The longitudinal investigation of infants' attentional control and its associations with self-regulatory functions in toddlerhood and maternal mental distress

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Abbreviations

ACEs	Adverse Childhood Experiences
ADHD	Attention-Deficit/Hyperactivity Disorder
ASD	Autism Spectrum Disorder
BAI	Beck Anxiety Inventory
EPDS	Edinburgh Postnatal Depression Scale
IP	Interpersonal
LITE	Life Incidence of Traumatic Events
LP	Look Percentage
NIP	Non-interpersonal
TPH1	Tryptophan Hydroxylase 1

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"This is the first, and wisest thing I know, that the soul exists,
and that is built entirely out of attention"

Mary Oliver

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1. Introduction

Attention, broadly speaking, is a multifaceted and important cognitive operation involving orienting toward stimulation, filtering information, processing input, and maintaining focus on a target (Colombo, 2001; Colombo, Kapa, & Curtindale, 2011; Hendry, Johnson, & Holmboe, 2019). Attention develops rapidly in the first years of life when the brain is highly plastic (Swingler, Perry, & Calkins, 2015; Xie, Mallin, & Richards, 2019) and continues into adulthood (Hoyer, Elshafei, Hemmerlin, Bouet, & Bidet-Caulet, 2021), playing a fundamental role in learning (Holland & Maddux, 2010; Johnson, Posner, & Rothbart, 1991; Markant & Amso, 2016). More specifically, before the age of one, infants show learning behaviors through actively directing their attention to informative events and interacting with them (Raz & Saxe, 2020; Tummeltshammer & Amso, 2018). It has been suggested that attention is linked to the development of self-regulation (Cuevas & Bell, 2014; Posner & Rothbart, 2009), cognitive functioning (Lawson & Ruff, 2004a), social development (Bowers et al., 2019), language development (Yu, Suanda, & Smith, 2019), and academic skills in childhood (Shannon, Scerif, & Raver, 2021). Moreover, poor attention skills are related to many neurodevelopmental disorders, such as attention-deficit/hyperactivity disorder (ADHD; Barkley, 1997; Lawson & Ruff, 2004b) autism spectrum disorder (ASD; Allen & Courchesne, 2001; Matson, Rieske, & Williams, 2013), and Fragile X syndrome (Scerif, Longhi, Cole, Karmiloff-Smith, & Cornish, 2012).

Looking onwards – from infancy to toddlerhood

In developmental literature, measurements of attentional control have heavily relied on various looking behaviors (Bornstein, 1985; Colombo, Harlan, & Mitchell, 1999; Gredebäck, Johnson, & von Hofsten, 2009). Different parameters of looking behavior have been used to access different aspects of attentional control, such as the latency of orienting to stimuli (Pyykkö et al., 2020), the duration of looking at stimuli (Johansson, Marciszko, Gredebäck, Nyström, & Bohlin, 2015), or speed of processing visual stimuli (Blankenship et al., 2019), etc. Though it has been reported that different aspects of the development of attentional control are stable across the first two years of life (Brandes-Aitken, Braren, Swingler, Voegtline, & Blair, 2019; Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; Rose & Feldman, 1987; Rose, Feldman, & Jankowski, 2001), most results were based on a single and brief period of observation (e.g. total looking time or the peak of the longest looking duration from a 5-minute video). In this thesis, I employ a data-driven method to explore a longitudinal dataset which contains a great amount of eye-tracking data at the age of 6, 10, and 18 months (Section 1.1.2). This allows us to observe the developmental changes of attentional control from a different perspective. More importantly, I aim at identifying stable and robust measures (Section 1.1.2) that can be used to relate to major or key variables from other domains, for instance, self-regulation. Attention in infancy is often used as an earlier marker or a predictor of self-regulatory functions. Self-regulation commonly emphasizes effortful control and executive functions (Posner & Rothbart, 2000; Rothbart & Rueda, 2005; Rothbart, Sheese, Rueda, & Posner, 2011). These functions are reported to support learning and school readiness (Blair & Diamond, 2008), to impact academic performance (Ahmed, Tang, Waters, & Davis-Kean, 2019; Best, Miller, & Naglieri, 2011; Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; McClelland & Cameron, 2011; Morgan et al., 2019), and to correlate with life satisfaction (Brown & Landgraf, 2010). It is suggested that attention might be fundamental to the development of self-regulatory functions (Colombo & Cheatham, 2006; Posner & Rothbart, 2009; Rueda, Posner, & Rothbart, 2004). Based on this, several recent studies have claimed a positive association between attention and self-regulation in the early years (Blankenship et al., 2019; Cuevas & Bell, 2014; Geeraerts et al., 2019; Papageorgiou et al., 2014). In this thesis, I will review the body of literature that claims that the association between attention and self-regulation exists and examine the overall evidence (Section 1.2.2). Furthermore, following the same assumption that attention is related to self-regulation, I will present the experimental findings examining this association between attention measures in infancy (established based on the data-driven method) and measures of self-regulatory functions at 18 and 30 months of age. Different from previous literature, this is the first time that the theoretical concept and a data-driven method are combined to establish robust attention measures in infancy. In Publication 1, I report that a high degree of internal consistency of attention measures is observed. Intriguingly, the association between attention in infancy and self-regulation in toddlerhood is not significant. I further elaborate on the possible reasons in the discussion.

Looking retrospectively – from infancy back to pregnancy and mother's childhood

Given the importance of attention in infancy and its role in later development addressed above, studies in infancy and childhood have attempted to identify the early risk factors that might hinder the development of attention. This brings the focus retrospectively to the *in-utero* period and even maternal childhood experiences. There is substantial evidence showing that maternal distress can change cortical and subcortical connectivity in infants (Rifkin-Graboi et al., 2013; Scheinost, Spann, McDonough, Peterson, & Monk, 2020) and has negative impacts on children's cognitive development (Keim et al., 2011; Kingston, McDonald, Austin, & Tough, 2015; Laplante et al., 2004; Tarabulsy et al., 2014). Furthermore, recent studies also reported that maternal adverse childhood experiences (ACEs) may have cumulative effects on maternal mental health (Sacchi, Merzhvynska, & Augsburger, 2020; Weltz, Armeli, Ford, & Tennen, 2016), and in turn, lead to structural neurodevelopmental consequences in *in-utero* (Andescavage et al., 2017; Moog et al., 2018). In line with these findings, several large scale studies have demonstrated negative associations between maternal distress and maternal childhood trauma and their children's attention-related problems (Ross, Letourneau, Climie, Giesbrecht, & Dewey, 2020; Wang & Dix, 2017), suggesting an elevated risk for ADHD symptoms (Moon, Bong, Kim, & Kang, 2021; Mulraney et al., 2019; Vizzini et al., 2019), and autism (Roberts, Lyall, Rich-Edwards, Ascherio, & Weisskopf, 2013). Even though extensive literature has shown that maternal distress affects children's attention, it is difficult to distinguish the impact among mother-child interaction, environment factors, and other biological factors. In this thesis, I review the theoretical rationales and empirical evidence supporting the role of maternal distress in offspring's attentional development (Section 1.3.1). Next, to better understand the cross-generational impact, I will elaborate on my study which included 118 mother-infant dyads and focused on mother-specific factors using a multi-dimensional investigation. Specifically, maternal depressive and anxiety symptoms as well as maternal exposure to interpersonal and non-interpersonal traumatic events in childhood are included to examine the associations between maternal distress and infants' attention (Section 1.3.2 and Publication 2).

Taken together, there are three main aims of this thesis addressed by two publications. First, I investigated the development of attention at the age of 6, 10, and 18 months using approx. 0.5 million fixations from eye-tracking measures and examined the data based on a data-driven method. Second, I aimed to analyze the associations between attention in infancy and self-regulatory functions in toddlerhood using robust attention measures (Publication 1 Tu et al., 2022). Third, based on the same attention measures, I retrospectively examined whether maternal childhood adverse experiences and maternal distress during pregnancy and infancy affected infants' attention (Publication 2 Tu, Skalkidou, Lindskog, & Gredebäck, 2021). In the following sections, I will first review the development of attentional control in infancy (Section 1.1). I will also discuss the advantages and disadvantages of attention measures used in previous infants' studies and describe our approach to integrating theoretical-based and data-driven methods to establish the measures in this thesis. In the second section (Section 1.2), I will introduce self-regulation and the theoretical background that links it to attention. Moreover, I review the current research landscape regarding the predictive role of attention to self-regulation in the developmental literature. In the last section (Section 1.3), I would like to invite readers to move the timeline from infancy back to pregnancy, and to the mothers' childhood. I will discuss the risk factors caused by maternal distress that might hinder infants' and children's attention. In sum, this thesis attempts to establish reliable measures for examining the development of attention in infancy and its relationship to self-regulation, as well as to identify early risk factors and to underpin the importance of early screening and targeted prevention in supporting both infants and their mothers.

1.1 Attentional Control in Infancy

1.1.1 Development of Attentional Control in Infancy

In the first few months of life, infants start to develop several attentional processes such as alertness, orienting, attention to features, sustained attention (maintaining focus), pre-attention termination, and attention termination (Colombo, 2001, 2002; Courage, Reynolds, & Richards, 2006; Richards & Casey, 1991). Several neural networks are presumably involved, such as the alerting, orienting, neural attending, and executive networks (Johnson, 1990; Johnson et al., 1991; Moore & Zirnsak, 2017; Petersen & Posner, 2012). With the maturation of the oculomotor control, from 4 months old and onwards, infants gradually gain more voluntary control of their eye movements in a more goal-directed manner (Johnson, 1990; Johnson et al., 1991; McConnell & Bryson, 2005). Before reaching the age of one, infants can actively deploy their attention in a top-down manner to environmental cues and selectively allocate their attentional resources to relevant information (Johnson et al., 1991; Lewkowicz & Hansen-Tift, 2012; Markant & Amso, 2016; Ross-Sheehy, Schneegans, & Spencer, 2015; Tummeltshammer & Amso, 2018; Werchan & Amso, 2020). The maturation of neural connectivity accompanies the improvement of attentional control in infancy (Xie et al., 2019), and this improvement of attention continue throughout childhood (Konrad et al., 2005; Rueda, Fan, et al., 2004).

Studies focused on attentional control in infancy have conceptualized attention as the support of the allocation of cognitive resources, the prioritization of incoming information, the updating of previous information, and the regulation of behavior (Colombo et al., 2011; Esterman & Rothlein, 2019). Due to the immature verbal and motor skills of infants, a large body of research measuring those conceptual aspects of infants' attention has heavily relied on various measures of infants' visual behavior (Bornstein, 1985; Colombo et al., 1999; Gredebäck, Johnson, & von Hofsten, 2010; Oakes, 2010, 2012). Such measures are thought to reflect attentional control to a great extent based on the strong link between the neural systems of visual attention, oculomotor movements, and oculomotor control (Amso & Scerif, 2015; Colombo, 2001; Corbetta et al., 1998; Johnson, 1990). Thus, different aspects of attentional processes have been measured by observing infants' looking behavior, such as the latency of an infant looking at a visual stimulus (orienting) (Pyykkö et al., 2020), the duration in which an infant looked at stimuli or engaged in tasks (sustained attention) (Johansson et al., 2015), the speed an infant visually processed a novel stimulus (information processing and updating) (Blankenship et al., 2019), the duration in which an infant looked at the targeted stimulus with the presence of a distractor in the peripheral visual field (endogenous control) (Geeraerts et al., 2019), etc.

Among different looking behavior measures, paradigms based on the peak looking duration or the dwelling time, such as the habituation and novelty preferential looking paradigms (Bornstein, 1985; Fantz, 1964; Sokolov, 1966), have long been applied to detect individual differences in looking behavior and early learning abilities. Colombo and colleagues further extended the concept of preferential looking paradigms and operationalized infants' ability to encode and process information in terms of *attentional styles* (Colombo, 2001; Colombo, Mitchell, Coldren, & Freeseman, 1991; Freeseman, Colombo, & Coldren, 1993). According to Colombo et al. and others, short-lookers process visual information quickly and efficiently, while long-lookers do so to a lesser degree (Colombo, 2001; Colombo et al., 1991; Freeseman et al., 1993). Whether an infant is a short- or long-looker is determined by the mean or median of the longest (or peak) looking durations during a trial in a free-looking task. This conceptual operation of the longest/peak looking duration has resulted in a systematic way of observing individual differences in attentional control in infancy and established the significance of looking duration for evaluating information processing efficiency (Hendry et al., 2019).

Another commonly used measure based on looking behavior is the overall looking time. The total amount of time infants spent looking at stimuli is used to access individual differences in endogenous attention (Goldman, Shapiro, & Nelson, 2004; Kopp & Vaughn, 1982; Ruff, Capozzoli, & Saltarelli, 1996; Vivanti, Fanning, Hocking, Sievers, & Dissanayake, 2017). In the developmental literature, the total exploration time can be referred to as a measure of focused attention and sustained attention. The former is defined as the ability to actively focus on the targeted stimuli without being distracted while the latter refers to the ability to maintain focus over prolonged periods of time (Cohen, 2014). However, it is also seen that these two terms are used interchangeably (Ruff & Lawson, 1990). In the current thesis, attentional control is measured based on an eye-tracking paradigm with multiple audio-visual stimuli. Given the properties of our screen-based tasks, the total time of continuously looking at the screen and engaging in the tasks forms a broad definition of sustained attention in the present context. (Note that this thesis and Publication 1 define overall looking time as a proxy of sustained attention while Publication 2 defines it as a proxy of focused attention. To be consistent, sustained attention will be used in the rest of the thesis.)

Behaviorally, the stability and the continuity of the development of different attentional aspects in infancy have been reported in several longitudinal studies. For example, previous results have reported stability of novel information processing from 6 to 8 months of age (Rose & Feldman, 1987), of visual patterns processing from 5 and 12 months of age (Rose et al., 2001), of sustained attention from 3 to 15 months old of age (Brandes-Aitken et al., 2019; Colombo et al., 2004), of look duration from 3 to 9 months of age (Colombo et al., 2004) and the stability of endogenous control against distractors from 9 to 31 months of age (Kannass, Oakes, & Shaddy, 2006). Moreover, the steady improvement of visual orienting from 2 to 9 months of age (Colombo et al., 2004; McConnell & Bryson, 2005) and the improvement of selective attention and visual anticipation from 7 and 9 months of age (Pyykkö et al., 2019) have also been reported.

However, it is also argued that there is an inconsistency of attentional development based on the observation of looking behavior. It is suggested that multiple underlying attention systems might be responsible for the changes in looking behavior depending on the developmental status or tasks (Kannass & Oakes, 2008). Indeed, complex changes in looking behavior in the first months of life have been observed. For example, the looking duration toward a visual stimulus first increases and then decreases over the course of the first year (Colombo, 2001; Courage et al., 2006). Evidence indicates that shorter looking duration (e.g. short-lookers with respect to looking style, see Colombo et al., 1991) toward novel stimuli is associated with more efficient information processing ability (Colombo, Freeseman, Coldren, & Frick, 1995), while longer looking duration during task exploration generally increases with age (Richards & Cronise, 2000) and is related to better endogenous control (Casey & Richards, 1988; Pérez-Edgar et al., 2010; Ruff et al., 1996). Both short looking durations toward novel stimuli and long looking durations in exploring tasks are intermediately related to better cognitive abilities in infancy and childhood (Blankenship et al., 2019; Bornstein & Sigman, 1986; Courage, Howe, & Squires, 2004; Cuevas & Bell, 2014; Tamis-LeMonda & Bornstein, 1989).

Taken together, behavioral evidence to date indicates that attentional control is a multi-faceted and stable construct in infancy. Individual differences may be examined from different aspects of the looking behavior which are possibly governed by different underlying mechanisms.

1.1.2 The Application of a Data-driven Method for Attention Measures Using Eye-tracking Data

To date, data-driven methods are regularly applied in the field. A data-driven approach has several advantages including relaxing theory-driven constraints and allowing new knowledge to emerge while fundamental assumptions are challenged, and thus brings substantial benefits to research (Jack, Crivelli, & Wheatley, 2018). In this thesis, by integrating theory-based and data-driven methods, I explore a great amount of eye-movement data and retain the advantages of theoretical insight while increasing the freedom of exploration.

