundation defined by the American Association of Intellectual and Developmental Disabilities. Based on theoretical models and definitions of the broad construct of self-regulation discussed above, adaptive behaviour ability in both personal and interpersonal contexts can be viewed as the outcome of successful self-regulation. Previous research in typical and atypical populations indicates a robust association between regulatory abilities, such as EF, and adaptive functioning (Clark et al., 2002; Gardiner & Iarocci, 2018; Gligorović & Buha Đurović, 2014; Pugliese et al., 2015), and scores on the ABAS-II, specifically, are associated with regulatory abilities (Ashford et al., 2014; Shultz et al., 2016). The scale has shown strong psychometric properties, with good test-retest reliability for this particular age group ( $r = > 0.80$ ), and good construct validity (Floyd & Bergeron, 2008). Parents evaluated items on a 4-point scale indicating how often their child performs the skill described by the item; 1 = *my child cannot perform this skill*, to 4 = *always or almost always performs when needed*. Importantly, the skills described on both subskills used in this study are directly observable.

The Self-Direction Skills subscale includes items relating to responsibility and self-control, such as staying on task, following instructions, and keeping schedules. Items include (translated from the Swedish version); “*Keeps track of his/her belongings (for example schoolbooks, keys)*,” and “*Concentrates on a single activity for at least 15 min.*” The subscale has 23 items, with possible scores ranging from 23 to 92. Internal consistency (Cronbach's alpha) of the subscale was good,  $\alpha = 0.87$ .

The Social Adaptive Skills subscale includes items relating to keeping and maintaining friendships, quality of communication with peers, and displaying manners and emotions. Items include (translated from the Swedish version); “*Communicates in a polite and friendly manner (uses words such as “please” and “thank you”)*,” and “*Asks for forgiveness when he/she has hurt someone else.*” The subscale has 23 items, with possible scores ranging from 23 to 92. Internal consistency of the subscale in the EFFECT sample was good,  $\alpha = 0.92$ .

### **Emotion Questionnaire (EQ)**

*Emotion regulation* was measured at 6 years, using the Swedish version of the shortened Emotion Questionnaire (EQ; (Rydell et al., 2003), a parent report questionnaire. While the EQ includes a total of 16 items that measure both reactivity and regulation, items pertaining to regulation only (8 items) were selected as a measure of emotion regulation (as in e.g. Frick et al., 2022). Items

assess the child's ability to regulate emotions (anger, fear, joy, sadness) independently or with support. Example items include "*It is easy for others, for instance a parent, to calm him/her down*", and "*He/she has difficulties calming down on his/ her own*" (reversed item). Parents rated items on a 5-point scale (1 = *does not apply at all*, to 5 = *applies very well to my child*). Previous research has indicated reliability, construct and predictive validity, and internal consistency of the scale (Brocki et al., 2019; Frick et al., 2022; Rydell et al., 2003). Internal consistency (Cronbach's alpha) of the whole scale was high in the EFFECT sample;  $\alpha = .89$ . Internal consistencies of measures of regulation of each emotion were somewhat lower, albeit acceptable with only two items, ranging from  $\alpha = .60$  (regulation of sadness) to  $\alpha = .75$  (regulation of anger).

### **Strengths and Difficulties Questionnaire**

*INT* and *EXT* were assessed at 9 – 10 years, using the second-order Internalizing and Externalizing subscales from the Swedish Strengths and Difficulties Questionnaire (SDQ;(A. Goodman et al., 2010; R. Goodman, 1997), a parent-report measure. The SDQ includes 25 items across five subscales (emotional problems, peer problems, behavioural problems, hyperactivity, and prosocial behaviour). These represent broader Internalizing (emotional, peer problems) and Externalizing (behavioural, hyperactivity) scales, plus a Prosocial scale (Caci et al., 2015), which was excluded as it doesn't measure emotional or behavioural problems. Research suggests that second-order Internalizing and Externalizing scales are more informative than the five built-in subscales of the questionnaire for typically developing samples (A. Goodman et al., 2010). Each broad subscale therefore consists of 10 items in the form of statements, with the parent or guardian rating items on a 3-point scale (1 = *not true*, to 3 = *certainly true*). Example items from the Internalizing subscale include; "*Often unhappy, depressed or tearful*", and "*Picked on or bullied by other children*". Example items from the Externalizing subscale include; "*Restless, overactive, cannot stay still for long*", and "*Often fights with other children or bullies them*". Convergent and discriminant validity between the internalizing and externalizing subscales has been shown to be satisfactory (A. Goodman et al., 2010). Internal consistency differed between the two subscales in the EFFECT sample;  $\alpha = .63$  for the Internalizing subscale, and  $\alpha = .88$  for the Externalizing subscale.

### **Statistical analyses**

Hypotheses and analytical plans for Study I were formally preregistered on OSF. For Study II, a preregistration was drafted on OSF and used internally, but not made public.

We chose path analysis as the main analytical approach for the longitudinal models in Study I and Study II. Path analysis (a form of structural equation modelling (SEM) with observed variables) allows for analysis of more complex models than traditional multiple regression. Multiple regression equations are estimated simultaneously, which offers the possibility of analysing models with multiple outcome variables, and for testing direct and indirect (mediated) pathways, including longitudinal paths (Streiner, 2005). Simple relationships between study variables were explored by calculating Pearson correlations between all study variables in Study I and Study II. In Study I, a data-driven decision was made to not perform the planned path analysis on the theoretical model, as bivariate correlations indicated a lack of linear associations between the study variables. In Study II, a more theoretical decision was made to perform the path analysis, despite some lack of correlations.

### Study III

#### **Backward Digit Span**

Children and adolescents completed the Digit Span task from the WISC-V (Wechsler, 2014), while adults completed the Digit Span task from WAIS-IV (Wechsler, 2008). In its entirety, the Digit Span task includes different components; Forward Digit Span (FDS), Backward Digit Span (BDS), and Sequencing Digit Span (SDS). In Study III, we chose to use the BDS. While FDS entails repeating a sequence of numbers and storing it in short-term memory, BDS additionally requires manipulation of the stored information to repeat the sequence of numbers in reversed order, and is therefore often described as a measure of working memory (Conway et al., 2005; Cowan, 2008).

In Backward Digit Span, the participant is asked to listen to a sequence of numbers and then repeat them in reversed order. The task starts with a two-number sequence, and the length of the sequence is increased after each right answer. The raw score of the task is based on how many sequences are repeated correctly; it is the sum of points across all administered sequences. Each sequence is repeated twice, meaning each length of sequence is worth 0 – 2 points. There is evidence of good test-retest reliability of this task in children and adults (Lipsey et al., 2017; Waters & Caplan, 2003). In WISC-V, the BDS consists of 9 test trials (first two trials are two-number sequences), making the possible score range from 0 – 18. In WAIS-IV, the BDS consists of 8 trials (first trial consists of a two-number sequence), making the possible score range from 0 – 16. For harmonization, we changed the maximum score on the WISC-V version to 16 (one participant's score of 17 was changed to 16).

### **Trail-making task B**

Participants completed age-appropriate versions of the Trail Making Test, part B (TMT-B). In the task, participants were presented with a piece of paper with scattered numbers and letters, and asked to draw a line between the numbers and letters in numerical and alphabetical order (1-A-2-B-3-C-4-D etc). If an error was made, the participant was directed to go back to the number or letter before the error, and try again. In the child-version of the task, numbers from 1 to 8 and letters from A to G were to be connected in numerical and alphabetical order. In the version completed by adolescents and adults, numbers from 1 to 13 and letters from A to L were alternated. Ahead of task administration, the youngest participants (6 - 8 years old) were asked to recite the alphabet up to G as a control task. Scores were based on the number of items (numbers and/or letters) circled, relative to completion time (time per item), increasing comparability between task versions. Therefore, a lower score would indicate better performance.

### **Flanker task**

We used the short version of the Attention Network task (the CRSD-ANT; (Weaver et al., 2013). While the CRSD-ANT provides measures for the three attentional functions of the attentional network proposed by Posner and colleagues (alerting, orienting, and executive attention), we exclusively looked at scores on the measure for executive attention, which is based on the Eriksen Flanker task (Eriksen & Eriksen, 1974). Participants are asked to respond to a central stimulus, while ignoring surrounding stimuli. The participant is asked to press a button on a keyboard to indicate the direction of the central stimulus. The task includes two conditions; congruent, and incongruent. In a congruent condition, the central stimulus faces the same direction as the surrounding stimuli. In an incongruent condition, the central stimulus faces the opposite direction from the surrounding stimuli. The incongruency creates an interference effect, as the primed response needs to be inhibited and replaced by the target-based response. There is evidence of good test-retest reliability of this interference effect in adults (Bogdanov et al., 2025). The score on this task was a conflict score, based on the difference between response time (for both correct and incorrect answers) on incongruent tasks and congruent tasks.