With the advancement of technology, looking behavior of infants containing rich information can be decoded at the micro-level from an enormous amount of eye-tracking data (Gredebäck et al., 2010). Eye movements are thought to reflect overt attention that is strongly linked to oculomotor control (Amso & Scerif, 2015; Johnson, 1990; for the study regarding the development of covert attention please see Richards, 2005). During the construction of eye-tracking datasets, visual information is often categorized into two main types, *saccades* and *fixations* (Salvucci & Goldberg, 2000), which are also the most fundamental aspects of eye movements (Becker & Fuchs, 1969). *Saccades* are ballistic and rapid shifts of eye movements that bring an image or object of interest onto the fovea (Purves et al., 2001). *Fixations* are dynamic and relative, but not completely, still eye movements resulted from the maintaining of the visual gaze on a location. Compared to saccades, fixations have substantial effects on perception as it enables the stabilization and illustration of visual imagines (Krauzlis, Goffart, & Hafed, 2017). In turn, fixations are important for processing visual input and allow the retina to detect images with greater sensitivity (Tanke, Barsingerhorn, Boonstra, & Goossens, 2021).

In the context of attention measures in the current thesis, I used a longitudinal dataset of 118 infants from 6, 10, to 18 months of age. Overall, the dataset contains approx. 0.5 million fixations collected across 11 different age-appropriate tasks. By using this approach, I intentionally deal with the eye-tracking data by exploring the statistical patterns among fixations. While combining theoretical concepts with a data-driven method increases the sensitivity of detecting individual differences, I might, in fact, also challenge some theoretical aspects defining "success" on the trial-basis. For instance, instead of considering the looking duration within a trial terminates when the infant looks away twice, I include all data as long as fixations are detected. This should be kept in mind when interpreting results. For the detailed methods of preprocessing and analyzing eye-tracking data, please see Section 3.2 and Publication 1 (for the list of tasks and their descriptions please see Table 1 in Publication 1). In addition, a series of videos depicting the stimuli can be viewed on the Databrary (Gredebäck, Forssman, Lindskog, & Kenward, 2019, https://nyu.databrary.org/volume/828).

To explore and identify the stable indices of attention measures using all fixations from different tasks and different age points, there were a series of steps to preprocess data. Previous evidence has shown that individual looking or fixation duration is quite stable (Jankowski & Rose, 1997; Wass & Smith, 2014) and consistent across stimulus' types in early development (Reynolds, Zhang, & Guy, 2013; Wass & Smith, 2014). Thus, in the first step, I visually examined the mean and variance of individual fixations across different tasks in each age group using density plots (see Figure 1). As Figure 1 illustrates, the mean and variance of fixation durations show stability across different tasks within the same age group. In addition, the density distribution of individual mean fixations shows two clusters. This pattern is observable at all age points. In the second step, the internal consistency of the mean fixation duration across individuals in each age group allows us to aggregate all fixations within the same age group. Meanwhile, outliers in each age group are removed (+/- 3 z-score).

Inspired by previous literature focusing on the association between attention and self-regulation, I systematically analyzed fixation data from 11 age-appropriate eye-tracking tasks and focused on two attention measures, *look percentage* and *short fixation ratio*, after. These two attention measures were observed to be more plausible candidates to predict self-regulatory function at the latter age points compared with other attention measures, such as visual anticipation, visual disengagement, shift rate, selective attention, etc. (for more details of the literature review, please see the later Section 1.2.2.). Look percentage and short fixation ratio conceptually mimic previously well-established measures of sustained attention (Casey & Richards, 1988; Richards & Turner, 2001; Ruff & Capozzoli, 2003) and attentional styles (Colombo et al., 1995; Courage et al., 2006; Jankowski & Rose, 1997; Reynolds, Guy, & Zhang, 2011), respectively.

The *look percentage* measure is a straightforward assessment based on the amount of time an infant spends on targeted tasks (Colombo, 2001; Ruff, 1986; Ruff et al., 1996). It is defined as the total fixation duration of the stimuli divided by the total duration of all tasks (within the same age group) across a variety of free-looking tasks. I calculated the look percentage separately for infants at the age of 6, 10, and 18 months. The *short fixation ratio*, on the other hand, indicates the processing efficiency at the micro-level. Previously, attentional styles (short- and long-lookers) have been used as a proxy for individual differences in information processing (Colombo, Richman, Shaddy, Follmer Greenhoot, & Maikranz, 2001). This dichotomic index is based on the mean or median of the individual's longest looking duration among a group of infants. If an infant's longest looking duration is higher than the mean or median of the group, then the infant will be considered as a long-looker. Long-lookers tend to process local (not global) information and they take more time to process the overall information (Colombo et al., 1995; Freeseman et al., 1993) while short-lookers process information in a global and more efficient manner.

The attentional styles have been applied to examine attention in infants for decades. However, even up to date, it is often measured by presenting infants with a very brief video clip (e.g. 5 minutes). This might not reflect the general attentional control as attention fluctuates over an extended period of time. In addition, the dichotomic variables might limit the observation of individual differences. Hence, the *short fixation ratio* using fixation data can provide a continuous measure that is more sensitive to individual differences than attentional styles. Under the data-driven concept, I observed that two clusters of mean fixation durations can be consistently seen at three different age points (see Figure 2). Based on this observation, I used the lowest point between two clusters as the splitting point. The percentage of an individual's fixations under the splitting point value was calculated as the *short fixation ratio*. Compared to attentional styles, the short fixation ratio allows us not only to detect individual differences in a more sensitive way, but also to represent the information processing across tasks.

Based on a data-driven method, I was able to show the stability and consistency within the same measures from 6, 10, to 18 months (see Table 1). The skewness, kurtosis, as well as the distributions of each variable at three age points indicate that there are no extreme asymmetric patterns of the attention measures (see Table 1 and Figure 3). In summary, the results based on the longitudinal dataset are consistent with previous literature. Attentional control is a steady and multi-faceted construct. More specifically, information processing and endogenous control, presented in this thesis, show the stable continuity in the first one and half years of life.

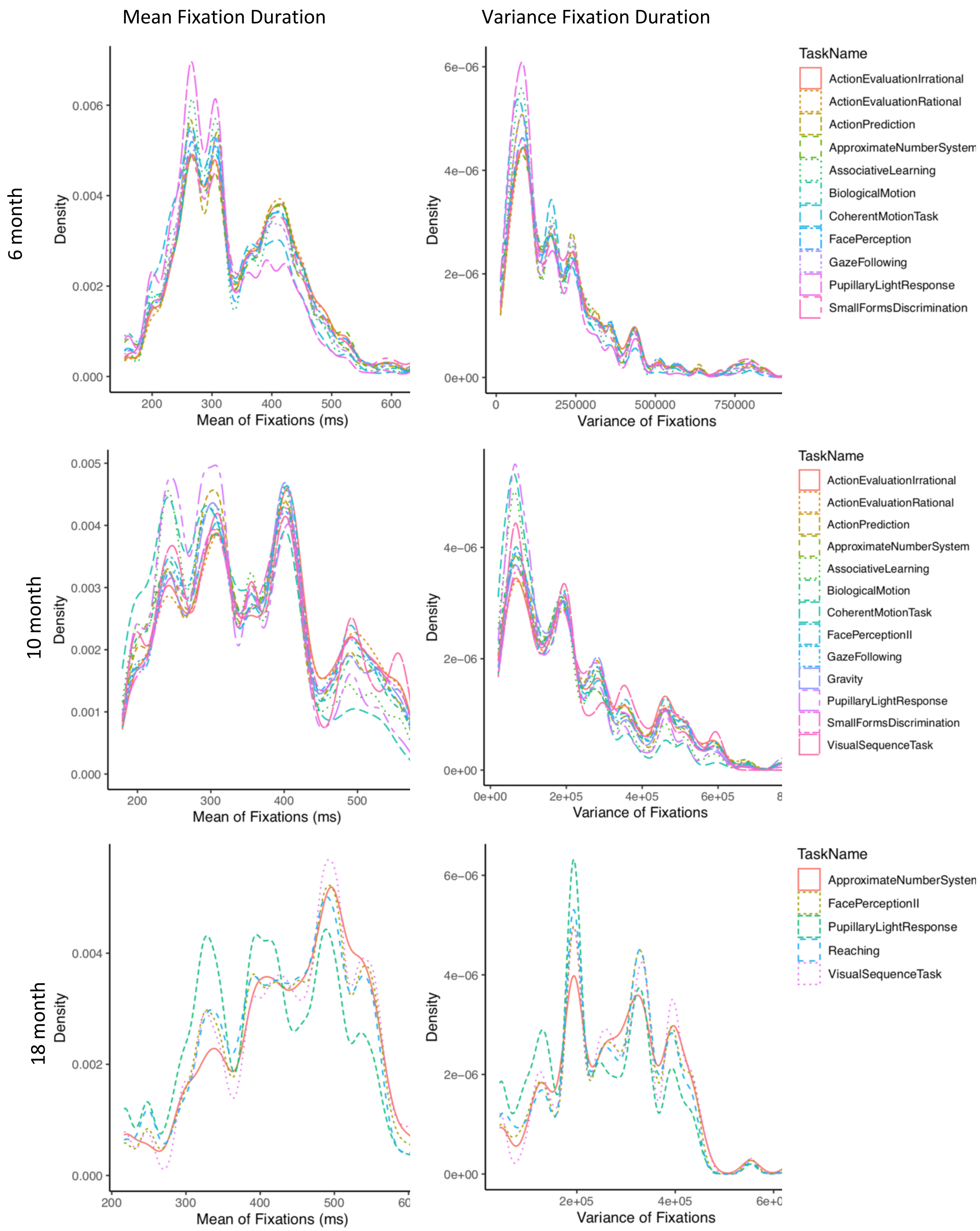

Figure 1: Internal consistency of fixations across tasks at three age points
This figure presents the density distribution of mean (left column) and variance (right column) of fixation durations at three age points across different age-appropriate tasks. (Figure is reprinted with the permission from American Psychological Association.)

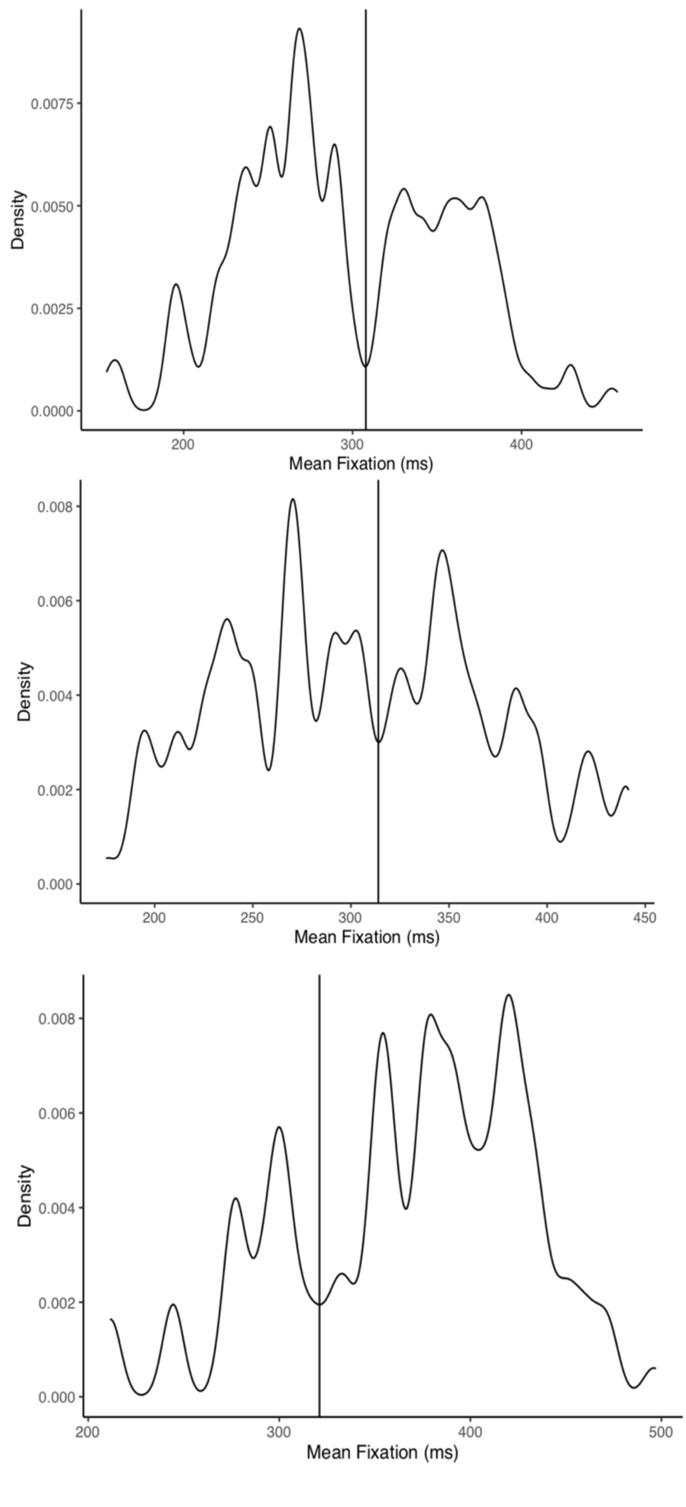

Figure 2: Splitting point at each age group for short fixation ratio
This figure illustrates the distribution of mean fixations generated from aggregated data across tasks and at the ages of 6, 10, and 18 months. The X-axis indicates the mean fixation duration in ms. The Y-axis is the value of density in distribution. From the distribution of mean fixation durations, the lowest point between the two highest peaks of two clusters was chosen as a splitting point. The splitting values for 6-, 10-, and 18-month-old are 307.8, 314, and 321 ms, respectively. An individual's short fixation ratio is defined based on the percentages of overall complete fixations with durations that are under this splitting point. (This figure is reprinted with the permission of American Psychological Association.)

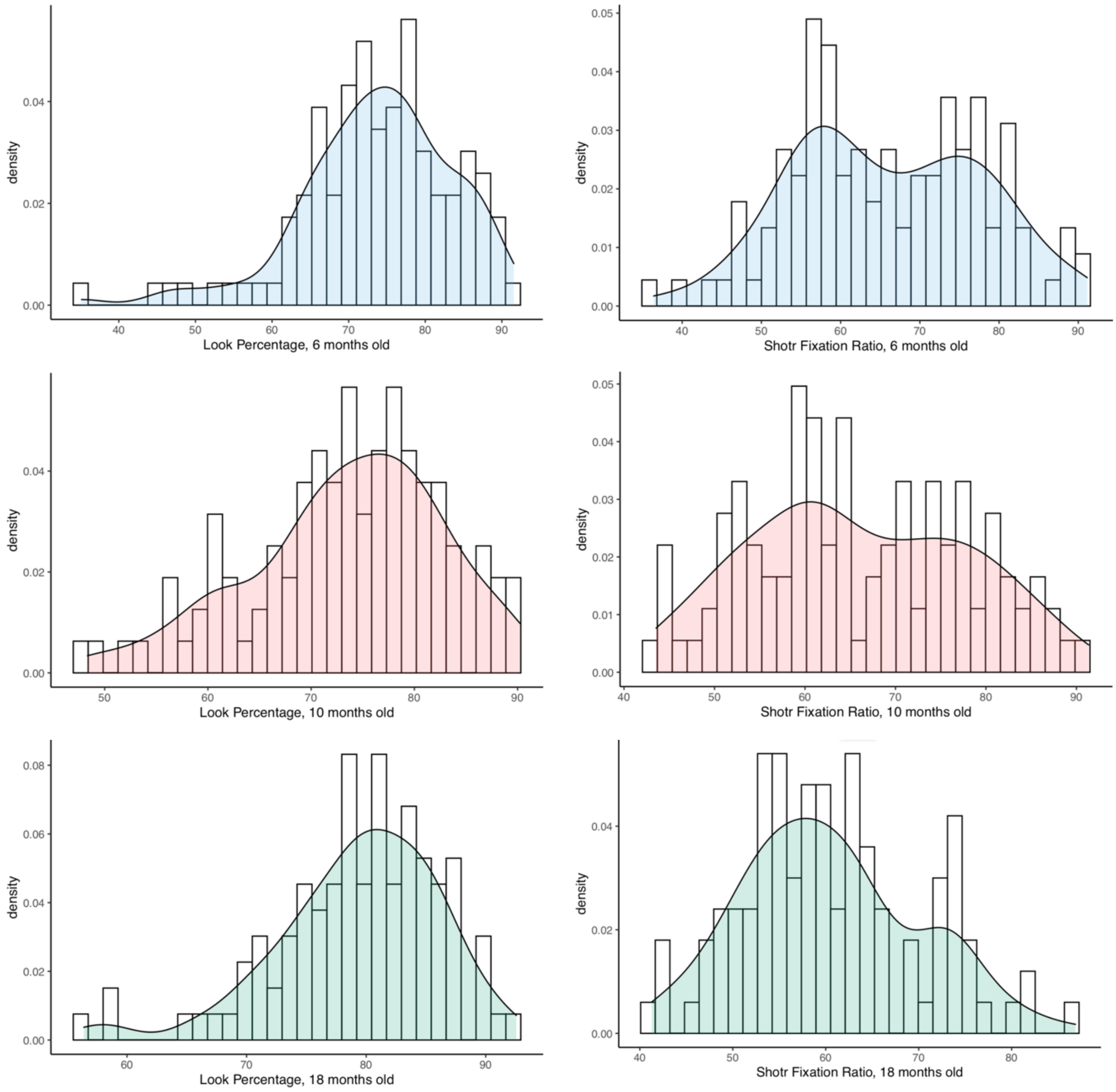

Figure 3: Density distribution of two attention measures
Distributions of look percentage and short fixation ratio at 6 (blue), 10 (red) and 18 (green) months of age are presented on the left side and the right side, respectively.

Table 1. Pearson correlation with multiple comparisons with Benjamini-Hochberg correction of short fixation ratio and look percentage

	Variable	Month	1.	2.	3.	4.	5.	6.	Skewness	Kurtosis
1.	LP	6	1						-0.78	1.52
2.	LP	10	0.33*** (n=110)	1					-0.52	-0.16
3.	LP	18	0.21 (n=103)	0.31*** (n=100)	1				-0.85	1.09
4.	SF	6	-0.12 (n=118)	-0.01 (n=110)	-0.02 (n=103)	1			0.02	-0.77
5.	SF	10	-0.02 (n=110)	-0.13 (n=110)	-0.06 (n=100)	0.63*** (n=110)	1		0.10	-0.96
6.	SF	18	-0.22 (n=103)	-0.20 (n=100)	-0.15 (n=103)	0.26* (n=103)	0.43*** (n=100)	1	0.38	-0.36

*Pearson correlation: * p < .05; *** p < .001; SF: short fixation ratio; LP: look percentage; n: sample size. This table is adopted with the permission of American Psychological Association.)*

1.2 Attention and Self-regulatory Functions

1.2.1 Distinct yet Approximate Aspects of Self-regulatory Functions in Early Years of Life

Self-regulatory functions include a set of abilities to monitor, direct, and redirect feelings, thoughts, or actions in attaining and deliberately pursuing adaptive goals (Nigg, 2017). Previous studies suggest that self-regulation is strongly linked to temperament and can be defined in various emotion-related terms (Posner & Rothbart, 2000; Rothbart, Ellis, & Posner, 2011; Rothbart, Sheese, et al., 2011; Sheese, Rothbart, Posner, White, & Fraundorf, 2008). The developmental literature emphasizes two main components of self-regulation: *effortful control* (Kochanska, Murray, & Harlan, 2000; Rueda, Posner, & Rothbart, 2005; Spinrad & Eisenberg, 2015) and *executive functions* (McClelland & Cameron, 2011; Montroy, Bowles, Skibbe, McClelland, & Morrison, 2016). Effortful control is conceptualized as "the ability to choose a course of action under conditions of conflict, to plan for the future, and to detect errors" (Rothbart, 2007, p. 207). That is, the ability to voluntarily control attention, inhibit impulses (Rothbart, Ahadi, Hershey, & Fisher, 2001), and detect and resolve conflicts (Rothbart & Bates, 2006). Executive functions include several distinct components, such as working memory (updating), cognitive flexibility (shifting), and inhibitory control (Friedman & Miyake, 2017; Kirkham, Cruess, & Diamond, 2003; Miyake & Friedman, 2012; Miyake et al., 2000). Although conceptualized as different constructs, effortful control and executive functions, including their sub-components, are difficult to measure and dissociate in children under three (Hendry, Jones, & Charman, 2016; Zhou, Chen, & Main, 2012). For instance, whether working memory, which is commonly categorized as a sub-component under executive function, is also a part of effortful control is still debatable (see N. Eisenberg, 2017; Nigg, 2017 for further elaboration).

Conceptually, effortful control and executive functions show some extent of overlaps (Lin, Liew, & Perez, 2019). As a result, most performance-based tasks measuring self-regulation in infancy and early childhood either emphasize inhibitory control and working memory separately or at the same time. Inhibitory control often reflects the temperamental aspects of self-control in infancy (Rothbart, Ellis, et al., 2011) and impulse control in early childhood (Montroy et al., 2016). Working memory plays a role in updating and actively representing self-regulatory goals (Best & Miller, 2010; Hofmann, Schmeichel, & Baddeley, 2012). However, while some recent studies focused on the sub-components of executive function demonstrated that inhibitory control and working memory are uncorrelated (Frick et al., 2018; Kraybill, Kim-

Spoon, & Bell, 2019; Miller & Marcovitch, 2015; Van Reet, 2020), other studies showed positive correlations at different age points, but the correlations vary across different studies and are not consistent, cross-sectionally or longitudinally (Blankenship et al., 2019; Jenkins & Berthier, 2014; Johansson, Marciszko, Brocki, & Bohlin, 2016; Mulder, Verhagen, Van der Ven, Slot, & Leseman, 2017). In short, it is still debatable whether inhibitory control is related to working memory (Nigg, 2017) and to what extent effortful control and executive functions share commonalities (Tiego, Bellgrove, Whittle, Pantelis, & Testa, 2020). Furthermore, there are also ongoing discussions about the organizations of affective (hot) and cognitive (cool) executive functions (O'Toole, Monks, & Tsermentseli, 2018; Peterson & Welsh, 2014; Zelazo & Carlson, 2012) and how they are related to self-regulation (Zhou et al., 2012). Taken together, along with ongoing debates, several mixed results appear in the literature. How effortful control, executive function, and the subcomponents of executive function are related remains under debate. For the purpose of this thesis, I selected tasks that are commonly used in developmental literature to measure self-regulatory functions in toddlers.

1.2.2 The Relation between Attentional Control and Self-regulatory Functions

There is considerable overlap between attentional control and self-regulatory functions (Posner, Rothbart, & Voelker, 2016; Rueda, Posner, et al., 2005). Based on the neurocognitive model of attention, three distinct networks—alerting, orienting, and executive attention—are involved (Petersen & Posner, 2012; Rueda, Posner, et al., 2005). Under this account, executive attention functions as a process that resolves conflict, which is the definition of effortful control (Petersen & Posner, 2012; Posner, Rothbart, Sheese, & Tang, 2007; Posner et al., 2016; Rothbart, Sheese, & Posner, 2007).

Based on the assumption that attention in infancy is linked to the development of self-regulation, researchers have investigated this relationship using various attention measures. For instance, the dichotomic use of short- or long- lookers has been reported to successfully predict later executive functions (Cuevas & Bell, 2014). However, other studies using similar methods have only partially supported such a relation (Blankenship et al., 2019; Devine, Ribner, & Hughes, 2019; Kraybill et al., 2019; Q. Zhang & Wang, 2022). Meanwhile, one recent study found only relation in the first year of life but not later in toddlerhood or childhood (Blankenship et al., 2019). Moreover, while some researchers have found that mean fixation duration in infancy is associated with effortful control in early childhood (Papageorgiou et al., 2014), others failed to find a significant relation between median fixation duration and self-regulatory functions (Geeraerts et al., 2019). In addition, although used as measures of attentional control, neither anticipatory looking behavior nor voluntary disengagement in the first year are associated with self-regulatory functions in infancy (Holmboe, Bonneville-Roussy, Csibra, & Johnson, 2018) nor later in toddlerhood (Geeraerts et al., 2019; Nakagawa & Sukigara, 2013; Pyykkö et al., 2020).

Sustained attention, on the other hand, is associated with effortful control at both 22 months (Kochanska et al., 2000) and 2 years (Johansson et al., 2015), but not at 14 or 33 months (Kochanska et al., 2000). Sustained attention is often measured by accessing the level of attending (Ruff & Capozzoli, 2003) using, for example, the total time elapsed in the task, frequency of attending, or frequency of looking away. Concerning executive functions, sustained attention in infancy is partially linked to global executive functions at the age of 18 months (Frick et al., 2018) and 24 months (Johansson et al., 2015), and to inhibitory control at the age of 18 months (Frick et al., 2018), 3 years (Johansson et al., 2016), and 5 years (Brandes-Aitken et al., 2019). In the same studies, sustained attention is related to working memory at 5 (Brandes-Aitken et al., 2019) but not 3 years of age (Johansson et al., 2016).

In sum, an existing extensive body of work exploring the impact of attentional control on self-regulatory functions (Blankenship et al., 2019; Brandes-Aitken et al., 2019; Cuevas & Bell, 2014; Devine et al., 2019; Frick et al., 2018; Geeraerts et al., 2019; Holmboe et al., 2018; Johansson et al., 2016; Johansson et al., 2015; Kochanska et al., 2000; Kraybill et al., 2019; Nakagawa & Sukigara, 2013; Papageorgiou, Farroni, Johnson, Smith, & Ronald, 2015; Papageorgiou et al., 2014; Pyykkö et al., 2020; Rose, Feldman, & Jankowski, 2012; Q. Zhang & Wang, 2022) argues that attention in early years is related to self-regulation later in life. However, although empirical evidence exists to support this claim, the findings are not consistent. In Figure 4, I illustrate the findings from 17 studies described above that target the relation between attention and self-regulation to provide an overview of the field (Note: Study number 17 by Zhang & Wang (2022) is added only in the current thesis but not available when Publication 1 & 2 were published or in press). Each of these studies was identified as having assessed long-term effects that were included in the above text. Each line represents the relation between one attentional control measure (on the left) and one outcome measure (on the right). Even though the relations between several marker tasks for both attentional control and self-regulatory functions have been repeatedly tested at different age points, significant findings (in solid lines, $p < 0.05$, two-tailed if it is correlational) appear to be in the minority compared to insignificant ones (in dotted lines). Overall, only 19.5% of the correlations were significant (18.2% from 16 studies reported in Publication 1 & 2). An additional 11 cross-sectional measurements of attentional control (sustained attention or visual disengagement) and self-regulatory functions within the same age point (12, 18, 24, or 36 months) from 3 different studies (Johansson et al., 2016; Johansson et al., 2015; Nakagawa & Sukigara, 2013) were not included in the figure, due to lack of longitudinal data. However, among them, only 4 out of 12 tests from two studies showed significant effects (Johansson et al., 2016; Nakagawa & Sukigara, 2013).

Collectively, the vast majority of studies have failed to demonstrate an association between the two constructs (see Figure 4). In addition to the lack of empirical consistency, the field is also currently debating how to best define attention and self-regulation (Bridgett, Burt, Edwards, & Deater-Deckard, 2015; Doebel, 2020; N. Eisenberg, 2017; Engle, 2018; Mancas, Ferrera, Riche, & Taylor, 2016; Morra, Panesi, Traverso, & Usai, 2018; Nigg, 2017; Zhou et al., 2012), what the underlying mechanisms are (N. Eisenberg, 2017; Friedman & Miyake, 2017; Karr et al., 2018; Tiego et al., 2020), what predictive relations we should expect (Hendry et al., 2019; Hendry et al., 2016), and if there are benefits of training attention on self-regulation (Simons et al., 2016; Smid, Karbach, & Steinbeis, 2020). Taken together, previous studies have attempted to examine the predictive role of early attentional control. Due to inconsistencies and a diverging set of approaches, the predictive effects of attentional control on later self-regulatory functions remain unclear.

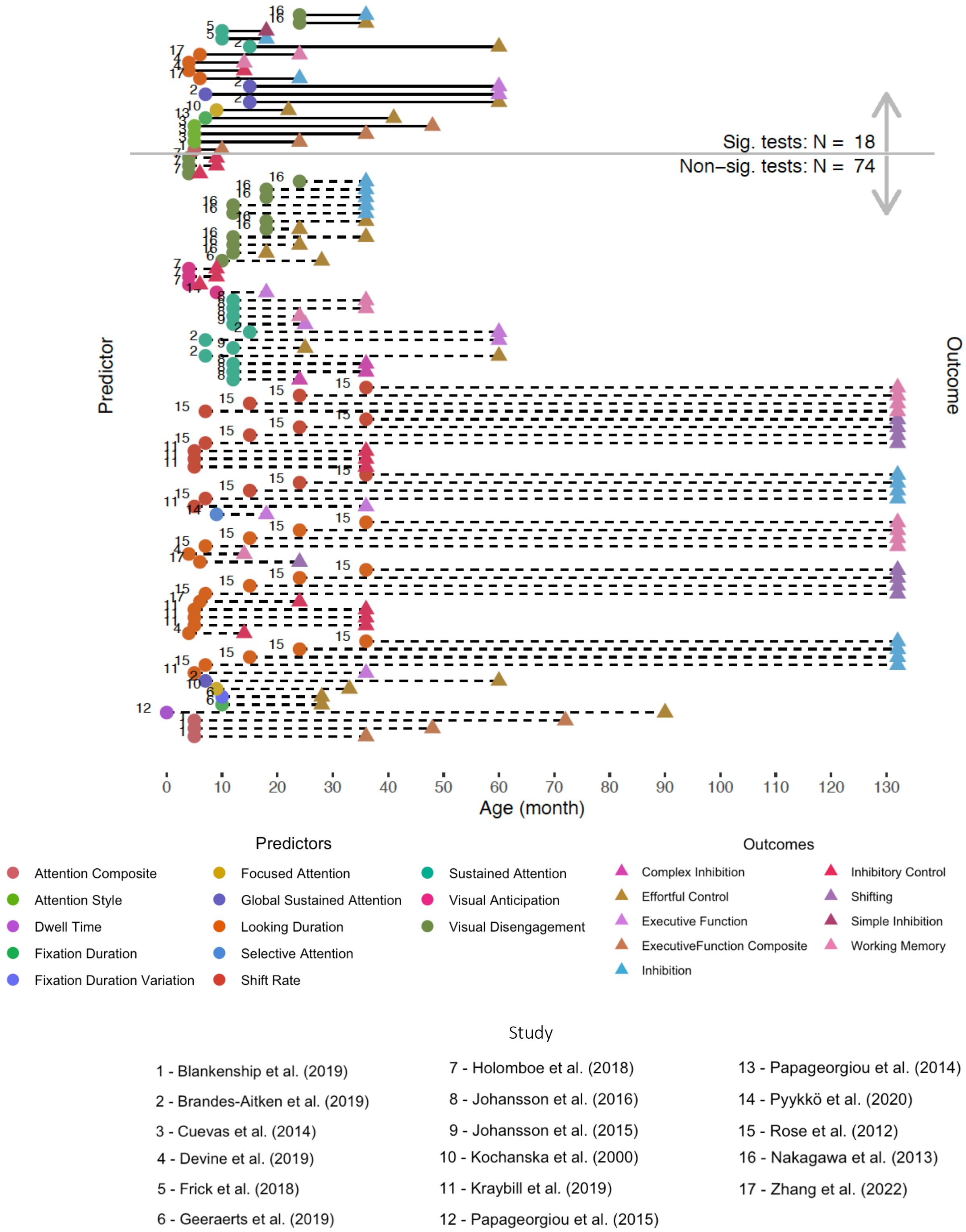

Figure 4. Associative results from studies investigating the relation between attention and self-regulation

This illustration shows the overview of 17 studies investigating the relationship between attentional control and self-regulation. Each line represents the relationship between the results of a predictive task and one outcome measure. Solid lines indicate significant results while dotted lines show non-significant findings. Circles on the left indicate tasks used to measure attention control as a predictor. Triangles on the right represent outcome measures from different tasks. In both circles and triangles, different colors represent different marker tasks. Circles with the same number labeled on the left were from the same study. The X-axis shows the age when tasks were performed. This figure is adapted with permission from American Psychological Association, Publication 1 Tu et al., 2021.

Despite the unclear evidence, a few positive empirical findings and theoretical frameworks have motivated researchers to promote attention training studies or to attempt to improve self-regulatory functions through attentional training (Diamond & Lee, 2011; Wass, Porayska-Pomsta, & Johnson, 2011; Wass, Scerif, & Johnson, 2012). While some report positive training effects on executive functions (Kirk, Gray, Ellis, Taffe, & Cornish, 2017; Kirk, Gray, Ellis, Taffe, & Cornish, 2016; Rueda, Checa, & Cómbita, 2012; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; Scionti, Cavallero, Zogmaister, & Marzocchi, 2020), two meta-analytic studies and one narrative study show conflicting and inconclusive results (Kirk, Gray, Riby, & Cornish, 2015; Peng & Miller, 2016; Rapport, Orban, Kofler, & Friedman, 2013). Studies focusing on children with developmental disorders or low social-economic-status have reported no training effect (Steiner, Frenette, Rene, Brennan, & Perrin, 2014), or small partial training effects on trained or little transfer effects on tasks that are close to trained ones (Barnes et al., 2016; Kirk et al., 2017; Kirk et al., 2016; Powell, Wass, Erichsen, & Leekam, 2016). Admittedly, only a few attention training studies have focused on infancy (Ballieux et al., 2016; Forssman & Wass, 2018; Wass et al., 2011). These studies indicated that within-task attention training effects might be seen at the end of the first postnatal year, but the evidence is still limited.