### **Tower Task**

The Tower task was used as an indicator of cognitive control. This task originates from the Delis-Kaplan Executive Function System (D-KEFS), which is a collection of tests designed to measure higher level cognitive function in

children and adults, and is designed to capture spatial planning, rule learning, inhibition, and working memory (Delis et al., 2001).

In this task, participants are presented with a flat wooden board with three equidistant pegs, containing up to five wooden disks of increasing size. In each trial, the disks are initially set up in a specific pattern on the pegs. The participant is then asked to move the disks, one at a time, to recreate a tower presented by the experimenter, while only placing smaller disks on top of larger disks. The participant is asked to do this in as few moves as possible. A maximum of 9 trials (each with a different pattern to solve) is presented. In the first 3 trials, only two disks are presented. The number of disks, and/or complexity of the pattern, is increased for each subsequent trial. Test-retest reliability for this task has been found to be moderate for all ages, and there is evidence supporting convergent and discriminant validity (Delis et al., 2001). For Study III, the score on this task is based on “correctness”, that is, the number of moves used to solve the pattern within each trial relative to the minimum number of moves required to solve that pattern. For each participant, the sum of all trial correctness scores was used to indicate cognitive control.

### **<sup>1</sup>H - Magnetic Resonance Spectroscopy (MRS)**

Anatomical T1-weighted images and MRS data were acquired on a Philips Achieva dStream 3T scanner (Philips Healthcare, Best, The Netherlands) with a 32-channel head coil. Participants underwent an anatomical T1-weighted imaging sequence (echo time (TE)=3.8ms; repetition time (TR)=8.2ms; inversion time=685.5ms; flip angle=8°; field of view=240 × 240 mm<sup>2</sup>; voxel size=1 × 1 × 1 mm<sup>3</sup>; 220 contiguous slices) for anatomical referencing. A J-difference Mescher-Garwood spectral editing sequence (MEGA-PRESS) (Mescher et al., 1998)TR/TE 1800/68 ms, spectral bandwidth 2000 Hz, 1024 points, phase cycling 4) was used to acquire the spectra. With this sequence, choline appears as a peak at around 3.2 ppm on the chemical shift spectrum, and represents several choline-containing compounds (free choline, phosphocholine, and glycerophosphocholine). Thirty groups of a total of 120 pairs of edit-ON and edit-OFF spectra were measured. We here use the edit-OFF spectra for quantification of choline and creatine. The volume of interest (voxel) was positioned in the dACC, in parallel with the cingular gyrus, with the anterior part of the voxel placed in line with the anterior tip of the genu of the corpus callosum. The lower boundary of the voxel was immediately dorsal to the corpus callosum. The voxel size was 40 × 40 × 20 mm<sup>3</sup> in the left-right, anterior-posterior, and feet-head directions, respectively.

Concentrations of metabolites were quantified from the unedited spectra (PRESS) using the software Osprey 2.5.0 (Oeltzschner et al., 2020) in

MATLAB (The Mathworks Inc.). Standard processing steps in Osprey were followed. Preprocessing included frequency and phase alignment via robust spectral registration. A linear combination model with a cubic spline baseline (knot spacing of 0.55 ppm) was used to model spectra between 0.5 ppm and 4 ppm employing the TE- and sequence-specific basis sets provided by Osprey. The model also included a standard basis set of simulated macromolecule and lipid components as implemented in Osprey to account for underlying broad background signals. Although the model included 19 metabolites, choline here was the primary metabolite of interest.

Choline concentration was quantified as the ratio of the concentration of choline-containing compounds (tCho; phosphocholine + glycerophosphocholine) to the concentration of total creatine (tCr; creatine + phosphocreatine); tCho/tCr, in line with recent studies on the development of other metabolites (Perica et al., 2022), and because the ratio is often considered a more robust measure than alternatives in the presence of motion or B<sub>0</sub>-inhomogeneities. A limitation with using tCr as the denominator is the increase of creatine from childhood to adulthood observed in previous research (Cichocka & Bereś, 2018; Thomson et al., 2024), which potentially affects the ratio measure and the results from group comparisons. For sensitivity analyses, tissue and relaxation corrected water referenced tCho and tCr was calculated, reported as institutional units. Individual participant fractions of grey matter (GM), white matter (WM), and cerebrospinal fluid (CSF) in the MRS voxel were calculated from voxel placement images co-registered to anatomical T<sub>1</sub>-weighted images and used as input to these calculations together with standard metabolite and water T<sub>1</sub> and T<sub>2</sub> relaxation and tissue water concentration values from the literature as implemented in Osprey, in accordance with another recent study of metabolite changes across development (Thomson et al., 2024). Standard values rather than age- and region-specific relaxation and water concentration values were used, as this is the standard in the field, and because of the difficulty finding exact values for the study's voxel placement and age distribution.

Spectral quality was assessed by visual inspection and quantitatively using several parameters generated by Osprey. Specifically, signal-to-noise ratio (SNR) was calculated as the maximum amplitude of the total creatine (tCr) peak divided by twice the standard deviation of the noise. We applied an SNR threshold of > 20. Creatine full width at half maximum values (FWHM) were determined as the average width at half-maximum of the tCr peak from both the raw data and a Lorentzian fit, with the threshold of <11 Hz for sufficient quality.

## **Analytical approach**

Hypotheses and secondary data analysis plan for Study III were preregistered on the Open Science Framework (OSF) platform (<https://osf.io/mz7c2>). Deviations from the preregistered analysis plan were stated in the final version of the manuscript. Data on cognitive control was reduced using a Principal Component Analysis (PCA), conducted in JASP (JASP Team, 2026). A PCA extracts a linear combination of variables that maximally explain their variance.

In this study, data was analysed using Bayesian multiple regression models. To best address the research questions posed, models with reference coding were fitted. Reference coding enables quantification of group differences. Adolescents were set as a reference group; regression coefficients therefore indicate size of difference from adolescents. In addition, group differences between children and adults were estimated from the fitted models. Weakly informative (regularizing) priors were set for all models, and according to expert guidelines on best practices (see <https://github.com/stan-dev/stan/wiki/prior-choice->), standard normal priors, i.e.  $N(0,1)$ , were used on all fixed effects. Between group differences and interactions were quantified using prespecified Bayesian linear regression models with interaction terms, and this analysis was conducted in R (v. 4.5.2 (R Core Team, 2025) using the package brms (v. 2.23.0; (Bürkner, 2017).

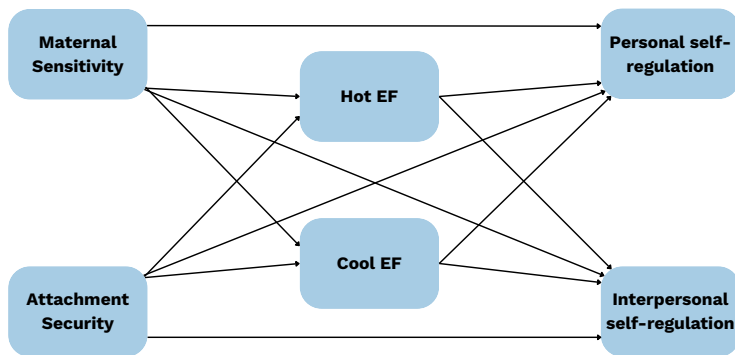
# Study I

## Background and aims

Self-regulation skills are utilized in both personal and interpersonal (social) contexts, for the purpose of adaptive behaviour. These skills become especially important at the start of formal schooling, when increased demands are placed on children's behaviour and independence. In addition, childhood self-regulation is a meaningful predictor of future academic achievement, health, and behaviour problems (Drake et al., 2014; Moffitt et al., 2011; Robson et al., 2020). Identifying potentially malleable predictors of self-regulation in childhood is therefore important. While the early caregiving environment has been implicated as an important predictor of later self-regulation (Bernier et al., 2012; Rhoades et al., 2011; Samdan et al., 2020), it is unclear whether differentiated aspects of the early caregiving environment are to the same degree predictive of self-regulation in later childhood. At the same time, more fine-grained aspects of self-regulation, such as EF, may play a mediating role during development of broader personal and interpersonal self-regulation, but it is unclear whether a distinction between hot and cool EF is informative in characterizing such associations.

The main aim of this study was to examine specific longitudinal associations between different aspects of the early caregiving environment (caregiver sensitivity and attachment security) in infancy, and self-regulation in the first year of school (at 6 years), and whether hot and cool EF in toddlerhood (at 4 years) differentially mediate these associations.

We hypothesized that the early caregiving environment (caregiver sensitivity and attachment security) would positively predict hot and cool EF at 4 years, and personal and interpersonal self-regulation at 6 years, and that cool and hot EF would positively predict personal and interpersonal self-regulation. Due to a lack of previous studies, no specific hypothesis was put forth regarding the relative contributions of the aforementioned associations to personal and interpersonal self-regulation. Finally, we hypothesized that hot and cool EF would each partially mediate the relationship between the early caregiving environment and later personal and interpersonal self-regulation. Hypotheses and analysis plans were preregistered at OSF (see <https://osf.io/c8nw3>).



**Figure 2.** Theoretical path model of study variables and their expected associations

## Method

Data were drawn from the EFFECT study, specifically waves 1, 2, and 4. Data from a final sample of 108 children (46% girls ( $n = 50$ ) and 54% boys ( $n = 58$ )) and their caregivers. Three timepoints were designated; T1 (10 – 12 months), T2 (4 years), and T3 (6 years). At T1, infants and their caregivers first (at 10 months) participated in a semi-structured play session, which was videotaped and later coded using the Maternal Sensitivity Scales (Ainsworth, 1969). In a later visit (at 12 months), the children and caregivers participated in the SSP, which was also videotaped and coded. For this analysis, attachment security was recoded into a dichotomous variable (0 = insecure, 1 = secure). At T2, children participated in a series of behavioural tasks measuring hot and cool executive function. The intent was to combine their scores if significantly correlated ( $\alpha = 0.05$ ), into specific measures of hot and cool EF (using the mean of task  $z$ -scores). At T3, caregivers rated children’s personal and interpersonal self-regulation using the ABAS-II.

Pearson correlations between continuous variables, point-biserial correlations between continuous and categorical variables, and correlations between pairs of categorical variables (estimated using the Phi coefficient), were computed using the R package *miceadds* (Robitzsch & Grund, 2022), which uses Fisher's transformation in computing correlation coefficients.

## Results

No significant intercorrelations between cool and hot EF tasks, respectively, were found. Therefore, no combination of scores for cool EF tasks or hot EF tasks was performed. Analyses including EF were therefore conducted on a subskill/task level. In addition to previously reported significant associations between maternal sensitivity at T1 and delay of gratification, working memory, and set shifting at T2 (Frick et al., 2019), we found a significant negative correlation between attachment security and set shifting ( $r = -.26$ , 95% CI [-.45, -.05],  $p < 0.05$ ). However, this relationship did not hold when controlling for SES and child sex in a partial correlation. No other significant correlations were found between study variables. Due to the lack of credible evidence for bivariate associations between early caregiving and self-regulation variables, as well as for the associations between scores on the EF tasks and self-regulation, further path and mediation analysis were deemed inappropriate.

**Table 1.** Bivariate Relationships Between Study Variables and Covariates (Pearson Zero-Order Correlations, point-biserial correlations, and Phi), With 95% Confidence Intervals.

|                            | T1 (10 – 12 months) |               | T2 (4 years)  |               |      |     | T3 (6 years) |     |     | Covariates (reported at T1) |      |
|----------------------------|---------------------|---------------|---------------|---------------|------|-----|--------------|-----|-----|-----------------------------|------|
|                            | (1)                 | (2)           | (3)           | (4)           | (5)  | (6) | (7)          | (8) | (9) | (10)                        | (11) |
| <b>T1 (10 – 12 months)</b> |                     |               |               |               |      |     |              |     |     |                             |      |
| 1. Maternal sensitivity    | 1.00                |               |               |               |      |     |              |     |     |                             |      |
| 2. Attachment security ‡   | -0.03               | 1.00          |               |               |      |     |              |     |     |                             |      |
|                            | [-0.22, 0.16]       |               |               |               |      |     |              |     |     |                             |      |
| <b>T2 (4 years)</b>        |                     |               |               |               |      |     |              |     |     |                             |      |
| 3. DoG                     | 0.28**              | 0.12†         |               |               |      |     |              |     |     |                             |      |
|                            | [0.07, 0.47]        | [-0.08, 0.32] | 1.00          |               |      |     |              |     |     |                             |      |
| 4. Delay inhibition        | 0.04                | -0.12†        | 0.03†         |               |      |     |              |     |     |                             |      |
|                            | [-0.17, 0.24]       | [-0.31, 0.08] | [-0.19, 0.23] | 1.00          |      |     |              |     |     |                             |      |
| 5. WM                      | 0.26*               | 0.15          | 0.40***       | 0.14          |      |     |              |     |     |                             |      |
|                            | [0.04, 0.46]        | [-0.07, 0.34] | [0.21, 0.57]  | [-0.07, 0.34] | 1.00 |     |              |     |     |                             |      |

|                     | T1 (10 – 12 months)       |                              |                          | T2 (4 years)              |                           |                           | T3 (6 years)              |                            |      | Covariates (reported at T1) |    |
|---------------------|---------------------------|------------------------------|--------------------------|---------------------------|---------------------------|---------------------------|---------------------------|----------------------------|------|-----------------------------|----|
|                     | 1                         | 2                            | 3                        | 4                         | 5                         | 6                         | 7                         | 8                          | 9    | 10                          | 11 |
| 6. Inhibitor        | -0.01<br>[-0.22,<br>0.21] | -0.19<br>[-0.38,<br>0.02]    | 0.17<br>[-0.05,<br>0.38] | -0.07<br>[-0.28,<br>0.15] | 0.02<br>[-0.23,<br>0.26]  | 1.00                      |                           |                            |      |                             |    |
| 7. Set shifting     | 0.25*<br>[-0.04,<br>0.43] | -0.26*<br>[-0.45, -<br>0.05] | 0.15<br>[-0.06,<br>0.35] | -0.09<br>[-0.30,<br>0.11] | 0.05<br>[-0.16,<br>0.27]  | 0.11<br>[-0.13,<br>0.34]  | 1.00                      |                            |      |                             |    |
| <b>T3 (6 years)</b> |                           |                              |                          |                           |                           |                           |                           |                            |      |                             |    |
| 8. Personal SR      | -0.13<br>[-0.31,<br>0.07] | 0.16<br>[-0.04,<br>0.36]     | 0.16<br>[-0.07,<br>0.37] | 0.07<br>[-0.15,<br>0.28]  | -0.10<br>[-0.32,<br>0.13] | 0.03<br>[-0.21,<br>0.27]  | 0.01<br>[-0.22,<br>0.20]  | 1.00                       |      |                             |    |
| 9. Interpersonal SR | -0.17<br>[-0.35,<br>0.03] | 0.17<br>[-0.03,<br>0.36]     | 0.09<br>[-0.13,<br>0.31] | 0.13<br>[-0.07,<br>0.34]  | -0.10<br>[-0.34,<br>0.14] | -0.06<br>[-0.30,<br>0.18] | -0.13<br>[-0.34,<br>0.09] | 0.59***<br>[0.45,<br>0.71] | 1.00 |                             |    |

|                                    | T1 (10 – 12 months)      |                                |                          | T2 (4 years)             |                           |                          | T3 (6 years)             |                           |                           | Covariates (reported at T1) |      |
|------------------------------------|--------------------------|--------------------------------|--------------------------|--------------------------|---------------------------|--------------------------|--------------------------|---------------------------|---------------------------|-----------------------------|------|
|                                    | 1                        | 2                              | 3                        | 4                        | 5                         | 6                        | 7                        | 8                         | 9                         | 10                          | 11   |
| <b>Covariates (reported at T1)</b> |                          |                                |                          |                          |                           |                          |                          |                           |                           |                             |      |
| 10. SES                            | 0.03<br>[-0.22,<br>0.16] | -0.37***<br>[-0.52, -<br>0.19] | 0.06<br>[-0.15,<br>0.27] | 0.01<br>[-0.19,<br>0.21] | -0.03<br>[-0.25,<br>0.20] | 0.26*<br>[0.03,<br>0.46] | 0.19<br>[-0.02,<br>0.39] | -0.05<br>[-0.24,<br>0.15] | -0.08<br>[-0.27,<br>0.11] | 1.00                        |      |
| 11. Sex §                          | [-0.10,<br>0.28]         | [-0.26,<br>0.12]               | [-0.29,<br>0.11]         | [-0.28,<br>0.12]         | [-0.06,<br>0.36]          | [-0.30,<br>0.10]         | [-0.28,<br>0.12]         | [-0.35,<br>0.02]          | [-0.47, -<br>0.12]        | [-0.30, -<br>0.07]          | 1.00 |

*Note:* DoG = delay of gratification. WM = working memory. SR = self-regulation. SES = socioeconomic status. \*  $p < 0.05$  (2-tailed). \*\*  $p < 0.01$  (2-tailed). \*\*\*  $p < 0.001$  (2-tailed). † Phi. ‡ Dummy coded (0 = Insecure, 1 = Secure). § Dummy coded (0 = girls, 1 = boys)

## Conclusions

Overall, we did not find credible evidence of longitudinal associations between early caregiving (maternal sensitivity or attachment security) and self-regulation at 6 years, nor between EF at 4 years and self-regulation at 6 years, in our data. As previously reported by Frick et al. (2019), maternal sensitivity in infancy was associated with later performance on specific EF tasks at 4 years (including both hot and cool EF measures). However, these EF associations did not extend to broader self-regulation at school start. We did not find robust associations between attachment security and EF or self-regulation after accounting for covariates, nor did we find an association between performance on EF tasks at 4 years and self-regulation at 6 years.