Taken together, findings from longitudinal studies and training studies, taken together, suggest that attentional control and self-regulatory functions might be unstable constructs that are difficult to capture in infancy and early childhood or that a relation between the two constructs is elusive at best. Similarly, to better understand the relation between attention and self-regulation, it is critical to use robust measures that can reliably evaluate these functions as well as the developmental changes. One way to increase the validity of the evaluations is to establish the measures using a large amount of high-quality data. Therefore, in this thesis, I approached this issue by identifying two robust attention measures and examined how they correlated with self-regulatory functions. Using a data-driven method described in 1.1.2, two attention measures with high degrees of stability and consistency (see Table 1) were used to examine the relationships between attention and self-regulation. For this purpose, several commonly used tasks (see Figure 5) for evaluating self-regulatory functions were applied when the same group of participants in the longitudinal measures of attention (from 6, 10, to 18 months) turned age 18 and 30 months. As seen in Table 2, none of the significant correlations survive after correction. In addition, results between different self-regulatory tasks were also noted as unrelated. These results add to a growing body of research suggesting that a relation between attentional control and self-regulation is unsupported. Along with current ongoing debates, the field needs more research and perhaps new frameworks that can help us explore the developmental pathways that lead to self-regulation. More details are described in Publication 1. Materials including a series of videos depicting the tasks for measuring self-regulatory functions in this thesis and Publication 1, are available on the Databrary (Gredebäck et al., 2019, https://nyu.databrary.org/volume/828).

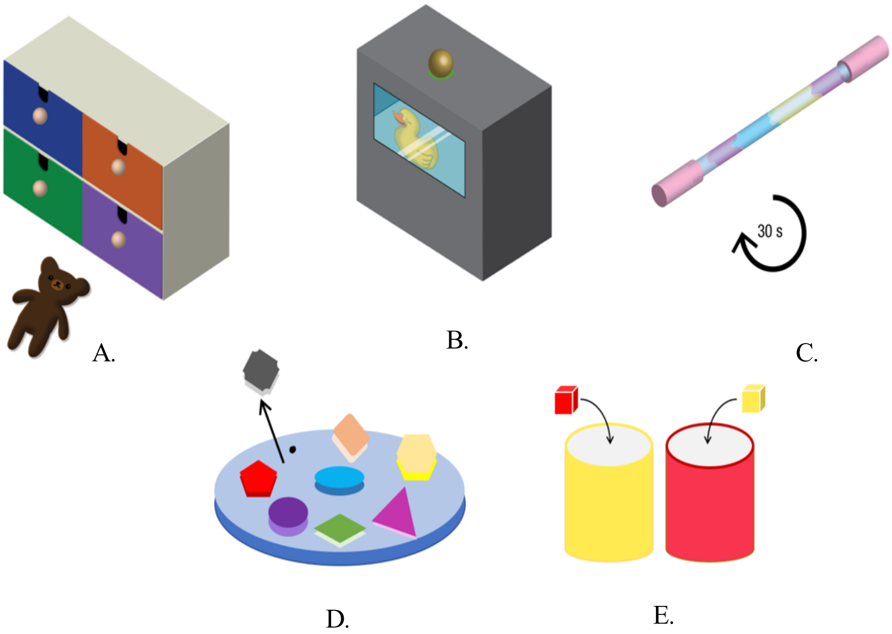

Figure 5. Tasks used to measure self-regulatory functions
A. Hide-and-seek Task was used to evaluate working memory at 18 months. B. Tricky Box was used to assess complex inhibition at 18 and 30 months of age. C. An attractive toy (a glittering wand) was used to measure simple inhibition at 18 months. D. Spin-the-Pots task was used to measure working memory at 30 months. E. After the same colors of cubes and buckets were placed together, the child was asked to place the cubes in a reversed way. This was used to measure both inhibitory control and working memory at 30 months. Additionally, the task "Delayed Gratification" which is not illustrated here was used to measure inhibitory control at 30 months. A bag with a reward was presented to the child and the child was asked to wait for opening the bag until the experimenter returned. Note: A, B, and C illustrated by Mattias Stridbeck are reprinted with permission from" An embodied account of early executive-function development: prospective motor control in infancy is related to inhibition and working memory," by J.M. Gottwald et al., 2016, *Psychological Science*, 27, p 1603.

Table 2. Pearson correlation with multiple comparisons (with Benjamini-Hochberg correction) between attentional control and self-regulatory functions

		Age (in months)						
		18			30			
		Self-regulatory function			Self-regulatory function			
Attention Measure	Age (in months)	Working Memory	Simple Inhibition	Complex Inhibition	Working Memory	Complex Inhibition	Delayed Gratification	Reversed Categorization
LP	6	0.02 (n=98)	0.13 (n=88)	-0.03 (n=93)	-0.14 (n=89)	0.02 (n=85)	-0.11 (n=71)	-0.01 (n=92)
LP	10	-0.11 (n=95)	0.24 (n=86)	0.03 (n=90)	-0.15 (n=86)	0.18 (n=81)	0.05 (n=68)	-0.12 (n=89)
LP	18	0.04 (n=97)	0.10 (n=87)	0.15 (n=92)	-0.25 (n=86)	-0.07 (n=81)	-0.05 (n=68)	-0.02 (n=89)
SF	6	0.07 (n=98)	0.02 (n=88)	0.23 (n=93)	-0.18 (n=90)	0.04 (n=85)	-0.02 (n=71)	-0.06 (n=92)
SF	10	-0.07 (n=95)	0.09 (n=86)	0.11 (n=90)	-0.12 (n=90)	-0.07 (n=81)	-0.04 (n=68)	-0.20† (n=92)
SF	18	-0.01 (n=97)	-0.09 (n=87)	0.10 (n=92)	0.04 (n=86)	0.02 (n=81)	0.04 (n=68)	0.04 (n=89)

Note: LP: look percentage; SF: short fixation ratio; n: sample size. This table is adopted with permission of American Psychological Association.

1.3 Maternal Distress and Infants' Attention

1.3.1 Cross-generational Effects on Offspring's Attention

Operationally, maternal psychological distress is often symptomized by an unbalanced and/or strained emotional state from pregnancy to postpartum and commonly includes depression and/or anxiety (Fontein-Kuipers, 2016; Priest, Austin, Barnett, & Buist, 2008). Previous evidence has shown that maternal psychological distress influences the trajectories of attentional development in childhood. Several large cohort studies have shown that maternal depressive and/or anxiety symptoms are associated with attention problems in offspring at the ages of 2 years (Ross et al., 2020), 3, and 4 years (Van Batenburg-Eddes et al., 2013), as well as 5, 6.5, and 14 years (Clavarino et al., 2010; Wang & Dix, 2017). Maternal distress is also linked to ADHD symptoms at the age of 4 and 8–9 years (Mulraney et al., 2019; Vizzini et al., 2019). Moreover, recent studies also reported that maternal childhood adverse experiences contribute to ADHD and ASD in children (Moon et al., 2021; Roberts, Liew, Lyall, Ascherio, & Weisskopf, 2018; Roberts et al., 2013).

In nonhuman primates, exposure to mild stress during pregnancy is related to less visual exploration and higher distractibility of offspring (Schneider, 1992). In humans, maternal stress during pregnancy has a negative impact on infants' attention shifting at the age of 18 months (Plamondon et al., 2015). It is been shown that infants whose mothers perceived higher stress during pregnancy needed more time than others to process visual information at the age of 7.5 months and looked away from the tasks significantly more than infants whose mothers had low perceived stress during pregnancy (Merced-Nieves, Dzwilewski, Aguiar, Lin, & Schantz, 2020). Preliminary evidence also suggests that this cross-generational association between maternal distress and infant development might be linked to trauma exposure prior to pregnancy (Bosquet Enlow et al., 2017; Bouvette-Turcot et al., 2020).

Furthermore, infants of depressed mothers have less synchronous mutual gaze with their mothers than infants of non-depressed mothers (Lotzin et al., 2015). In turn, mutual gaze has been associated with visual attention in the first postnatal year of life (Niedźwiecka, Ramotowska, & Tomalski, 2018). The impact of maternal distress on mother-infant interactions (Granat, Gadassi, Gilboa-Schechtman, & Feldman, 2017) and maternal sensitivity (Bernard, Nissim, Vaccaro, Harris, & Lindhiem, 2018) have been related to infants' selective attention (Juvrud, Haas, Fox, & Gredebäck, 2021) and gaze-following ability (Astor et al., 2020). In short, the extensive evidence so far has shown that maternal mental health has significant impacts on children's attention. However, compared with studies in children, evidence focusing on how maternal mental health affects the development of attention in infants is less studied.

1.3.2 A Multi-dimensional Investigation of the Impact of Maternal Distress on Infants' Attention

Based on the previous literature, it seems evident that a mother's mental health, during both antenatal (Kingston et al., 2015; Koutra et al., 2013; Laplante et al., 2004; Merced-Nieves et al., 2020; Plamondon et al., 2015; Ross et al., 2020; Tarabulsy et al., 2014) and postpartum (Juvrud et al., 2021; Kingston et al., 2015; Koutra et al., 2013; Lotzin et al., 2015; Niedźwiecka et al., 2018; Ross et al., 2020), has a significant impact on offspring's attention; but the underlying mechanisms are still unclear. Previous evidence has shown that the complex and dynamic interactions between multiple biological, psychological and environmental factors contribute to both mothers' mental health and children's attention. For example, based on a reciprocal model, children's attention problems might worsen mothers' mental health, which in return negatively influences children's attention (Breaux & Harvey, 2019; Sfelinioti & Livaditis, 2017; Van Steijn, Oerlemans, Van Aken, Buitelaar, & Rommelse, 2014).

Evidence supporting an association between maternal distress and neurological development, more broadly, indicates changes in cortical and subcortical connectivity in human infants (Rifkin-Graboi et al., 2013; Scheinost et al., 2020) and children (H. Zhang et al., 2021), and also indicates negative impacts on neurogenesis and gene expression in neonates of rodents (Fatima, Srivastav, Ahmad, & Mondal, 2019). From biological and environmental perspectives, while tryptophan hydroxylase 1 (TPH1) enzyme mutations in mothers are related to the impaired maternal serotonin production and an increase in a higher risk of inattention in their children (Halmøy et al., 2010). On the other hand, adoption studies demonstrated environmental but not genetic factors are associated with children's ADHD symptoms (Rice et al., 2010; Tully, Iacono, & McGue, 2008). Furthermore, it has also been reported that increased cortisol levels during the 2^{nd} trimester and increased subjective maternal distress in the 3^{rd} trimester are associated with weaker connectivity of the anterior cingulate cortex of neonates (Scheinost et al., 2020). The connectivity of anterior cingulate cortex has been linked to infant's attention (Reynolds, Courage, & Richards, 2010), and ADHD in children (Kelly et al., 2009) and adults (Seidman et al., 2006). Intriguingly, one previous study investigating infants' cognitive development at 12 months of age reported that high cognitive performance is linked to lower maternal cortisol levels in the 2^{nd} trimester and higher cortisol levels in the 3^{rd} trimester (Davis & Sandman, 2010), suggesting that the link between mother's cortisol levels and children's cognitive development is not linear.

Another layer of the complexity comes from the interactions and/or comorbidities among various different aspects of maternal psychological distress at different time points. Whether the symptoms are chronic or not is also critical. In particular, adverse childhood experiences that continue to contribute to psychological distress later in life are common. Previous studies have demonstrated that the severity of psychological distress is strongly linked to exposure to traumatic experiences earlier in life (Chu, Williams, Harris, Bryant, & Gatt, 2013; Sexton, Hamilton, McGinnis, Rosenblum, & Muzik, 2015). Studies also suggested that different types of traumatic events, such as interpersonal and non-interpersonal trauma, have different impacts on mental distress and psychiatric symptoms (Baker et al., 2020; Haldane & Nickerson, 2016). This moderating effect of adverse childhood experiences on maternal psychological distress might result from the alternation of hypothalamic-pituitary-adrenal axis functioning (Tarullo &

Gunnar, 2006) and an increase in sensitivity to negative cues (Dannlowski et al., 2012). These changes, in turn, leads to an increase in anxiety (Dannlowski et al., 2012; Etkin, Egner, & Kalisch, 2011). In addition, evidence shows that individual differences contribute to different trajectories related to life satisfaction and well-being after traumatic events (Sacchi et al., 2020). For example, some individuals develop higher risks of post-traumatic stress disorder, depression, and anxiety (Suliman et al., 2009). Thus, when studying the relationships between different aspects of maternal mental health and infants' attention, it is crucial to take maternal adverse childhood experiences into account.

Collectively, compelling evidence has shown that early adverse experiences increase the risks of depression and anxiety later in life (Bifulco, Harris, & Brown, 1992; Heim & Nemeroff, 2001) and during different perinatal phases (Buist, Gotman, & Yonkers, 2011; Racine et al., 2021). Maternal psychological distress significantly hinders the development of attention in offspring's childhood (Clavarino et al., 2010; Ross et al., 2020; Van Batenburg-Eddes et al., 2013; Wang & Dix, 2017). However, the overarching effect of maternal distress on sustained attention in infancy, a time period when the brain is highly plastic, remains less understood. Besides the challenges of assessing infants' attention, it is very difficult to disentangle the effects of different aspects of maternal distress (e.g. types and timing), biological, and environmental factors. The analysis of multiple risk factors together is essential due to the high likelihood of comorbidities and high correlations among risk factors. To distinguish possible interactions among different aspects of maternal mental health on infants' attention will be beneficial for targeted prevention and early intervention.

Hence, to better understand the possible underlying mechanisms and to examine whether maternal early childhood adverse experiences affect infants' attention, my second longitudinal study access the full course of mothers' depressive and anxiety symptoms from the 2nd trimester to 6 months postpartum as well as mothers' childhood traumatic exposure (Publication 2). This time window focused on the in-utero period and the first 6 months postpartum, a period when most infants and mothers share proximal contacts, allowing us to address the maternal-specific factors and to study their associations with infants' sustained attention from 6 to 18 months. When relating mothers' mental health to infants' attention, I used a robust sustained attention index based on a data-driven method combing fixation data from a wild range of audio-visual tasks (Publication 1). I hypothesized that maternal childhood trauma exposure which contributes to maternal distress negatively affects infants' attention.

In Figure 6 shows a timeline of the collection of the data from mothers and infants at 7 different time points. For more details with regard to maternal data please see the method section in Publication 2. From our longitudinal data, I observed a direct impact of mothers' childhood non-interpersonal trauma on infants' look percentage (see Figure 7). At the same time, childhood interpersonal trauma moderates the negative impact of maternal anxiety during the 2nd trimester on infants' look percentage (see Figure 8). This effect, however, is not seen in information processing (based on the measure of the short-fixation ratio).

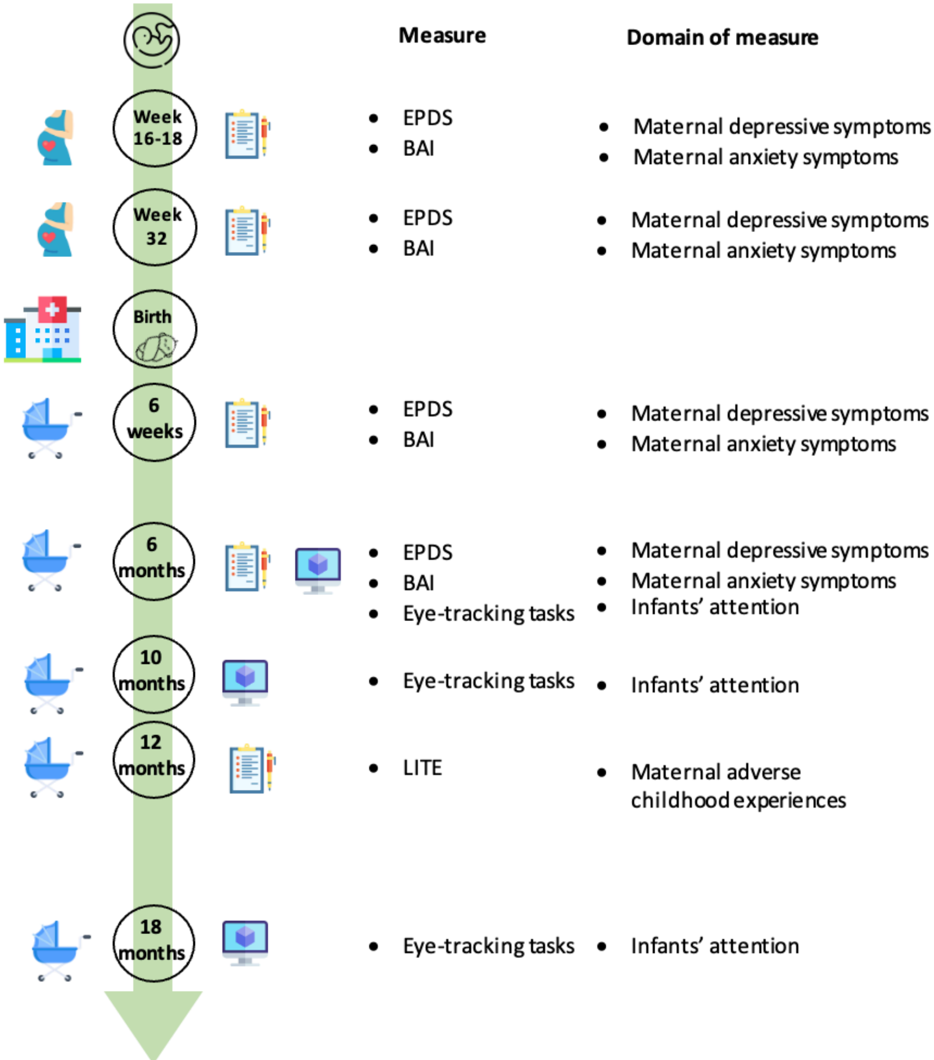

Figure 6. Timeline of the data acquisition at different phases from pregnancy to infancy
The figure shows the timeline of the longitudinal study from the 2nd trimester of pregnancy to postpartum at 18 months (see Publication 2). Abbreviations: EPDS, Edinburgh Postnatal Depression Scale; BAI, Beck Anxiety Inventory; LITE, Lifetime Incidence of Traumatic Events. Age-appropriate eye-tracking tasks were used when infants were at the age of 6, 10, and 18 months. Mothers were invited for web-based questionnaires during the 2nd, the 3rd trimesters, and 6 weeks, 6 months, and 12 months postpartum.

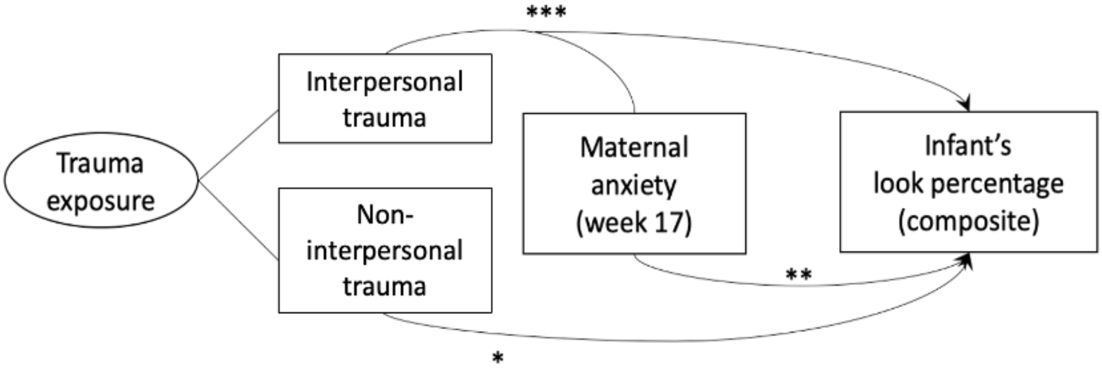

Figure 7. Impact of the maternal adverse childhood experiences on infants' look percentage
Illustration of the final linear regression model after adjusting for the sex of the infant, mother's education level, smoking history, and the maternal age at birth. Non-interpersonal traumatic experiences and maternal anxiety in early pregnancy had a direct impact on the infants' look percentage ($p = 0.015$ and 0.005, respectively). When anxiety at week 17 of pregnancy interacts with interpersonal traumatic exposure, the negative impact on the infants' look percentage is highly significant ($p < 0.001$).

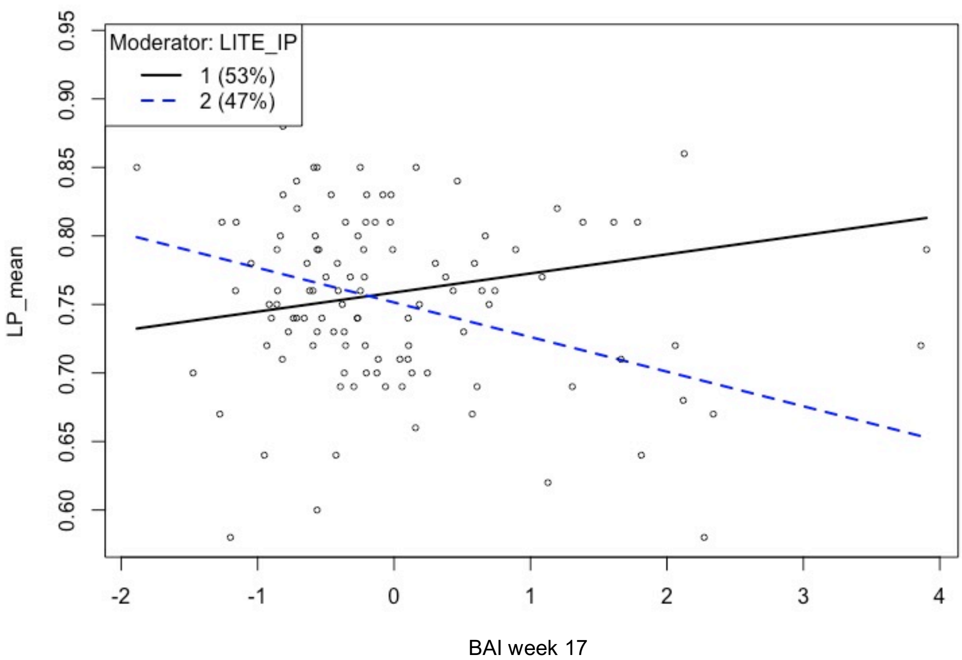

Figure 8. Moderator effect of the interpersonal trauma on infants' look percentage
The relationship between maternal anxiety (Beck Anxiety Inventory at antenatal 17 weeks, BAI week 17) and infants' look percentage (LP) is moderated by the level of interpersonal traumatic events (IP) in childhood measured by Life Incidence of Traumatic Events (LITE). Level 1 (solid line) represents mothers who exposed to less trauma in childhood compared to those at the level 2 (dotted line).

Taken together, in line with literature examining the association between maternal distress and the development of attention in childhood, my data show that maternal distress, especially during the 2nd trimester, as well as mothers' adverse experiences in childhood negatively affect infants' attention. However, maternal distress and infants' attention are both very complex and multifaceted. Hence, further work is needed in the future to understand the dynamics between them.

2. Experimental Work

2.1 Publication 1 – Tu et al., (2022)

Attentional control is a stable construct in infancy but not steadily linked with self-regulatory functions in toddlerhood*

Tu, HF., Lindskog, M., & Gredebäck, G.

Developmental Psychology (2022).
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Attentional Control Is a Stable Construct in Infancy but Not Steadily Linked With Self-Regulatory Functions in Toddlerhood

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Attentional control in infancy has been postulated as foundational for self-regulation later in life. However, the empirical evidence supporting this claim is inconsistent. In the current study, we examined the longitudinal data from a sample of Swedish infants (6, 10, and 18 months, n = 118, 59 boys) across a broad set of eye-tracking tasks to find stable markers of attention. Two attention indices showed a high degree of stability and internal consistency but were not related to self-regulatory functions measures at 18 or 30 months. Our findings add to a growing body of research suggesting that a relation between attentional control and self-regulation is unsupported. We discuss the need for a revision of the idea of attention as foundational for self-regulation.

Keywords: information processing, sustained attention, effortful control, executive function, eye-tracking paradigm

Supplemental materials: https://doi.org/10.1037/dev0001362.supp

During the first 2 years of life, children start to develop self-regulatory functions, including both effortful control and executive functions (Colombo & Cheatham, 2006; Fisher, 2019; Fiske & Holmboe, 2019; Garon et al., 2008; Hendry et al., 2016; Rothbart et al., 2011). These cognitive functions allow children to regulate behavior, thoughts, and impulses as well as plan future actions and goals (Blair & Razza, 2007; Hofmann et al., 2012; Zhou et al., 2012). Studies have shown that self-regulatory functions support learning, school readiness (Blair & Diamond, 2008), impact academic performance (Ahmed et al., 2019; Best et al., 2011; Brock et al., 2009; McClelland & Cameron, 2011; Morgan et al., 2019), and correlate with life satisfaction (Brown & Landgraf, 2010). In addition, poor self-regulatory skills are related to neurodevelopmental disorders such as attention-deficit/hyperactivity disorder (Sjöwall et al., 2013; Sonuga-Barke et al., 2010) and autism spectrum disorder (Gilotty et al., 2002; Rosenthal et al., 2013; Samson et al., 2014). Given their importance, many studies have tried to find the roots, or precursors, of these abilities in infancy (Frick et al., 2018; Gottwald et al., 2016; Hendry et al., 2016; Rothbart et al., 2011; Sheese et al., 2008; Ursache et al., 2013). It has been suggested that attention might be one such fundamental ability (Colombo & Cheatham, 2006; Posner & Rothbart, 2009).

There exists an extensive body of work exploring the impact of attentional control on self-regulatory functions (Blankenship et al., 2019; Brandes-Aitken et al., 2019; Cuevas & Bell, 2014; Devine et al., 2019; Frick et al., 2018; Geeraerts et al., 2019; Holmboe et al., 2018; Johansson et al., 2015, 2016; Kochanska et al., 2000; Kraybill et al., 2019; Nakagawa & Sukigara, 2013; Papageorgiou et al., 2014, 2015; Pyykkö et al., 2020; Rose et al., 2012). In short, these studies argue that attention is related to self-regulation later in life. However, although empirical evidence exists to support this claim, the findings are not consistent. The vast majority of studies have failed to demonstrate an association between the two constructs (see Figure 1). In addition to the lack of empirical consistency, the field is also currently debating how to best define attention and self-regulation (Bridgett et al., 2015; Doebel, 2020; Engle, 2018; Mancas et al., 2016; Morra et al., 2018; Nigg, 2017; Zhou et al., 2012), what the underlying mechanisms are (Eisenberg, 2017; Friedman & Miyake, 2017; Karr et al., 2018; Tiego et al., 2020), what predictive relations we should expect (Hendry et al., 2016, 2019), and if there are benefits of training attention on

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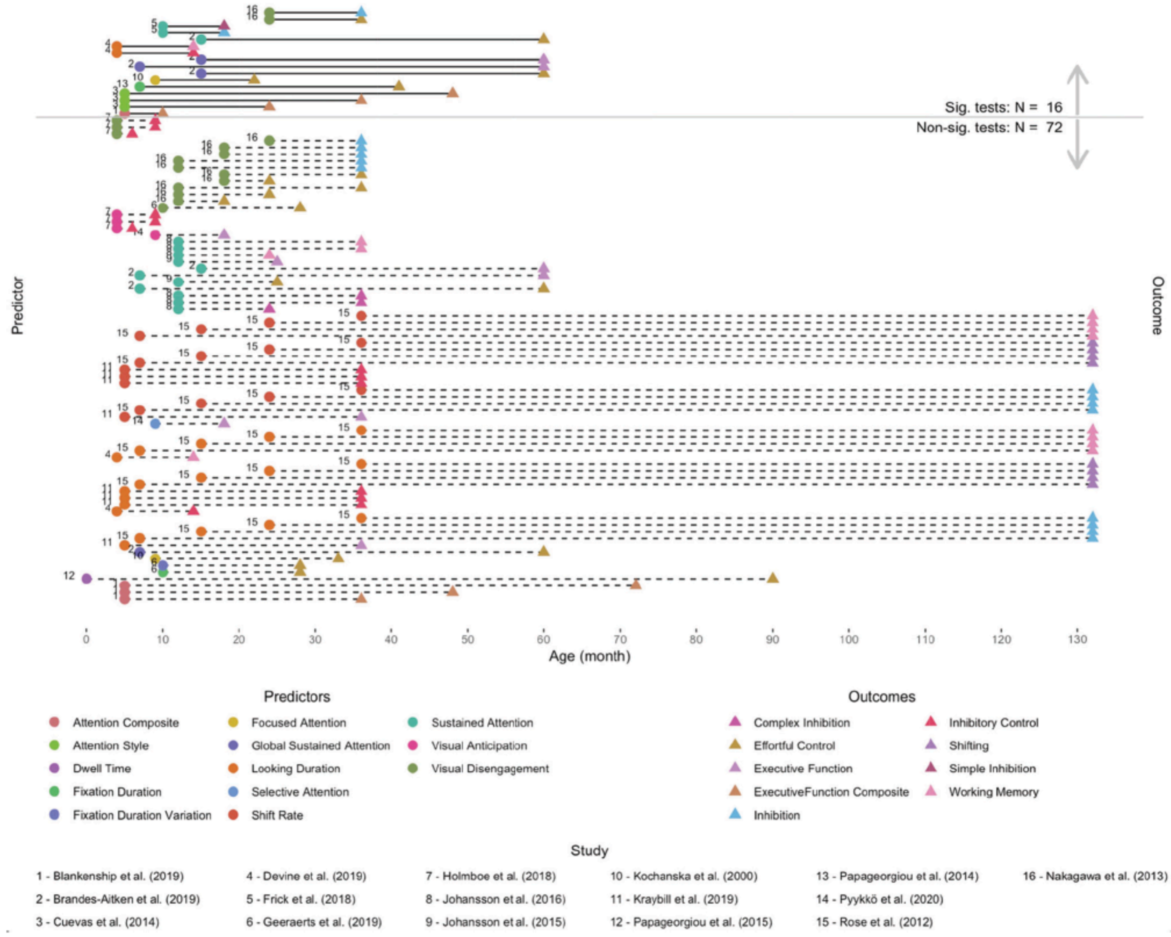
Figure 1

Review From Studies Investigating the Relation Between Attentional Control and Self-Regulatory Functions



Note. Each line represents the relation between the results of a predictive task and one outcome measure. Solid lines indicate significant results while dotted lines show findings that were not significant. Circles on the left indicate tasks used to measure attentional control as a predictor. Triangles on the right represent outcome measures from different tasks. In both circles and triangles, different colors represent different marker tasks. The same number on the left of circles means they were reported in the same study. The *x*-axis shows the age when tasks were performed.

self-regulation (Simons et al., 2016; Smid et al., 2020). Moreover, there are also ongoing discussions about the organizations of affective (hot) and cognitive (cool) executive functions (Lin et al., 2019; O'Toole et al., 2018; Peterson & Welsh, 2014; Zelazo & Carlson, 2012) and how they are related to self-regulation (Zhou et al., 2012).

The current study was motivated by these questions and discussions. Unlike previous studies using isolated attention measures during the first few months of life to predict self-regulatory function (e.g., Blankenship et al., 2019; Cuevas & Bell, 2014; Devine et al., 2019; Papageorgiou et al., 2014, 2015), we aimed to (a) explore and examine robust attention measures based on a longitudinal dataset from 6 to 18 months of age. Using a data-driven method, a broad range of eye-tracking data across 11 audio-visual tasks were included to examine the individual differences in infants' attention. Furthermore, we (b) investigated to what degree such individual differences relate to self-regulation in toddlerhood accessed with several established self-regulation measures.

Before we present our empirical study results, we review the existing evidence for a relation between attention early in life and self-regulatory functions later in life. In this brief review, we focus on the purported relation between attentional control early in development and later self-regulatory functions. By doing so, we admittedly leave out an extensive literature separately investigating attention or self-regulatory control (for previous reviews, see Colombo et al., 2011; Hendry et al., 2019; Posner et al., 2016;

Rothbart et al., 2011). Our choice is motivated by the vast theoretical and practical implications of viewing attentional control as the foundation for self-regulatory functions.

Attentional Control in Infancy

Studies focused on attentional control as an early marker of later cognitive development have conceptualized attention as supporting the allocation of cognitive resources, prioritization of incoming information, updating of previous information, and regulation of behavior (Colombo et al., 2011; Esterman & Rothlein, 2019). In the first postnatal months, infants develop several attentional processes such as alertness, orienting, attention to features, sustained attention (maintaining focus), preattention termination, and attention termination (Colombo, 2001, 2002; Courage et al., 2006; Richards & Casey, 1991). Before 1 year of age, infants can actively deploy their attention in a top-down manner to environmental cues and selectively allocate their attentional resources to relevant information (Johnson et al., 1991; Lewkowicz & Hansen-Tift, 2012; Markant & Amso, 2016; Ross-Sheehy et al., 2015; Tummeltshammer & Amso, 2018; Werchan & Amso, 2020). The maturation of neural connectivity accompanies the improvement of attentional control in infancy (Xie et al., 2019), and the improvement and development of attention continue throughout childhood (Konrad et al., 2005; Rueda et al., 2004).