While these (mostly) null results were unexpected, there are several plausible explanations for these findings; (a) effects may be small or context-dependent in a typically developing, relatively high-SES sample; (b) the timing of measurement may not capture developmental periods when these associations are strongest; and/or (c) measurement characteristics, including single-trial behavioural EF tasks and the mismatch between behavioural/observational predictors and parent-reported outcomes, may have attenuated associations.

Taken together, the present results suggest that links from early caregiving to later self-regulation, especially in low-risk samples, may be weaker, more developmentally specific, or more method-dependent than commonly assumed. Study II.

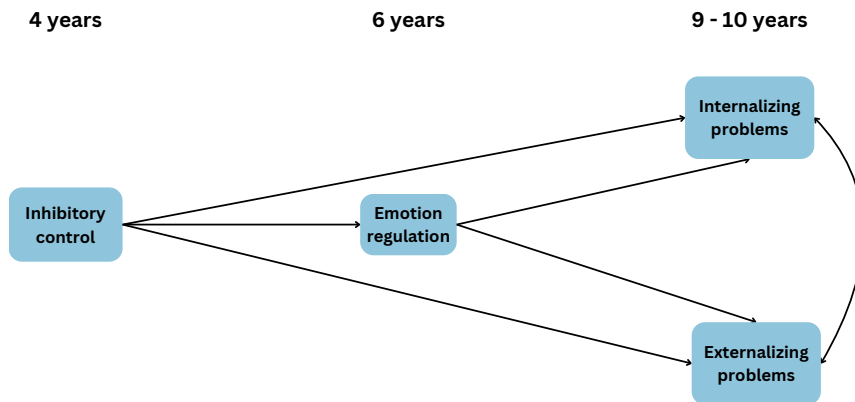
# Study II

## Background and aims

Many children experience behavioural, emotional, and social problems that, when persistent and severe, can impair functioning, and may signal risk for later maladjustment and psychopathology. These difficulties are often described as two correlated dimensions: internalizing problems (INT; e.g., worry, sadness, social withdrawal) and externalizing problems (EXT; e.g., impulsivity, defiance, aggression) (Achenbach et al., 2016; Cicchetti & Natsuaki, 2014), which frequently co-occur (Lahey et al., 2017; Willner et al., 2016). Identifying predictors and mechanisms in the development of childhood INT and EXT is crucial for early intervention. Executive function (EF) predicts both INT and EXT (Bloemen et al., 2018; Halse et al., 2022; Yang et al., 2022), and inhibitory control has been proposed as a particularly important component, but specific pathways to INT and EXT remain unclear.

One plausible mechanism linking early inhibitory control to later INT and EXT is the development of emotion regulation (ER). Inhibitory control is theoretically closely tied to ER (Bartholomew et al., 2021; Joormann, 2010; Ochsner et al., 2012; Pruessner et al., 2020), though longitudinal evidence of associations in early childhood remains limited. In turn, ER is a robust trans-diagnostic factor associated with both behavioural and emotional problems (Aldao et al., 2016; Cavicchioli et al., 2023; Compas et al., 2017). Relatively few longitudinal studies model both INT and EXT simultaneously, leaving uncertainty about specific associations.

The main aims of Study II were threefold; (1) to examine the specific longitudinal associations between inhibitory control in toddlerhood (4 years), ER at 6 years, and INT and EXT, respectively, in late childhood (9–10 years), in a typically developing sample; (2) to examine whether the potential longitudinal associations between inhibitory control and INT and EXT are mediated by ER in early childhood (6 years); and (3) to examine the possibly distinct roles of regulation of specific emotions in these associations.



**Figure 3.** Theoretical path model of study variables

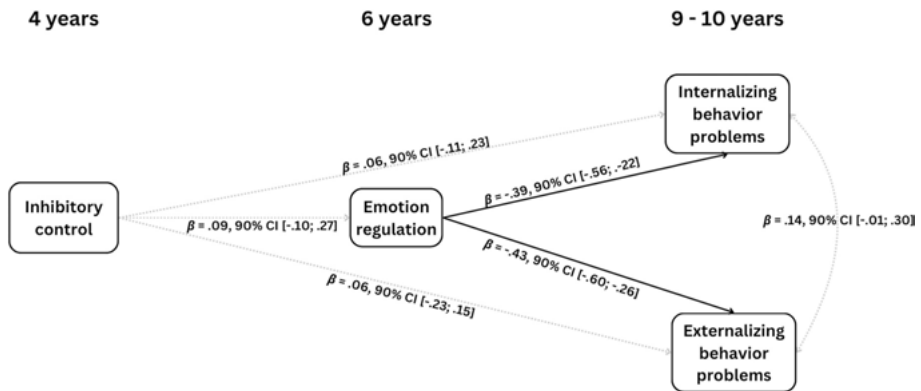
## Method

Data were drawn from the EFFECT study, specifically waves 5, 6, and 7. Data from a final sample of 94 participants was analysed (49 boys, 52.1%; 45 girls, 47.9%). At 4 years, inhibitory control was measured using the Day/Night Stroop task. At 6 years, parents reported on emotion regulation by responding to the EQ. At 9–10 years, parents reported on INT and EXT by filling out the SDQ. Path models were constructed and analysed using path analysis. Missing data was addressed using MICE. Models were run using the package lavaan.mi in R (Jorgensen, 2024). A Bonferroni-Holm correction was conducted to address multiple comparisons.

## Results

While both models were just-identified with 0 degrees of freedom, the obtained path coefficients and confidence intervals provide interpretable

information about the associations between variables (see Figure 4 for standardized path coefficients and 90% CIs). No associations were found between inhibitory control at T1 and INT or EXT at T3, or between inhibitory control and ER at T2. Conversely, in line with our hypotheses, ER at T2 was significantly negatively associated with INT and EXT at T3, indicating that more successful ER longitudinally predicts lower scores on INT and EXT.

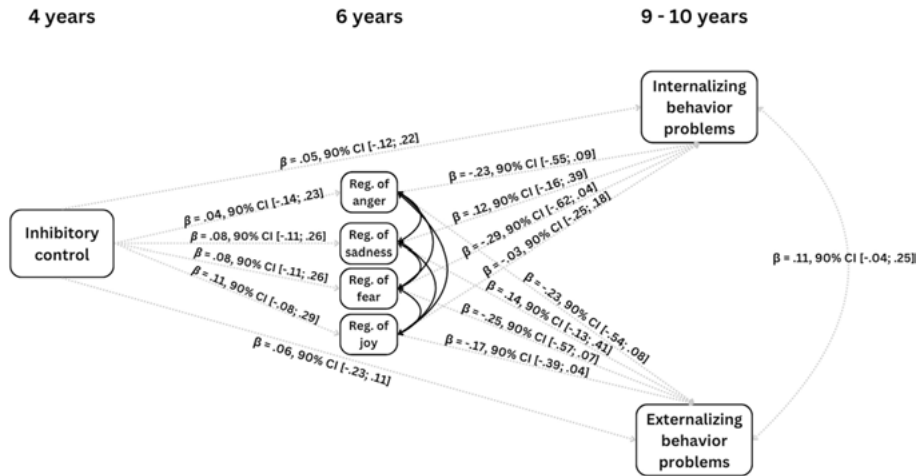


**Figure 4.** Simplified path diagram depicting results of fitting Model 1 to our data.

*Note.* All path coefficients are standardized. Black, solid lines indicate significant pathways. Gray, dashed lines indicate nonsignificant pathways. Socio-economic status and child sex were included as covariates in the model, but are excluded from the simplified diagram.

Model 2 included regulation of specific emotions instead of general emotion regulation (see Figure 5 for standardized path coefficients and 90% CIs). Model 2 contained no statistically significant paths. Coefficients for theoretically relevant paths varied from negative to positive, with relatively wide confidence intervals, indicating imprecise estimates. The

largest, negative effect sizes were observed between regulation of anger and fear to later INT and EXT.