Self-Regulatory Functions

Self-regulatory functions include a set of abilities to monitor, direct, and redirect feelings, thoughts, or actions in attaining and deliberately pursuing adaptive goals (Nigg, 2017). Previous studies suggest that self-regulation is strongly linked to temperament and can be defined in various ways that are emotion-related (Posner & Rothbart, 2000; Rothbart, Ellis, et al., 2011; Rothbart, Sheese, et al., 2011; Sheese et al., 2008). The developmental literature often emphasizes two main components of self-regulation: *effortful control* (Kochanska et al., 2000; Rothbart & Rueda, 2005; Spinrad & Eisenberg, 2015) and *executive functions* (McClelland & Cameron, 2011; Montroy et al., 2016). Effortful control is conceptualized as "the ability to choose a course of action under conditions of conflict, to plan for the future, and to detect errors" (Rothbart, 2007; p. 207). That is, the ability to voluntarily control attention, detect and resolute conflict, and inhibit impulses. Executive functions include several distinct components, such as working memory (updating), cognitive flexibility (shifting), and inhibitory control (Friedman & Miyake, 2017; Garon et al., 2008; Miyake et al., 2000; Miyake & Friedman, 2012). Conceptually, effortful control and executive functions show some extent of overlaps (Lin et al., 2019). As a result, most performance-based tasks measuring self-regulation in infancy and early childhood emphasize inhibitory control and working memory separately or at the same time. Inhibitory control often reflects the temperamental aspects of self-control in infancy (Rothbart et al., 2011) and impulse control in early childhood (Montroy et al., 2016). Working memory plays a role in updating and actively representing self-regulatory goals (Best & Miller, 2010; Hofmann et al., 2012). In the current study, we selected tasks that are commonly used to measure self-regulatory functions in toddlers.

Review of the Relation Between Attentional Control and Self-Regulatory Functions

There is considerable overlap between attentional control and self-regulatory functions (Posner et al., 2016; Rueda, Posne, et al., 2005). Based on the neurocognitive model of attention, three distinct networks—alerting, orienting, and executive attention—are involved (Petersen & Posner, 2012; Rueda, Posne, et al., 2005). Under this account, executive attention functions as a process that resolves conflict, which is the definition of effortful control (Petersen & Posner, 2012; Posner et al., 2007, 2016; Rothbart et al., 2007).

From the assumption that attention in infancy is linked to the development of self-regulation, researchers have developed several attention indices based on behavioral observations and measures. Commonly used measures include dwelling time (Papageorgiou et al., 2015), looking duration (Kraybill et al., 2019; Rose et al., 2012), anticipatory looks (Holmboe et al., 2018; Pyykkö et al., 2020), visual disengagement (Geeraerts et al., 2019; Holmboe et al., 2018), or looking behavior in play contexts (Brandes-Aitken et al., 2019; Johansson et al., 2016). Indeed, due to the immature motor and verbal skills of infants, studies investigating attentional control in infants have heavily relied on various measures of looking behavior (Bornstein, 1985; Colombo et al., 1991; Colombo & Mitchell, 2009; Gredebäck et al., 2010; Oakes, 2010, 2012). Such measures are thought to reflect attentional control due to the strong link between the neural systems of visual attention, oculomotor movements, and oculomotor control (Amso & Scerif, 2015; Colombo, 2001; Corbetta et al., 1998; Hendry et al., 2019; Johnson, 1990).

Among different looking behavior measures, paradigms based on habituation and novelty preferential looking paradigms (Bornstein, 1985; Fantz, 1964; Sokolov, 1966) have long been applied to detect individual differences in looking behavior and early learning abilities. Colombo and colleagues further extended the concept and operationalized infants' ability to encode and process information in terms of *attentional styles* (Colombo, 2001; Colombo et al., 1991; Freeseman et al., 1993). According to them, *short-lookers* process visual information fast and efficiently, while *long-lookers* do so to a lesser degree (Colombo, 2001; Colombo et al., 1991; Freeseman et al., 1993). Whether an infant is a short- or long-looker is determined by the mean or median of the longest looking durations during a trial of a free-looking task. This conceptual operation of looking duration has resulted in a systematic way of observing individual differences in attentional control in infancy and in establishing the significance of looking duration for information processing (Hendry et al., 2019). The dichotomic use of short- or long- lookers has been reported to predict later executive functions (Cuevas & Bell, 2014). However, recent studies have only partially supported such relation (Blankenship et al., 2019; Devine et al., 2019; Kraybill et al., 2019).

Based on the same idea, researchers have used fixation duration for various measures of attention based on the eye-tracking paradigm to capture attention as it unfolds during visual processing. However, while some have found that mean fixation duration in infancy is associated with effortful control in early childhood (Papageorgiou et al., 2014), others have failed to find a significant relation between median fixation duration and self-regulatory functions (Geeraerts et al., 2019).

Although used as measures of attentional control, neither anticipatory looking behavior nor voluntary disengagement in the first year are associated with self-regulatory functions in infancy (Holmboe et al., 2018) nor later in toddlerhood (Geeraerts et al., 2019; Nakagawa & Sukigara, 2013; Pyykkö et al., 2020). Sustained attention, on the other hand, is associated with effortful control at both 22 months (Kochanska et al., 2000) and 2 years (Johansson et al., 2015), but not at 14 or 33 months (Kochanska et al., 2000). Sustained attention is often measured by accessing the level of attending (Ruff & Capozzoli, 2003), for example, the total time elapsed in the task, frequency of attending, or frequency of looking away. Concerning executive functions, sustained attention in infancy is partially linked to global executive functions at the age of 18 months (Frick et al., 2018) and 24 months (Johansson et al., 2015), and to inhibitory control at the age of 18 months (Frick et al., 2018), 3 years (Johansson et al., 2016), and 5 years (Brandes-Aitken et al., 2019). In the same studies, sustained attention is related to working memory at 5 (Brandes-Aitken et al., 2019) but not 3 years of age (Johansson et al., 2016).

In Figure 1, we illustrate the findings from 16 studies targeting the relation between attention and self-regulation to provide an overview of the field. Each of these studies was identified as having assessed long-term effects that were included in the above text. Each line represents the relation between one attentional control measure (on the left) and one outcome measure (on the right). Even though the relations between several marker tasks for both attentional control and self-regulatory functions have been repeatedly tested at different age points, significant findings (in solid lines, $p < .05$; some results reported significance based on one-tailed tests are considered insignificant in this figure) appear to be in the minority compared to insignificant ones (in dotted lines). An additional 11 cross-sectional measurements of attentional control (sustained attention or visual disengagement) and self-regulatory functions within the same age point (12, 18, 24, or 36 months) from three different studies (Johansson et al., 2015, 2016; Nakagawa & Sukigara, 2013) were not included in the figure, due to lack of longitudinal data. However, among them, only four out of 12 tests from two studies showed significant effects (Johansson et al., 2016; Nakagawa & Sukigara, 2013). In sum, previous studies have attempted to examine the predictive role of early attentional control. Due to inconsistencies and a diverging set of approaches, the relation between attentional control and later self-regulatory functions remains elusive at best. The overall evidence suggests that attentional control and self-regulatory functions might be unstable constructs that are difficult to capture in infancy and early childhood.

Current Study

The previous literature has yielded an inconsistent picture regarding the foundational role of attentional control for the development of self-regulation. We approach this issue by first examining a large amount of longitudinal data from 6- to 18-month-old infants across a wide set of eye-tracking paradigms to establish stable individual markers of attention. Next, to investigate predictive relations, we relate our identified markers of attention to self-regulation measures at 18 and 30 months. Our approach integrates theory-based and data-driven methods to allow us a high degree of freedom in exploring behavioral data. The ultimate goal of this approach is to identify robust measures that allow us to reliably relate them to other variables. In the current study, we developed two attention measures, *short fixation ratio* and *look percentage*, after systematically analyzing fixation data from 11 age-appropriate eye-tracking tasks. These two measures conceptually mimic previously well-established measures of attentional style, *short fixation ratio* (Colombo et al., 1995; Courage et al., 2006; Jankowski & Rose, 1997; Reynolds et al., 2011), and sustained attention, *look percentage* (Casey & Richards, 1988; Richards & Turner, 2001; Ruff & Capozzoli, 2003). After stable measures of attention were established, then we proceeded with the examination of the relation between attention and self-regulation.

Method

Participants

Participants in this study were involved in the longitudinal cohort project (The BasicChild Project, Gredebäck et al., 2019) and recruited from the sample of a population-based study in Uppsala (Axfors et al., 2019). The final samples at the four measurement points included 118 infants at 6 months of age (M = 185 days, SD = 7.5 days, 59 boys), 110 infants returned to be tested at 10 months (M = 302 days, SD = 9.2 days, 53 boys), 104 children at 18 months (M = 544, SD = 12.1 days, 53 boys), and 94 children at 30 months (M = 912 days, SD = 13.6 days, 45 boys). Data acquisition took place between 2014 and 2018. Only healthy pregnant women (>18 years old) who received a routine examination at the local university hospital were invited to participate in this study. A university degree was held by 62% of the mothers, and 52% of the second parents. The number of infants living with both parents was 117. Most of the participants lived in White middle-class families living in a university town. Due to the conditions in our ethical approval in 2012, data on race was not collected. The data that support the findings of this study are available on request from the corresponding author.

All procedures in the study were conducted in accordance with the ethical standards of the Regional Ethical Review Board in Uppsala, Sweden (EPN; Title: *Den sociala grunden för utvecklingen av människans kognition;* Protocol number 2013/423) and the 1964 Declaration of Helsinki, as well as its later amendments. This study was not preregistered. Written informed consent was obtained from caregivers of all participants before the start of each visit. After each visit, participants received a gift voucher (ca. 30 euros) for their participation.

Procedure and Measures

All tasks included in the attention measure were recorded using an eye-tracking system with a sampling frequency of 60 Hz (Tobii TX300, Tobii Technology AB). Participants were all seated approximately 60 cm in front of a 23-in. test monitor. The calibration was executed based on a 5-point system. Tasks targeting self-regulatory functions were video recorded and analyzed offline.

Tasks Included in Attention Measure

The tasks used to calculate the attention measures included give-me gesture interactions (Gredebäck & Melinder, 2010;

Juvrud et al., 2019), a modified change detection task (Libertus & Brannon, 2010), multimodal events (Richardson & Kirkham, 2004), the biological motion task (Falck-Ytter et al., 2018), the coherent motion task (Wattam-Bell, 1994; Wattam-Bell et al., 2010), the gaze following task (Gredebäck et al., 2018; Szufnarowska et al., 2014), pupillary light response (Falck-Ytter et al., 2018), small forms discrimination task (Dillon et al., 2013; Izard & Spelke, 2009), face perception/emotional processing tasks (Ebner et al., 2010), visual sequence task (Sheese et al., 2008), and a prediction task (Henrichs et al., 2014). Considering previous evidence has shown that individual looking or fixation duration is quite stable and consistent (Jankowski & Rose, 1997; Wass & Smith, 2014) across stimulus' types in early development (Reynolds et al., 2013; Wass & Smith, 2014), a wide range of free viewing tasks were selected to assess infants' looking behavior and eye movements. Descriptions of the tasks and corresponding testing ages are listed in Table 1. A series of videos depicting the stimuli, as presented to participants, can be viewed on Databary (Gredebäck et al., 2019) at https://nyu.databrary.org/volume/828.

We aggregated gaze data across all tasks within the same age point and determined individual "short fixation ratio" and "look percentage" to capture important features of the participants' attentional control. Please see the Statistical Analyses section for how these variables are used in the analyses. As mentioned in the section Current Study, the short fixation ratio is based on previous work using short- and long-lookers as measures of information encoding and processing efficiency (Colombo et al., 1995; Courage et al., 2006; Jankowski & Rose, 1997; Reynolds et al., 2011). The look percentage is used as an index of sustained attention (Casey & Richards, 1988; Richards & Turner, 2001; Ruff & Capozzoli, 2003).

Assessments of Self-Regulatory Functions

Simple inhibition was measured at 18 months using the Prohibition task, established to measure simple inhibitory control (Friedman et al., 2011). The child was presented with an attractive toy (a colorful, glittering wand, 31 cm long and 2 cm in diameter) for 30 s. The experimenter made eye contact with the child, shook her head, and said, "now (child's name), you are not allowed to touch this." Simultaneously the experimenter placed the toy on the table within a reachable distance from the infant. Then the experimenter looked away with a neutral face. After 30 s, or earlier if the child had already touched the toy, the experimenter looked back and said, "It's okay, you can touch it now." The outcome variable was video-coded offline for time (in seconds) when the experimenter let go of the toy and, if applicable, the latency for the infant to touching the toy. Interrater reliability based on a randomly selected subset of 20 participants was excellent (ICC = 1.0).

Complex inhibition was assessed with a modified version of the Tricky Box (Garon et al., 2014) at 18 and 30 months. The child was presented with a black box (22 × 22 × 12.5 cm) with a Plexiglas front window (15 × 8.5 cm) openable only by pulling a knob (an electric switch, 4.5 cm in diameter) attached on the top. The child needed to inhibit reaching toward the toy directly behind the window and pull the knob first to retrieve it. In the warm-up phase, an attractive toy (a color-changing plastic duck) was shown, and the child had the opportunity to practice opening the window to play with the toy. In the test trials, the toy was placed in the box behind the window. The experimenter then moved the box forward to the child and asked the child to get the toy. If the child reached only for the window, the experimenter waited for 10 s and pointed out the knob while saying, "You have to pull here." If the child still did not pull the knob, the experimenter pulled the knob to open and window and took out the toy for the child to play. The children received 2 points if they reached the knob directly. One point was scored if they reached the window first and then self-corrected to reach for the knob. If they first reached for the window, then reached for the knob after being reminded by the experiment, or if they did not reach for the knob at all, then they were given the score of 0 points. The outcome variable of this task was the mean score over all test trials. Interrater reliability based on a random subset with 20 participants was excellent (κ = .98).

Working memory was evaluated with a hide-and-seek task (Garon et al., 2008) at 18 months, and with the Spin-the-Pots task (Bernier et al., 2010; Hughes & Ensor, 2005) at 30 months. For the hide-and-seek task, a small table chest with four colored drawers was used for hiding a toy. On two warm-up trials, a toy was hidden in front of the child, and the child could search for it without delay. In four test trials, the experimenter hid the toy in one of the drawers, in full visibility of the child, while saying simultaneously, "Now I am hiding it here." Then the experimenter covered the chest with a cloth. After 5 s, the chest was uncovered and moved toward the child. The child was then asked to search for the toy. If the child did not find the toy, the experimenter asked, "Where is it?" to motivate a search. Each trial allowed a maximum of four attempts. The toy was not hidden in any repeated location across trials. The children received the scores of 4 points, 3 points, 2 points, or 1 point according to whether they succeeded on the first, second, third, or fourth attempt. Infants who did not succeed after trying for four times were given 0 points. The mean score of overall trials was used as an outcome measure. Interrater reliability based on a random subset of 20 participants had a Kappa value of .96. For the Spin-the-Pots task, the material was a spinning plate with 10 small boxes that were placed upside down. The experimenter hid six raisins under six predetermined boxes and then put a black curtain over the plate. The plate was turned 180 °F before the curtain was removed. On each trial, the child was invited to search for one raisin after the plate was turned. If the first box the child opened had a raisin, 1 point was given, otherwise, the trial was scored with 0 points. The task proceeded until all six raisins were found or until 10 trials were reached. Interrater reliability based on a random subset with 20 participants was excellent (κ = .93).

Delayed gratification (Carlson et al., 2004; Kochanska et al., 2000) was used to measure the child's ability to wait for a reward at 30 months of age. The experimenter showed the child a bag and talked about the exciting toy inside the bag. The child was told that soon the toy will be available for playing after the experimenter came back into the room. The child was left with the bag for 2 minutes before the experimenter returned or until the child opened the gift. Scoring ranged from 1 to 5 and was based on Carlson et al. (2004) and Kochanska et al. (2000). Five points indicated that the child did not touch the bag or gift. Four points were given if the child looked at the bag but did not touch it. If the child touched the bag but did not check the gift in the bag, 3 points were given. If the child put its hands in the bag but did not take out the

Table 1
The Tasks Included in the Calculation of Attention Measures

Task	Description	Reference	Test age (months)
Give-Me	Give-Me gesture interactions were used to access action evaluation (Gredebäck & Melinder, 2010; Juvrud et al., 2019). A 40-second-context for a give-me gesture followed by appropriate or inappropriate giving was repeated three times (26 s in total). Four appropriate and four inappropriate trials were presented.	Gredebäck & Melinder, 2010; Juvrud et al., 2019	6, 10
Change detection task	Change detection task modified based on Libertus and Brannon's study was used to access the ability to discriminate between numericities (Libertus & Brannon, 2010). Two image streams simultaneously on both sides of a screen were presented to infants. Images alternated between different numbers of dots with three ratios (1:4, 1:2; 2:3). Each trial lasted for 10 s.	Libertus & Brannon, 2010	6, 10, 18
Multimodal events	Multimodal events were used to evaluate the ability of associative learning (multimodal events that were binding to locations; Richardson & Kirkham, 2004). Infants were shown short video clips that a particular sound was binding to a particular location of a stimulus.	Richardson & Kirkham, 2004	6, 10
Biological motion	Biological motion was used to access the perception of biological motion in infants (Falck-Ytter et al., 2018). There were two identical animated human-like stimuli presented side-by-side on the screen. One was upright and the other was reversed. They showed the same movements but in a reversed mirror direction. There was no auditory stimulation involved.	Falck-Ytter et al., 2018	6, 10
Coherent motion task	Coherent motion task was inspired by previous studies and it was to measure infants' ability to discriminate between two coherent or random movements (Wattam-Bell, 1994; Wattam-Bell et al., 2010). Two groups of moving dots were presented on two sides of the screen. One contained dots that all moved in random directions.	Wattam-Bell, 1994; Wattam-Bell et al., 2010	6, 10
Gaze following task	Gaze following task was used to examine the degree to which infants follow another person's gaze (Gredebäck et al., 2018; Szufnarowska et al., 2014).	Gredebäck et al., 2018; Szufnarowska et al., 2014)	6, 10
Pupillary light response	Pupillary light response was used to measure the constriction of the pupil diameter in response to a flash of light.	Falck-Ytter et al., 2018	6, 10, 18
Small forms discrimination task	Small forms discrimination task inspired by previous studies was used to investigate infants' perception and sensitivity of four geometrical forms (Dillon et al., 2013; Izard & Spelke, 2009). In the task, infants were presented with an array of four small forms each containing two connected lines that formed an angle. Each array included three forms that were identical and one form that deviated.	Dillon et al., 2013; Izard & Spelke, 2009	6, 10
Face perception	Face perception was used to access whether infants can perceive emotional expressions in faces. Happy, fearful, and neutral facial expressions of three young women were presented to infants at 6 months. Additional two emotions, sad, and scared expressions were presented to infants at 10 and 18 months. All visual stimuli in this task were from the FACES-database (Ebner et al., 2010).	Ebner et al., 2010	6, 10, 18
Visual sequence task	Visual sequence task was used to examine if infants can learn the pattern the stimuli were presented (Sheese et al., 2008).	Sheese et al., 2008	10, 18
Reaching	Reaching task was used to access how infants shift their gaze toward a reaching action (Henrichs et al., 2014).	Henrichs et al., 2014	18

Note. This table is reprinted from "Maternal Childhood Trauma and Perinatal Distress Are Related to Infants' Focused Attention From 6 to 18 Months," by H. F. Tu, A. Skalkidou, M. Lindskog, and G. Gredebäck, 2021, *Scientific Reports, 11*(1) (https://doi.org/10.1038/s41598-021-03568-2). CC BY.

gift, it was given 2 points. One point was given if the child took out the gift from the bag.

Reversed categorization was used to measure both inhibitory control and working memory (Carlson et al., 2004) at 30 months. In the first part of the task, the child was instructed to put yellow bricks in a yellow bucket and red bricks in a red bucket. The experimenter corrected the child if the bricks were placed in the wrong bucket. In the second part, the child was instructed to put yellow bricks in a red bucket and red bricks in a yellow bucket. There were 12 trials in the second part. No feedback was provided in the second part if the brick was misplaced. The score was the total number of correctly placed bricks in the second part.

Statistical Analyses

Statistical analyses were performed using R 4.3 (R Core Team, 2020). Attention measures were based on the eye-tracking raw data from all tasks listed in Table 1. All fixations retrieved for analysis were defined by the Tobii Fixation Filter. Behavioral measures of self-regulation based on offline coding are described in the previous section.

Before analyzing the eye-tracking data, it was preprocessed in five steps as follows. (a) The beginning and the end of each trial of each task were identified. They were also the beginning and the end of the visual stimuli. The number of trials varied from one task to another. (b) Fixation durations were determined from fixation data (Tobii Fixation Filter Velocity threshold = 35 pixels/window, distance threshold = 35 pixels). (c) Full fixations within the same trial were identified. Only fixations with both beginning and end within the same trial were considered valid, complete fixations. This was done to eliminate fixations that, for example, were initiated at the stimuli prior to actual experimental stimuli, or fixations to stimuli that the participant had not processed fully before the end of a trial. We identified these by comparing the recorded fixation durations to the time between the beginning and the end of the same fixation within the same trial. If the two values deviated by more than the temporal precision of 16 ms (sampling rate of 60 Hz), we discarded them as incomplete. (d) Outliers were removed. Outliers among fixation durations (+/−3 *z*-scores) from each age group were eliminated. (e) The consistency of fixation durations across tasks at the three different age points was examined. The within-group distributions of individual mean fixation durations and variances for each task are presented in Figure 2 Based on visual inspection of these distributions, it is reasonable to assume that individual differences of fixation durations are stable across different tasks. This allowed us to aggregate fixation durations from all available trials across all tasks within the same age group for further analyses.

After preprocessing all data, two separate variables were calculated. To calculate a *short fixation ratio*, we first estimated a *splitting value*. Using kernel density estimation on the mean individual fixation duration across all tasks within each age group, we determined the lowest point between the two largest clusters of the density distribution. This point was used as the splitting value for each age group. An individual's short fixation ratio was defined as the proportion of fixations with a duration below the splitting value. The splitting values for the 6-, 10-, and 18-month-olds were 307.8, 314, and 321 ms, respectively (see Figure 3). The *look percentage* measure was calculated as the total fixation duration divided by the total duration of all tasks at each age.

After the two measures were calculated, we further examined the stability of the short fixation ratio and the look percentage across groups using the Pearson correlation. The correlations between those two variables and seven outcome measures of self-regulatory functions from 18 and 30 months were assessed. All correlations were two-tailed, and *p*-values were corrected for multiple comparisons (Benjamini & Hochberg, 1995). Because previous studies have indicated unstable and elusive correlations between constructs, we also wanted a method that could quantify the relative support for the null hypothesis. Accordingly, for all correlations, we also calculated a Bayes factor (BF_{10}) using JAMOVI (The Jamovi Project, 2020) with the default stretched beta prior width = 1 (i.e., all correlations between −1 and +1 are given an equal prior probability). All scripts regarding data processing and analyses can be viewed on Databary (Gredebäck et al., 2019) at https://nyu.databrary.org/volume/828.

Results

Descriptive Statistics

Table 2 presents the descriptive statistics for all variables, including means, standard deviations, skewness, and kurtosis values. All variables show very good to acceptable kurtosis values and most variables are within the good to moderate range of an approximate symmetric distribution. None of the distributions of the values is considered extremely asymmetry (Kim, 2013). For demographic characteristics of participants, please see Table S1 in the online supplemental materials.

Main Analyses

Correlational Results of Short Fixation Ratio and Look Percentage

To evaluate the stability and internal consistency of the two developed attention measures, short fixation ratio and look percentage, we examined the Pearson correlation between and within them at the age of 6, 10, and 18 months. Table 3 shows that the short fixation ratio at 6 months is positively correlated with the short fixation ratio at 10 ($r(108) = .63$, $p < .001$, $BF_{10} = 4.4 \bullet 10^{10}$) and 18 months, $r(101) = .26$, $p = .004$, $BF_{10} = 4.3$. Short fixation ratio at the age of 10 months is also positively correlated with short fixation ratio at 18 months, $r(98) = .43$, $p < .001$, $BF_{10} = 1{,}948$. Furthermore, Table 3 also shows that look percentage at 6 months is significantly correlated with look percentage at the age of 10, $r(108) = .33$, $p < .001$, $BF_{10} = 47.9$. Look percentage at 10 months is also positively correlated with look percentage at 18 months, $r(98) = .31$, $p = .001$, $BF_{10} = 14.1$. In terms of Bayes factors, the results indicated moderate ($BF_{10} = 4.3$) to extreme ($BF_{10} = 4.4 \bullet 10^{10}$) support for the alternative hypothesis (H_1) for the short fixation ratio and anecdotal ($BF_{10} = 1.04$) to extreme ($BF_{10} = 1, 948$) support for H_1 for the look percentage measure.

Associations Between Attention and Self-Regulatory Functions

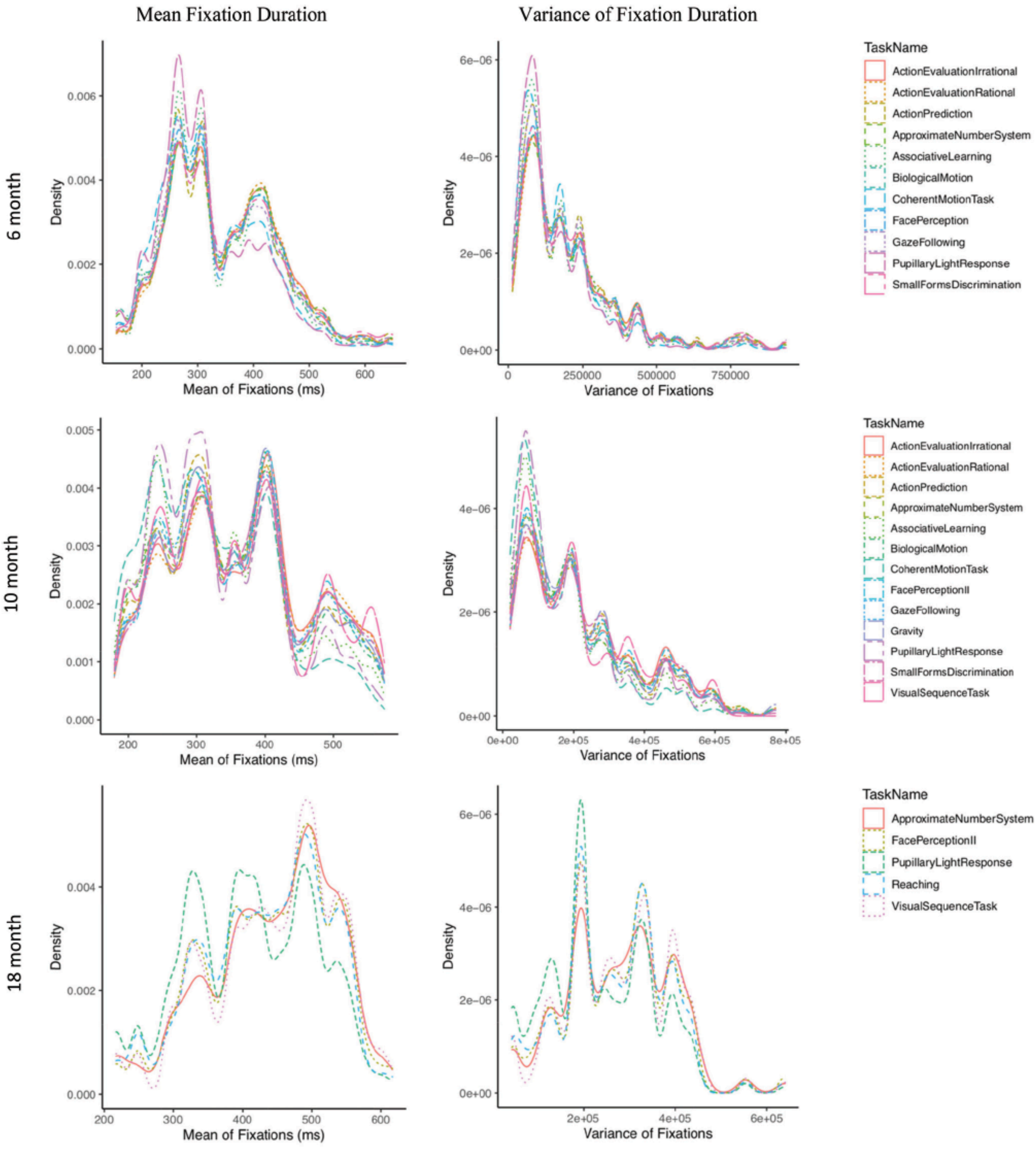
The analyses of the relations between the attention measures and the measures of self-regulatory functions are summarized in Table 4. None of the analyses showed significant correlations between attentional control (measured by short fixation ratio and look percentage) and self-regulatory function at both 18 and 30 months of age. When examining Bayes factors, only three out of 42 tested correlations had $BF_{10} > 1$ and none of these revealed more than anecdotal (all $BF_{10} < 3$) evidence for the existence of a correlation. Indeed, the remaining 39 correlations indicated support, to varying degrees, for the null hypothesis. Put differently, from multiple comparisons and Bayes factor analysis of correlations, the link between attentional control in infancy and self-regulation in toddlerhood is not supported. With regards to the different constructs of self-regulatory functions, we did not find any significant correlation between scores of tasks within and between both age points. For the zero-order Pearson correlation within different self-regulatory variables at 18 and 30 months of age, please see Table S2 in the online supplemental materials.

Discussion

In the current study, we investigated the predictive relation between attentional control and self-regulatory functions in early development. Our review of 16 previous studies that directly attempted to answer this question (presented in Figure 1) shows that the predictive role of attentional control for self-regulatory function is, at best, inconsistent. We approached the goal in two

Figure 2

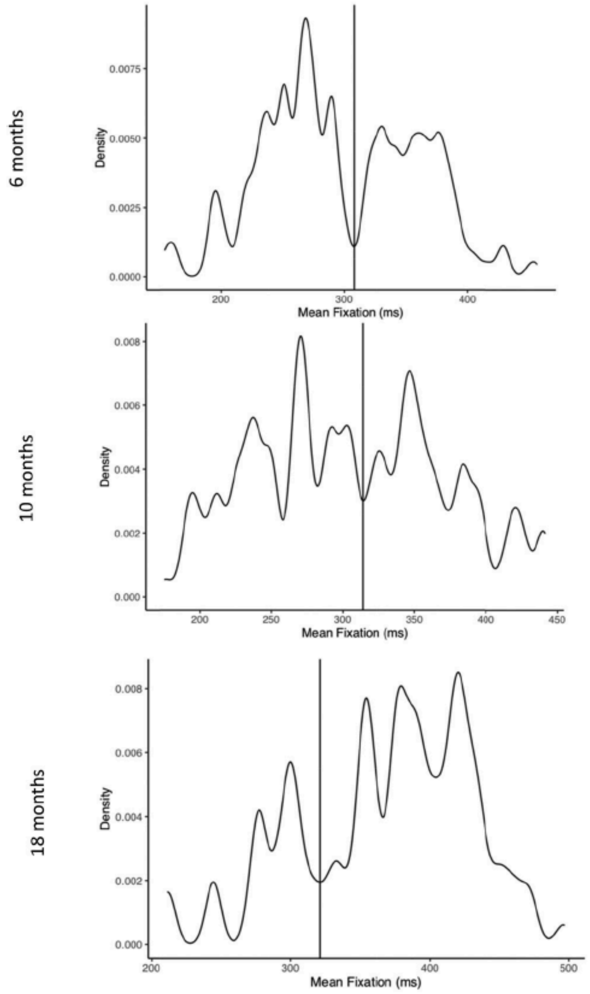
Illustration of the Distributions of Mean (Left Column) and Variance (Right Column) of Fixation Durations at Three Different Age Points Across Different Age-Appropriate Tasks



Note. This figure is reprinted from "Maternal Childhood Trauma and Perinatal Distress Are Related to Infants' Focused Attention From 6 to 18 Months," by H. F. Tu, A. Skalkidou, M. Lindskog, and G. Gredebäck, 2021, *Scientific Reports, 11*(1) (https://doi.org/10.1038/s41598-021-03568-2). CC BY.

Figure 3

Illustrations Show the Distributions of Mean Fixations Generated From Aggregated Data Across Tasks and at the Ages of 6, 10, and 18 Months



Note. The *x*-axis indicates the mean fixation duration in ms. The *y*-axis is the values of density in distribution. From the distribution of mean fixation durations, the lowest point between the two highest peaks of two clusters was chosen as a splitting point. The splitting values for 6-, 10-, and 18-month-olds are 307.8, 314, and 321 ms, respectively. An individual's short-look ratio is defined based on how many percentages of overall complete fixations with durations under this splitting point.

steps using a longitudinal dataset. First, combining theory-based and data-driven methods, we investigated the stability and internal consistency of two measures of attentional control, short fixation ratio and look percentage. Our results showed a high degree of stability and internal consistency from 6 to 18 months, even when correcting for multiple comparisons. These findings suggest a continuity of attentional control that can be captured and is stable from infancy to early toddlerhood.