**Figure 5.** Simplified path diagram depicting results of fitting Model 1 to our data.

*Note.* All path coefficients are standardized. Black, solid lines indicate significant pathways. Gray, dashed lines indicate nonsignificant pathways. Socio-economic status and child sex were included as covariates in the model, but are excluded from the simplified diagram.

## Discussion

Our results did not support the hypothesized links between toddler inhibitory control and ER at age 6, or INT and EXT at age 9–10. Consequently, we found no evidence for ER as a mediator. These null findings may reflect developmental discontinuity, non-linear associations, mixed measurement methods (behavioural vs. parent-report), and/or measurement error.

We did find that general ER at age 6 predicted less INT and EXT at age 9–10. No statistical significance was observed for paths between regulation of specific emotions and later INT and EXT. The available sample size may have reduced power to detect associations in this relatively complex model. Effect sizes indicated that more successful regulation of anger and fear at 6 years may be associated with INT and EXT at 9 years. However, these estimates were imprecise and non-significant, and could therefore be considered as potential patterns to be examined in future research with larger samples.

The findings of Study II add to longitudinal evidence linking poor ER to the development of childhood psychopathology (Caviccholi et al., 2023; Compas et al., 2017), and highlight ER as a plausible, modifiable target for early

prevention. Meanwhile, the results reflect the complexity of studying longitudinal effects of early inhibitory control, with conceptual and psychometric issues potentially impacting findings.

# Study III

## Background and aims

Cognitive control skills rapidly develop during childhood, and are further improved and refined during adolescence, in tandem with changes in structure, function, and integration of connectivity of associated brain areas. Previous research suggests an important role of maturation and increased engagement of the dorsal anterior cingulate cortex (dACC; an area implicated in error monitoring, action selection, and reward processing), in age-related improvements in cognitive control skills (Fjell et al., 2012; Velanova et al., 2008). Choline is a metabolite involved in cholinergic neurotransmission, methylation for epigenetic regulation, and the synthesis of phospholipids essential for dendritic growth, synapse formation, and myelination; all of which are particularly active during periods of structural and functional remodelling. Choline may therefore be especially important for optimal development and function of the dACC during childhood and adolescence, but this has, to our knowledge, not been previously explored.

Evidence from animal studies strongly implicates brain choline in the development of higher order cognition (Derbyshire & Obeid, 2020; McCann et al., 2006), but results from human developmental studies are mixed (Obeid et al., 2022). Most of these studies measure plasma levels of choline, or the effects of choline supplementation, with a focus on the prenatal period or infancy, or supplementation effects in clinical populations of young children. The specific developmental patterns of brain choline, and its associations with development of cognitive functions in humans, is therefore underexplored.

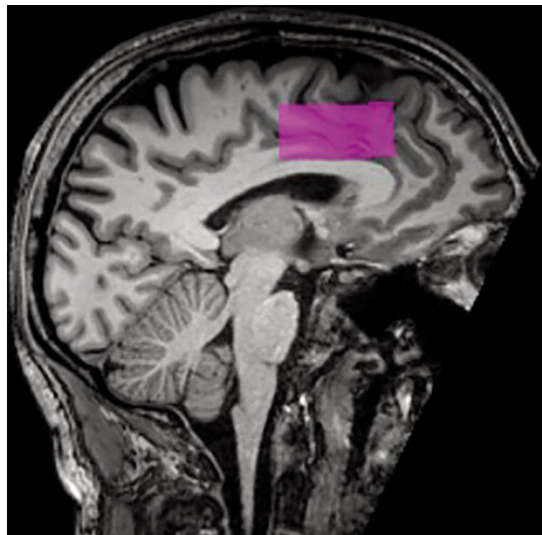
The aims of the Study III were twofold; 1) to examine age related differences in choline concentration in the dACC, by comparing levels across children, adolescents, and adults, and exploring variation within age groups; and 2) to examine whether choline concentration in the dACC is associated with performance on cognitive control tasks, and whether this association differs across developmental stages.

## Method

Data was analysed from a final sample of 23 children (15 female, 8 male), 38 adolescents (21 female, 17 male), and 45 adults (22 female, 23 male). Performance on cognitive control tasks was measured using the Tower Test, BDS, Flanker task, and TMT-B in all three age groups. To enable analyses of group differences, a pooled composite was created using PCA, run using JASP (JASP Team, 2026).

MRS was used to measure concentration of choline in the dACC, as well as creatine for reference. The volume of interest (voxel) was positioned in the dACC. The imaged voxel was placed in parallel with the cingular gyrus, with the anterior part of the voxel placed in line with the anterior tip of the genu of the corpus callosum. The lower boundary of the voxel was immediately dorsal to the corpus callosum. The voxel size was  $40 \times 40 \times 20 \text{ mm}^3$  in the left-right, anterior-posterior, and feet-head directions, respectively (see Figure 6). Metabolites were quantified using the software Osprey 2.5.0 (Oeltzschner et al., 2020) in MATLAB (Inc., 2023).

Prespecified Bayesian multiple regression models with reference coding, with and without interaction terms, were run using the package brms in R (Bürkner, 2017). In addition to the reference-coded parameter estimates, pairwise contrasts were derived between non-reference groups and extracted group-specific conditional slopes from the posterior distribution to facilitate interpretation.



**Figure 6.** Position of the  $^1\text{H}$  - magnetic resonance spectroscopy (MRS) voxel (violet) in the dorsal anterior cingulate cortex.

*Note.* Image credit: Widegren et al., 2024.

## Results

### **PCA of cognitive control measures**

A sample-wide component derived from scores on all tasks showed poor alignment with an adolescent group-specific PCA (same component for adolescents had low correlation with the sample-wide component). As scores on the Tower Test showed a negative loading on the component in adolescents (high uniqueness), these scores were removed, substantially improving alignment between pooled and adolescent group-specific PCA scores (from  $r = .55$  to  $r = .97$ ). We therefore used a sample-wide, three-indicator component, composed of scores on BDS, TMT-B, and the Flanker task, for the primary analysis, with 54% of variance explained. (see Table 2 for task specific scores and participant characteristics).

**Table 2.** Participant Characteristics and Task Performance by Age Group

|                                      | Children     |             |  | Adolescents |              |  | Adults      |             |  |
|--------------------------------------|--------------|-------------|--|-------------|--------------|--|-------------|-------------|--|
|                                      | Mean (SD)    | Range       |  | Mean (SD)   | Range        |  | Mean (SD)   | Range       |  |
| Age in years                         | 8.0 (0.8)    | 6 - 9       |  | 13.6 (1.2)  | 13 - 17      |  | 34.6 (3.1)  | 30 - 40     |  |
| SES                                  | 7.0 (1.7)    | 2.5 - 9.0   |  | 7.7 (1.1)   | 5.0 - 9.0    |  | 7.2 (1.6)   | 2.0 - 9.0   |  |
| <b>Cognitive control task scores</b> |              |             |  |             |              |  |             |             |  |
| BDS                                  | 7.8 (2.2)    | 3 - 12      |  | 10.3 (2.1)  | 7 - 17       |  | 9.4 (2.4)   | 4 - 15      |  |
| TMT-B                                | 4.4 (1.6)    | 1.5 - 7.7   |  | 1.9 (2.3)   | 0.6 - 3.2    |  | 2.3 (0.7)   | 0.9 - 4.4   |  |
| Flanker task                         | 107.1 (64.2) | -32 - 280   |  | 76.9 (29.5) | 37 - 187     |  | 72.0 (29.8) | 15 - 171    |  |
| Tower task                           | 14.3 (3.0)   | 8 - 19      |  | 17.8 (3.3)  | 11 - 27      |  | 19.0 (3.3)  | 12 - 29     |  |
| <b>MRS measures</b>                  |              |             |  |             |              |  |             |             |  |
| tCho/tCr                             | 0.26 (0.03)  | 0.21 - 0.31 |  | 0.26 (0.03) | 0.22 - 0.32  |  | 0.27 (0.03) | 0.22 - 0.38 |  |
| fGM                                  | 0.5 (0.04)   | 0.37 - 0.61 |  | 0.47 (0.03) | 0.38 - 0.51  |  | 0.41 (0.02) | 0.33 - 0.46 |  |
| fWM                                  | 0.4 (0.04)   | 0.30 - 0.55 |  | 0.43 (0.04) | 0.30 - 0.55  |  | 0.49 (0.03) | 0.43 - 0.58 |  |
| fCSF                                 | 0.08 (0.02)  | 0.04 - 0.10 |  | 0.08 (0.02) | 0.05 - 0.12  |  | 0.10 (0.02) | 0.05 - 0.14 |  |
| Cr FWHM                              | 5.26 (1.02)  | 3.83 - 7.81 |  | 5.68 (5.67) | 4.18 - 14.92 |  | 5.97 (0.69) | 4.92 - 7.68 |  |

|            | Children       |                 |                | Adolescents    |                |       | Adults          |       |  |
|------------|----------------|-----------------|----------------|----------------|----------------|-------|-----------------|-------|--|
|            | Mean (SD)      | Range           | Mean (SD)      | Range          | Mean (SD)      | Range | Mean (SD)       | Range |  |
| Cr SNR     | 182.99 (36.76) | 108.02 – 235.72 | 192.70 (44.11) | 94.00 – 280.19 | 191.88 (30.04) | –     | 122.33 – 251.95 |       |  |
| tCho/water | 3.52 (0.56)    | 2.14 – 4.40     | 3.76 (0.44)    | 2.50 – 4.82    | 4.30 (0.54)    |       | 2.67 – 6.08     |       |  |
| tCr/water  | 13.65 (1.24)   | 10.36 – 15.20   | 14.62 (1.34)   | 9.25 – 17.04   | 15.68 (1.10)   |       | 12.39 – 17.25   |       |  |

*Note.* N = 23 children, 38 adolescents, 45 adults. SES = socioeconomic status; BDS = Backward Digit Span; TMT-B = Trail Making Test B; tCho = total choline in dACC; tCr = total creatine in dACC; fGM = fraction grey matter; fWM = fraction white matter; fCSF = fraction cerebral spinal fluid; Cr FWHM = creatine full width half maximum; Cr SNR = creatine signal to noise ratio. For BDS and Tower task, higher scores indicate better performance. For TMT-B and Flanker task, lower scores indicate better performance.

### **Main analysis**

While main results will be reported in terms of group differences, Table 3 presents group-specific estimates for choline concentration, cognitive control performance, and their within-group associations with age and each other, as well as posterior probability of the estimate being higher or lower than zero.

**Table 3.** Standardized Group Means and Within-Group Brain-Behaviour Associations

|   | Estimate (beta) | 95% CI       | P( $\beta < 0$ ) | P( $\beta > 0$ ) |
|---|-----------------|--------------|------------------|------------------|
| <b>Children</b>                             |                 |              |                  |                  |
| tCho/tCr                                    | -0.28           | -0.67, 0.10  | 97%              | 3%               |
| tCho/Cr ~ age                               | -0.06           | -0.4, 0.27   | 64.7%            | 35.3%            |
| Cognitive control performance               | -1.01           | -1.32, -0.71 | 100%             | 0%               |
| Cognitive control performance<br>~ tCho/tCr | -0.32           | -0.63, -0.01 | 98%              | 2%               |
| <b>Adolescents</b>                          |                 |              |                  |                  |
| tCho/tCr                                    | -0.23           | -0.51, 0.05  | 97%              | 3%               |
| tCho/Cr ~ age                               | 0.12            | -0.18, 0.43  | 20.4%            | 79.6%            |
| Cognitive control performance               | 0.46            | 0.23, 0.70   | 0%               | 100%             |
| Cognitive control performance<br>~ tCho/tCr | -0.07           | -0.32, 0.18  | 72%              | 28%              |
| <b>Adults</b>                               |                 |              |                  |                  |
| tCho/tCr                                    | 0.29            | 0.02, 0.56   | 1%               | 99%              |
| tCho/Cr ~ age                               | 0.25            | -0.03, 0.53  | 4.3%             | 95.7%            |
| Cognitive control performance               | 0.25            | 0.03, 0.46   | 1%               | 99%              |

|   | Estimate (beta) | 95% CI      | $P(\beta < 0)$ | $P(\beta > 0)$ |
|---|-----------------|-------------|----------------|----------------|
| Cognitive control performance<br>~ tCho/tCr | 0.09            | -0.17, 0.34 | 23%            | 77%            |

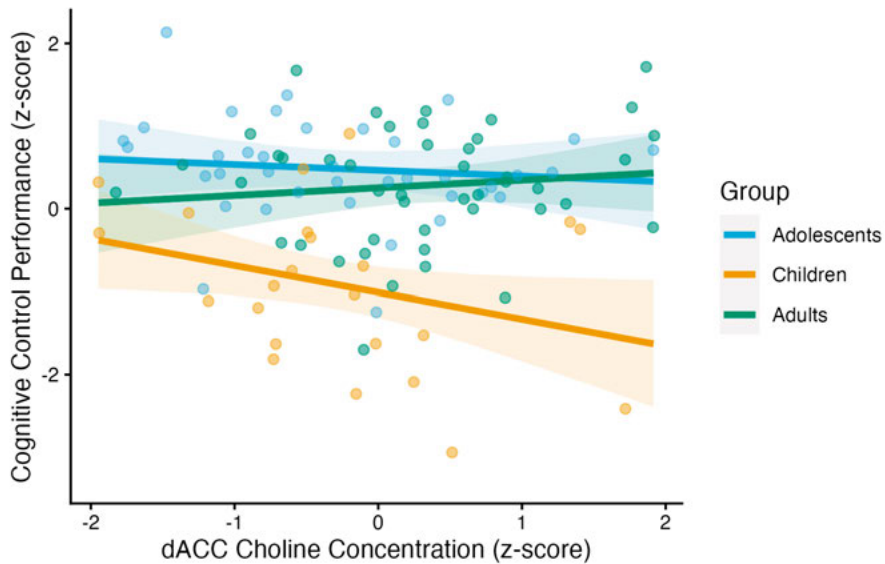
*Note.* tCho/tCr and cognitive control performance were standardized across the entire sample ( $M = 0$ ,  $SD = 1$ ). Group means represent each age group's position on these standardized distributions. Negative values indicate below-sample-average performance; positive values indicate above-sample-average performance. The final row shows the within-group association between standardized tCho/tCr and cognitive control performance. CI = Credible Interval;  $P(\beta < 0)$  = Posterior probability that the estimate is lower than zero;  $P(\beta > 0)$  = Posterior probability that the estimate is higher than zero.

Posterior mean difference in dACC choline concentration between children and adolescents was 0.05 95% CI [-0.51, 0.42] (posterior probability of difference being larger than 0 = 58%), indicating an effect near zero with substantial uncertainty. The posterior distribution for the adult–adolescent difference was shifted toward higher choline levels in adults (mean difference = 0.51, 95% CI [0.11, 0.91], posterior probability = 99%). Posterior contrasts indicated that children had lower dACC choline concentration than adults (posterior mean difference = -0.56 95% CI [-0.93, -0.19]; posterior probability was 99%).

The posterior distribution for the association between dACC choline concentration and cognitive control in the whole sample was centred near zero ( $\beta = -0.02$ ), with substantial uncertainty (95% CI [-0.21, 0.17]).

Posterior mean difference (standardized) between children and adolescents on cognitive control performance was -1.48, 95% CI [-1.80, -1.15] (posterior probability of lower cognitive control in children than adolescents = 100%). Posterior mean difference between adults and adolescents was -0.21, 95% CI [-0.54, 0.11] (indicating lower cognitive control in adults than adolescents, with a posterior probability of 90%). Posterior mean difference between children and adults on cognitive control was -1.26, 95% CI [-1.58, -0.95] (posterior probability of lower cognitive control in children than adults = 100%).

Mean standardized association between dACC choline concentration and cognitive control performance in adolescents was -0.07, 95% CI [-0.32, 0.18]. For children and adolescents, the difference in mean association between choline concentration and cognitive control performance was -0.26, 95% CI [-0.66, 0.15]. The posterior probability that children had a more negative slope than adolescents was 73%. Posterior mean difference between adolescents and adults was 0.16, 95% CI [-0.19, 0.52]. The posterior probability that adults had a more positive slope than adolescents was 80%. Posterior mean difference between children and adults was -0.42, 95% CI [-0.76, -0.08]. The posterior probability that children had a more negative slope than adults was 98%.



**Figure 7.** Group-Specific Associations Between tCho/tCr and Cognitive Control Performance.

*Note.* Individual data points and Bayesian regression lines (with 95% credible intervals) showing group-specific associations between dACC choline concentration (tCho/tCr ratio, standardized) and cognitive control performance (PCA-derived component, standardized).

## Discussion

Three main findings emerged from this study. First, dACC choline was substantially higher in adults than in both children and adolescents, while the difference between children and adolescents was unclear. This pattern may reflect reduced metabolic demand once structural brain maturation is complete. During childhood and adolescence, choline may be more actively consumed to support ongoing development.

Second, cognitive control followed a mostly expected pattern, with children performing worst. Unexpectedly, however, adolescents outperformed adults on average, which conflicts with prior literature consistently showing improvements in cognitive control into adulthood. Selection bias is a potential explanation for this, as adolescents with better cognitive control might be more likely to enrol in a scientific study.

Third, and most notably, the association between dACC choline and cognitive control shifted direction across development. In children, higher choline predicted worse performance, which may indicate that elevated choline

reflects active membrane turnover and circuit reorganization associated with less efficient processing. In adults, the association reversed, with higher choline predicting better performance, potentially reflecting maintenance of established neural networks. The pattern in adolescents was intermediate and uncertain. As a potential biological marker of cognitive control development, dACC choline therefore seems to serve different functions depending on developmental stage.

Several important limitations apply: the sample was modest, especially for children; the cross-sectional design prevents causal inference; and the composite cognitive control measure may not fully capture developmental differences in executive function. The findings are therefore preliminary and in need of replication in larger samples.

## General discussion

The three studies included in this thesis examined some of the different aspects of self-regulation, their predictors and correlates, and their role in socioemotional outcomes. In line with previous evidence and theory, longitudinal associations were expected between: earlier, simpler aspects of self-regulation and later, more complex self-regulatory abilities; the early caregiving environment and later self-regulatory outcomes; and early self-regulation and later socioemotional outcomes. Additionally, cross-sectional associations were expected between a potential biomarker of brain development and cognitive control. Broadly, the findings were mixed, with some hypotheses supported by the data, and others not. Importantly, these mixed results add to the self-regulation literature in different ways. Where hypotheses were supported, most notably the longitudinal association between general ER and later INT and EXT in Study II, and age dependent concentration of dACC choline in Study III, the results add to a growing evidence base, and invite replication in larger samples. Where hypotheses were not supported, as in the absence of associations between early caregiving and later self-regulation, or between inhibitory control at 4 years, ER at 6 years, and INT and EXT at 9–10 years, the null results raise important questions about theoretical assumptions, measurement validity, and study design. Study III additionally included an exploratory research question, based on insufficient prior evidence for directional predictions, which yielded findings of particular theoretical interest.

Broadly, three main conclusions can be deduced from the findings, in the context of the wider literature:

- Measurement and conceptual challenges remain an issue in the field of self-regulation research, which may have particular implications for the future of studies with modest sample sizes.
- Aspects of self-regulation do function as predictors of future outcomes in childhood, though associations may depend on the specific components measured and the developmental timing of assessment.
- Developmental differences in the biological foundations of self-regulation add a layer of complexity, highlighting the difficulty of characterizing self-regulation as a unitary construct across childhood and adolescence.

The implications of the findings presented in this thesis are discussed below, as well as the limitations that need to be considered in interpreting them, and what the results can tell us about future directions in the field of self-regulation research. Given the mixed nature of the findings, particular attention is given to what null results can and cannot tell us.

## Null results – theory or method?

When analysing and interpreting data based on a frequentist framework, the usual expected outcome is the rejection of the null hypothesis (most often that there is no effect), and subsequent ability to take up the alternative hypothesis (most often that there is an effect). In cases when a null hypothesis cannot be rejected, the result becomes difficult to interpret, as it remains unclear whether the effect is genuinely absent or whether it could not be detected in the sample, for instance due to insufficient power, or measurement error.

This ambiguity is a common challenge in developmental science, where effect sizes can often assumed to be small, samples are often modest, and constructs can be difficult to operationalize consistently across age (Byers-Heinlein et al., 2021; Gennetian et al., 2022). This may be particularly relevant for a field like self-regulation development, where theories and models are still being developed, and there is considerable conceptual confusion. A null result may therefore reflect a genuine absence of the expected association, a limitation of the specific measures used, insufficient statistical power to detect a small effect, or some combination of these factors. This uncertainty, coupled with incentives in academia to publish significant, novel and tidy findings (Nosek et al., 2022), can cause null findings to be underreported or dismissed, contributing to a literature that may overrepresent positive findings, leading to incorrect or incomplete theory.

The null results observed in Study I and Study II illustrate this challenge. The lack of expected associations between early caregiving and later self-regulation, and between inhibitory control at age 4, ER at age 6, and socioemotional outcomes at age 9–10, could reflect several things. One possibility is that the theoretical assumptions underlying these hypotheses require revision. For instance, the expected associations between early EF and later socioemotional outcomes might be more conditional on age or measurement than current models suggest, and the distinction between hot and cool EF, on which some hypotheses were based, may still be too theoretically underdeveloped to be consistently observed (Smith et al., 2024). Alternatively, methodological factors may have attenuated associations that would have otherwise been detectable. Potential causes, in the case of these studies, are the modest sample

size, single time-point measurement of key constructs, and the use of measures that may have captured different response modalities.

While null results present a challenge of interpretation, they are also essential for progress in science (Bespalov et al., 2019), and can present interesting opportunities for development within individual research fields. Where null findings converge across studies with different designs and samples, they may provide grounds for revising theoretical assumptions. Where they appear in isolated studies with known methodological constraints, they call for replication under improved conditions rather than theoretical revision. Convincing null results can save valuable and constrained research resources, by discouraging others from conducting fruitless studies.

Ultimately, whether the null results observed in Study I and Study II indicate limitations in current theory or methodological limitations remains an open question. Despite this uncertainty, transparent reporting of null findings, with effect sizes and uncertainty estimates, is a necessary step in building a coherent picture of self-regulation development.

## Self-regulation as a moving target

The findings presented in this thesis underscore that the longitudinal associations between early self-regulatory abilities and later socioemotional outcomes are not consistent, but seem to depend on what is measured, when, and at what level of specificity. This neatly maps onto the hypothesized hierarchical organization of the self-regulation universe across "...granularity, development, and time" (Nigg, 2017). The longitudinal association between ER in mid-childhood and later INT and EXT adds to the evidence base supporting early self-regulation as a meaningful predictor of socioemotional adjustment. As identifying reliable developmental precursors of later difficulties is fundamental for the design of targeted early interventions, such findings have practical relevance, and help map out risk and resilience factors during development.

While ER assessed in mid-childhood predicted later INT and EXT, earlier and more narrow measures of EF did not show comparable longitudinal associations to later outcomes. This pattern of inconsistent associations does not necessarily imply that early executive function is developmentally inconsequential, but rather suggests that detecting longitudinal effects requires measurement that reliably captures the construct, and that measurement is sufficiently proximal to the outcome of interest, both in time and measurement type. As discussed in Study I and Study II, attempting to associate data from measures that may capture different response processes, such as questionnaires and behavioural measures, or measure the construct on different levels

of analysis, might lead to attenuated associations (Dang et al., 2020; Saunders et al., 2018).

Reliably and validly capturing development of aspects of self-regulation in childhood is a major challenge, as self-regulation is in itself a moving target during development. Hierarchical models of self-regulation development suggest that regulatory abilities are not simply refined across childhood, but rather reorganized, with earlier, simpler processes becoming integrated into more complex abilities (Garon et al., 2008; Wu et al., 2021). Adding to existing literature on neurobiological reorganization in relation to self-regulation, the findings from Study III suggest that even when behavioural measurement is held constant, the neurobiological processes underlying cognitive control shift across development. These underlying shifts have direct implications for findings from longitudinal studies, as measures taken at different developmental stages may indicate somewhat distinct constructs. This potential lack of construct continuity is compounded by the practical realities of longitudinal research: attrition, extended follow-up intervals, and the often-necessary variation in measurement based on age can limit the ability to model developmental change with precision. Moreover, recent theoretical directions that now guide the field of self-regulation research, hierarchical, dynamic, and transactional models, have grown complex. Establishing evidence for these more complex models will require larger, longer, and likely more measurement intensive studies, as well as improved alignment between theory and measurement across timepoints. Taken together, the findings demonstrate that meaningful longitudinal predictions are detectable, while what is found may depend on the constructs targeted and the developmental windows in which they are assessed.

## Limitations

The three studies presented here have several limitations that are important to keep in mind when interpreting the findings.

Studies I and II drew on data from the same research project, and were therefore affected by some shared limitations. The sample size was modest relative to the complexity of the planned analyses, where many effects could be expected to be small. A related consequence in Study I was that a planned mediation analysis was abandoned due to a lack of linear associations between model variables; research questions were therefore addressed using simple, bivariate associations. As is common in longitudinal research, there was considerable missingness of data in Study I and Study II, that, while mitigated using multiple imputation, may have affected findings.

Beyond those shared between Study I and Study II, each study had limitations specific to its design and measures. In Study I, attachment security was operationalized as a binary variable, which, while motivated by analytical and theoretical considerations, may have affected the correlational analyses, especially considering the uneven distribution of participants in the secure and insecure groups. Measures meant to capture hot and cool EF were not intercorrelated, and each EF measure took place at a single time point, limiting the potential to establish reliability of the measures. In Study II, inhibitory control and ER were likewise measured at a single time point, precluding conclusions about developmental change. The single-task measurement of inhibitory control may additionally have reduced the reliability and validity of that construct. Measures of regulation of specific emotions and INT showed modest internal consistencies, suggesting they may not have fully captured the intended constructs.

Study III employed a Bayesian framework, within which statistical power is not a relevant concept. Nevertheless, the modest sample size, particularly within the child group, may have increased the uncertainty of parameter estimates. This is of particular concern in a developmental study of brain-behaviour associations, where effect sizes are typically small and sufficient data quality can be difficult to achieve (Szucs & Ioannidis, 2020). Although care was taken to collect high-quality MRS data, spectra can be affected by small movements, which may be especially relevant when scanning young children. Furthermore, quantifying dACC choline as a ratio to dACC creatine may have influenced the findings, as descriptives revealed that creatine concentrations increased from childhood to adulthood. The characterization of cognitive control performance as a single PCA-derived factor across development represents a necessary simplification that may not adequately capture developmental differences in the underlying construct; this component should therefore be interpreted as a data-driven summary of task performance rather than a theoretically validated measure. Finally, the cross-sectional design precludes direct causal inference regarding maturational effects, as cohort effects cannot be ruled out.

## Future directions

As stated in the introduction to this thesis, the field of self-regulation research is in a state of concurrent promise and confusion, which, arguably, is reflected in the findings presented here. For further successful mapping of the self-regulation universe, several directions for future work are of interest, from theoretical clarification, to methodological development, and measurement innovation.

## **Conceptual clarification**

Perhaps the most fundamental challenge facing the field is conceptual. There is broad consensus that the ability to regulate behaviour, emotion, and cognition is central to adaptive functioning and goal-directed behaviour. Yet the ways in which we are currently attempting to map out these capacities, and their potential as targets for intervention, often do not yield the answers we expect or need. Mixed findings are observed in studies of self-regulation development itself, as well as associations with later outcomes, and efficacy of interventions (McClelland & Cameron, 2012; Niebaum & Munakata, 2023; Tu et al., 2022).

Attempts to clarify conceptualization and appropriate measurement of foundational aspects of self-regulation, such as EF and ER, remain very much ongoing (Crowell et al., 2020; Doebel, 2020; Hendry & Scerif, 2023; Löffler et al., 2022; Spencer et al., 2025). For some constructs, such as the distinction between hot and cool EF, the usefulness of current conceptualizations has come into question on recent years (Smith et al., 2024). To enhance theory on self-regulation and its development, reliability and validity of measures should be strengthened through dedicated research, theoretically important findings should be replicated in larger samples when possible, and laboratory-based research should be more systematically connected to how self-regulation is expressed and functions in everyday contexts through integration of perspectives from different disciplines. Following this, there is also reason to theoretically explore the multilevel nature of self-regulation; there might be reason to be careful when mixing different levels of analysis (Saunders et al., 2018). In this way, we may move closer to connecting basic and applied perspectives, and perhaps more useful and fruitful research on self-regulation.

## **Integrating motivation and context**

Motivation and context are underrepresented factors in current accounts of self-regulation and its development. As the opening anecdote of this thesis illustrated, self-regulatory behaviour is shaped, moment to moment, by what an individual wants and cares about. While motivation and context are increasingly discussed in theoretical accounts of self-regulation (Fujita et al., 2025; Hendry & Scerif, 2023; McClelland & Cameron, 2012; Munakata & Michaelson, 2021; Wesarg-Menzel et al., 2023), actual operationalization of these factors in self-regulation research is less prominent.

While context and motivation are inherently subjective, there may be systematic or developmental patterns that warrant further study, and knowledge of such factors may enhance both theoretical models and empirical measures of self-regulation. Capturing this contextual dimension is a complex but

important challenge for the field. While it could be argued that these aspects may be more relevant for the broad, functional understanding of self-regulation than for more basic processes (such as response time in a Flanker task), the present knowledge base does not provide clear answers. If such a discrepancy exists, it could help explain the modest associations often observed between simpler and more complex indices of self-regulation across development. Accounting for the role of motivation and context may be an important step in clarifying patterns of self-regulation development and associations with later outcomes, and may also reveal important targets for intervention.

### **New directions in modest-sample research**

Longitudinal and brain-behaviour associations in developmental research are often small in magnitude and difficult to detect with smaller samples (Davis-Kean & Ellis, 2019; Szucs & Ioannidis, 2020). As the field of self-regulation research moves toward increasingly complex models with expectations of incremental effects, there is a temptation to discourage design of modestly sized studies, and increasingly recommend larger sample size to solve any issue of uncertainty. However, practical constraints (including cost, time, and challenges in recruitment and long-term study adherence of children) mean that small-to-medium sized samples will remain a reality in many areas of developmental and cognitive neuroscience. Bayesian analysis and inference offer one productive response to this challenge (Rognli et al., 2023). As illustrated by the analytical approach of Study III, Bayesian inference allows for a richer characterization of the evidence than the binary accept/reject decisions inherent in frequentist approaches. Rather than returning an ambiguous null result in the presence of limited power or lack of associations, Bayesian analysis yields a posterior distribution that is always informative, and allows for interpretation of the degree and direction of evidential support for an effect or theoretical claim (van de Schoot et al., 2021). In the business of theory-building and foundational work in developmental science, where clinical precision of estimates is not the primary goal, this capacity to quantify how much the data updates our beliefs, rather than simply whether a certain threshold is crossed, may allow more productive use of modestly sized datasets, given that studies are carefully designed. While the learning curve can be steep, developments in software are increasing accessibility. Wider adoption of these methods may ultimately support richer and more cumulative theory-building, by making better use of the data realistically available in developmental science.

## Measurement innovation

Finally, advances in measurement represent a concrete and promising avenue for future work. Developing valid and reliable measures that are easy and cost-effective to administer, and could also be administered in different age groups in a relatively unchanged form, should be a priority. Some interesting steps have recently been taken in this direction (Holmboe et al., 2021). In addition, digital tools and mobile app-based paradigms could support measures that are more ecologically valid, easy and cost effective to administer, and more scalable than traditional behavioural tests. Recent developments in this area are promising (Attarha et al., 2025; Berg et al., 2020), but further work is needed.

## Concluding remarks

The self-regulation universe is vast, and this thesis has examined only a small portion of it.

Across three studies, this thesis found that ER in mid-childhood predicts later INT and EXT, supporting its transdiagnostic relevance during development. An early, more narrow measure of executive function, however, did not show comparable longitudinal associations with later outcomes, suggesting that the predictive relevance of self-regulatory measures depends on developmental timing and level of specificity. Similarly, expected associations between the early caregiving environment and later self-regulatory outcomes were not observed, raising questions about theoretical assumptions and the measurement of both constructs in this age range. At the neurobiological level, the association between dACC choline and cognitive control was found to shift direction across development, adding to evidence that the biological foundations of self-regulation are reorganized rather than simply refined across childhood and adolescence. Taken together, these findings reflect the conceptual and methodological complexity of the field, and point toward the value of further refining how self-regulation is conceptualized, measured, and studied across development. Based on these findings, further developing, demarcating and enriching the conceptualization of self-regulation, and embracing novel methodological approaches, will help the field move forward.

The incident with the boys on the boulder has stuck with me. What then seemed like a straightforward lack of self-regulation, has been reframed by this work as stemming from a complex interplay of social, neural, and behavioural factors that were still very much developing. Understanding how regulatory capacities develop, what shapes their development, and how they

relate to later outcomes, remains one of the most important and complex challenges in developmental science. This thesis has taken a few steps towards that understanding by attempting to map small sections of the self-regulation universe, and finding that the conceptual landscape is more varied, and the measurement more demanding, than simple models would suggest. There is still much to explore.

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Vits er þörf  
þeim er víða ratar  
dælt er heima hvað.  
Að augabragði verður  
sá er ekki kann  
og með snotrum situr.

- From *Hávamál* (Codex Regius, 900 – 1000 AD) \*

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*\* English translation (by Edward Pettit):*

*Wits are required by the one who wanders widely  
everything is easy at home  
he who knows nothing and sits among the wise  
becomes the subject of winking.*

*Hávamál (Words of the High One) is a collection of old Norse poems from the Viking age. These poems contain life advice, general wisdom, and advice on proper conduct. (We Icelanders still reference these in our daily lives).*

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