Next, similar to previous studies, we investigated how several standard tasks of self-regulatory functions at 18 and 30 months were related to attentional control. We found none of which were significant after multiple comparisons correction. Furthermore, for the majority of the tested relations (39 out of 42), the BF_{10} indicated evidence for the null hypothesis (i.e., a correlation of zero [0] between constructs). Thus, our data did not support the widely assumed link between attentional control and self-regulatory functions. We conclude that attentional control develops steadily from infancy to early toddlerhood, but that it is not linked to self-regulation, at least in toddlerhood.

In previous studies that directly investigated the impact of early attentional control on later self-regulation, 72 out of 88 reports failed to reveal a significant link (see Figure 1). Together with our results, this common lack of significant associations is striking. There may be several reasons for this lack of observable association. First, the link between early attentional control and later self-regulation may not exist. Put differently, the available data simply cannot support a purported link. A second, more moderate interpretation is that there is an association but it is weak and difficult to capture. In support of this notion, Tiego et al. (2020) demonstrated that attention has only 30% of variance in common with effortful control and executive functions in children. Accordingly, other factors might contribute to self-regulatory functioning early in life and a strong focus on attention may fail to capture a potentially intricate relation between such factors. Studies have suggested that prospective motor control (Gottwald et al., 2016), social action understanding (Marciszko et al., 2020), communication (Kuhn et al., 2014), maternal scaffolding (Bibok et al., 2009; Hammond et al., 2012), maternal sensitivity (Hughes et al., 2013), postnatal growth, and level of parents' education (Aarnoudse-Moens et al., 2013) might impact later self-regulation and/or executive functions. It is possible that the solution to this puzzle lies in the combination of these factors rather than in one isolated process.

Finally, a third possibility is that neurological immaturity and interactive specialization (Karmiloff-Smith, 2015) lead to reorganization of the neural structures that support self-regulation, making it difficult to capture this concept early in life. Along these lines, an effect might be observed later in children and/or in teenagers (see, e.g., Ridler et al., 2006). Under this account, there is perhaps little to gain by studying infants and toddlers before the behavioral construct is better understood and more coherent, valid, and reliable measures have been developed.

Regardless of which alternative one favors, the extant evidence does not support the existence of an association. With the current and past results in mind, theories of early self-regulation and executive functions should consider toning down or revising their claims that attention is the driving force behind self-regulatory functions. Otherwise, a hypothesis that has not been supported by evidence might become the basis of further research. Thus, it repeats the weak evidence and reinforces itself as results. For example, in the context of attention and self-regulation, evidence that does not confirm the association might be dismissed and stay unreported.

Perhaps more importantly, in light of the existing evidence, it makes little sense to promote training studies that target early attention, seeking to support later self-regulation. Despite the unclear evidence, a few positive empirical findings and theoretical frameworks have motivated researchers to promote attention training studies or to attempt to improve self-regulatory functions

Table 2
Descriptive Statistics of Independent and Dependent Variables

Variable	Month	*M*	*SD*	Skewness	Kurtosis
SF	6	66.03	11.98	0.02	−0.77
SF	10	65.93	11.96	0.10	−0.96
SF	18	60.89	9.30	0.38	−0.36
LP	6	73.63	9.84	−0.87	1.52
LP	10	73.47	9.36	−0.52	−0.16
LP	18	79.24	6.86	−0.85	1.09
Working memory	18	2.83	0.64	−0.11	−0.56
Simple inhibition	18	6.4	10.45	1.62	0.90
Complex inhibition	18	0.92	0.59	0.10	−0.96
Working memory	30	0.49	0.14	0.22	−0.21
Complex inhibition	30	0.98	0.54	0.05	−0.63
Delay gratification	30	57.99	42.15	−0.22	−1.73
Reversed categorization	30	0.55	0.36	−0.22	−1.43

Note. SF = short fixation ratio; LP = look percentage.

through attentional training (Diamond & Lee, 2011; Wass et al., 2011, 2012). While some report positive training effects on executive functions (Rueda, Rothbart, et al., 2005, 2012; Scionti et al., 2020), two meta-analytic studies and one narrative study show conflicting and inconclusive results (Kirk et al., 2015; Peng & Miller, 2016; Rapport et al., 2013). Studies focusing on children with developmental disorders or low social-economic status have reported no training effect (Steiner et al., 2014), or small partial training effects on trained or close to trained tasks (Barnes et al., 2016; Kirk et al., 2016, 2017; Powell et al., 2016). Admittedly, only a few attention training studies have focused on infancy (Ballieux et al., 2016; Forssman & Wass, 2018; Wass et al., 2011). These studies indicated that within-task attention training effects might be seen at the end of the first postnatal year, but the evidence is still limited. Instead, it is essential to gain a clearer understanding of how dynamic and putative factors of self-regulation interact and emerge. In particular, more longitudinal studies that explore robust measures and their relations are necessary.

Furthermore, although conceptualized as different constructs, effortful control and executive functions, it is still unclear that to what extent effortful control and executive functions share commonalities (Tiego et al., 2020). Notably, it is very difficult to measure and dissociate in children under 3 (Hendry et al., 2016; Zhou et al., 2012). For example, while recent studies focused on the subcomponents of executive function demonstrated that inhibitory control and working memory are uncorrelated (Frick et al., 2018; Kraybill et al., 2019; Miller & Marcovitch, 2015; Van Reet, 2020), other studies showed positive correlations at different age points, but they vary across different studies and are not consistent, cross-sectionally or longitudinally (Blankenship et al., 2019; Jenkins & Berthier, 2014; Johansson et al., 2016; Mulder et al., 2017). Nevertheless, whether working memory is under executive function or is also a part of effortful control is still debatable (see Eisenberg, 2017 and Nigg, 2017 for further discussion).

Finally, and especially due to our homogenous sample, our results must be interpreted in light of some limitations. First, although we did not observe any significant correlation between our stable attention measures and self-regulation, it is crucial to bear in mind that the tasks we selected might not reliably measure self-regulatory functions. For the purpose of the current study, we

Table 3
Pearson Correlation With Multiple Comparisons (With Benjamini-Hochberg Correction) and BF_{10} of Short Fixation Ratio and Look Percentage

	Variable	Month	1	2	3	4	5	6
1.	SF	6	1					
2.	SF	10	0.63*** $BF_{10} = 4.4 \cdot 1{,}010$ (*df* = 108)	1				
3.	SF	18	0.26* $BF_{10} = 4.28$ (*df* = 101)	0.43*** $BF_{10} = 1{,}948$ (*df* = 98)	1			
4.	LP	6	−0.12 $BF_{10} = 0.26$ (*df* = 116)	−0.02 $BF_{10} = 0.16$ (*df* = 108)	−0.22 $BF_{10} = 1.35$ (*df* = 101)	1		
5.	LP	10	−0.01 $BF_{10} = 0.17$ (*df* = 108)	−0.13 $BF_{10} = 0.31$ (*df* = 108)	−0.20 $BF_{10} = 0.93$ (*df* = 98)	0.33*** $BF_{10} = 47.92$ (*df* = 108)	1	
6.	LP	18	−0.02 $BF_{10} = 0.15$ (*df* = 101)	−0.06 $BF_{10} = 0.15$ (*df* = 98)	−0.15 $BF_{10} = 0.41$ (*df* = 101)	0.21 $BF_{10} = 1.04$ (*df* = 101)	0.31* $BF_{10} = 14.1$ (*df* = 98)	1

Note. SF = short fixation ratio; LP = look percentage; *df* = degrees of freedom; BF = Bayes factor. Pearson correlation: * $p < .05$. *** $p < .001$.

Table 4
Pearson Correlation With Multiple Comparisons (With Benjamini-Hochberg Correction) and BF_{10} Between Attentional Control and Self-Regulatory Functions

		Age (in months)						
		18			30			
		Self-regulatory function			Self-regulatory function			
Attention measure	Age (in months)	Working memory	Simple inhibition	Complex inhibition	Working memory	Complex inhibition	Delayed gratification	Reversed categorization
SF	6	0.07 $BF_{10} = 0.17$ (*df* = 96)	0.02 $BF_{10} = 0.16$ (*df* = 86)	0.23 $BF_{10} = 1.32$ (*df* = 91)	−0.18 $BF_{10} = 0.56$ (*df* = 88)	0.04 $BF_{10} = 0.14$ (*df* = 83)	−0.02 $BF_{10} = 0.27$ (df = 69)	−0.06 $BF_{10} = 0.15$ (df = 90)
SF	10	−0.07 $BF_{10} = 0.16$ (*df* = 93)	0.09 $BF_{10} = 0.19$ (*df* = 84)	0.11 $BF_{10} = 0.23$ (*df* = 88)	−0.12 $BF_{10} = 0.24$ (*df* = 88)	−0.07 $BF_{10} = 0.17$ (*df* = 79)	−0.04 $BF_{10} = 0.15$ (*df* = 66)	−0.20 $BF_{10} = 0.78$ (*df* = 87)
SF	18	−0.01 $BF_{10} = 0.13$ (*df* = 95)	−0.09 $BF_{10} = 0.18$ (*df* = 85)	0.10 $BF_{10} = 0.20$ (*df* = 90)	0.04 $BF_{10} = 0.14$ (*df* = 84)	0.02 $BF_{10} = 0.14$ (*df* = 79)	0.04 $BF_{10} = 0.16$ (df = 66)	0.04 $BF_{10} = 0.14$ (df = 87)
LP	6	0.02 $BF_{10} = 0.13$ (*df* = 96)	0.13 $BF_{10} = 0.26$ (*df* = 86)	−0.03 $BF_{10} = 0.13$ (*df* = 91)	−0.14 $BF_{10} = 0.32$ (*df* = 87)	0.02 $BF_{10} = 0.14$ (*df* = 83)	−0.11 $BF_{10} = 0.23$ (*df* = 69)	−0.01 $BF_{10} = 0.13$ (*df* = 90)
LP	10	−0.11 $BF_{10} = 0.22$ (*df* = 93)	0.24 $BF_{10} = 1.61$ (*df* = 84)	0.03 $BF_{10} = 0.14$ (*df* = 88)	−0.15 $BF_{10} = 0.34$ (*df* = 84)	0.18 $BF_{10} = 0.50$ (*df* = 79)	0.05 $BF_{10} = 0.17$ (*df* = 66)	−0.12 $BF_{10} = 0.25$ (*df* = 87)
LP	18	0.04 $BF_{10} = 0.14$ (*df* = 95)	0.10 $BF_{10} = 0.20$ (*df* = 85)	0.15 $BF_{10} = 0.37$ (*df* = 90)	−0.25 $BF_{10} = 2.02$ (*df* = 84)	−0.07 $BF_{10} = 0.17$ (*df* = 79)	−0.05 $BF_{10} = 0.16$ (*df* = 66)	−0.02 $BF_{10} = 0.14$ (*df* = 87)

Note. SF = short fixation ratio; LP = look percentage; *df* = degrees of freedom; BF = Bayes factor.

selected the self-regulation measures that are commonly used as outcome measures. This choice was made so that we could observe whether the commonly claimed association between attention and self-regulation could be supported by the robust attention measures. The tasks have been commonly used in previous research, but it is still unclear how robus they measure different abilities. We suggest that the next step to move forward is to explore the stability of self-regulation measures and reexamine their association with attention. However, before reaching that point, similar to the attention addressed in our study, the field needs more research and perhaps new frameworks that can help us better capture the developmental trajectory of self-regulation.

Second, we applied a data-driven method to systematically identify attention measures. Though it gives us several advantages in processing and exploring large eye-tracking data, it is important to bear in mind that we do not know what happened during few trials where no data existed. Those trials could result from (a) that the infant failed to look, (b) that excessive movements of the infant caused difficulties of the eye-tracker to capture data, or (c) other causes. We believe that it would not be optimal to simply assume that infants all show poor attention when no data exist (see Table S3 in the online supplemental materials for the number of missing trials of eye-tracking data). With the advancing technology, perhaps future eye-trackers that allow a great degree of movements might help distinguish the behaviors of those unknown trials.

Finally, the conclusions of the empirical part of this study are based on a homogenous sample from a university town with more than half of the mothers holding a university degree or higher. Meanwhile, while we were not able to collect information on race or ethnicity, this essentially limited the generalization of our results. Different experiences (such as homogenous contexts, collectivistic contexts, individualistic contexts) and variations in socioeconomic status and community access might already show significant impacts on development early in life. In short, it will be very meaningful that future studies can ensure the inclusion of information such as race, ethnicity, and diverse cultures. This will increase the heterogeneity of participants and prevent the bias or underrepresentation of minorities in research.

The field needs further investigations that explore the developmental pathways that lead to self-regulation, emphasizing the multiphased nature of development. Theory and testable models specifically designed to assess early emerging foundations of self-regulation are essential models that acknowledge the complexity of the task at hand. What can be stated with certainty is the following: to date, there is little evidence that attention early in infancy is strongly and uniquely associated with self-regulation during childhood.

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Maternal childhood trauma and perinatal distress are related to infants' focused attention from 6 to 18 months

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Maternal childhood trauma and perinatal distress are related to infants' focused attention from 6 to 18 months

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Maternal distress is repeatedly reported to have negative impacts on the cognitive development in children and is linked to neurodevelopmental disorders (e.g. attention-deficit/hyperactivity disorder and autism spectrum disorder). However, studies examining the associations between maternal distress and the development of attention in infancy are few. This study investigated the longitudinal relationships between maternal distress (depressive symptoms, anxiety symptoms, and exposure to childhood trauma) and the development of focused attention in infancy in 118 mother-infant dyads. We found that maternal exposure to non-interpersonal traumatic events in childhood was associated with the less focused attention of the infants to audio-visual stimuli at 6, 10, and 18 months. In addition, exposure to interpersonal traumatic events in childhood was identified as a moderator of the negative effect of maternal anxiety during the 2nd trimester on the development of focused attention in infants. We discuss the possible mechanisms accounting for these cross-generational effects. Our findings underscore the importance of maternal mental health to the development of focused attention in infancy and address the need for early screening of maternal mental health during pregnancy.

Attention is a multifaceted construct and an important cognitive operation involving alerting, orienting, filtering, and attending to information in the environment[1,2]. The ability to focus and sustain attention develops rapidly in the first postnatal years[2–4] and continues to develop into adulthood[5] and has been postulated to play a fundamental role in learning[6–8]. More specifically, before the age of one, infants show learning behaviors through actively directing their attention to informative events and interacting with them[9,10]. Look duration, which is often used to measure focused attention, increases steadily from the second half of the first postpartum year and through the first four years of life[2,11]. To maintain focus for a period of time on tasks requires effort and hence it is often linked to the development of self-regulation and executive function in childhood[12–14]. There is substantial evidence showing that the ability to focus in infancy is predictive to social development[15], cognitive functioning[16], language development[17], and academic skills[18] later in life. In addition, poor focused attention is related to several neurodevelopmental disorders, such as attention-deficit/hyperactivity disorder (ADHD)[19] and autism spectrum disorder (ASD)[20]. Taken together, identifying the risk factors of the development of focused attention in the early years is crucial for targeted prevention and early intervention.

Maternal psychological distress, which is symptomized by an unbalanced and/or strained emotional state from pregnancy to postpartum commonly including depression and/or anxiety[21,22], is seen to influence the trajectories of attentional development in childhood. Several large cohort studies have shown that maternal depressive and/or anxiety symptoms are associated with attention problems in offspring at the ages of 2 years[23], 3 and 4 years[24], as well as 5, 6.5, and 14 years[25,26]. Maternal distress is also linked to ADHD symptoms at the age of 4 and 8–9 years[27,28]. Moreover, recent studies also reported that maternal childhood adverse experiences contribute to ADHD and ASD in children[29–31]. In nonhuman primates, exposure to mild stress during pregnancy is related to less visual exploration and higher distractibility of offspring[32]. In humans, maternal stress during pregnancy has a negative impact on infants' attention shifting at the age of 18 months[33]. It is been shown that infants whose mothers perceived higher stress during pregnancy needed more time than others to process visual information at the age of 7.5 months and looked away from the tasks significantly more than infants whose mothers had low

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perceived stress during pregnancy[34]. Preliminary evidence also suggests that this cross-generational association between maternal distress and infant development might be linked to trauma exposure prior to pregnancy[35,36]. Moreover, infants of depressed mothers have less synchronous mutual gaze with their mothers than infants of non-depressed mothers[37]. In turn, mutual gaze has been associated with visual attention in the first postnatal year of life[38]. The impact of maternal distress on mother-infant interactions[39] and maternal sensitivity[40] have been related to infants' selective attention[41] and gaze-following ability[42].

Though it seems evident that a mother's mental health, during both antenatal[23,33,34,43–46] and postpartum[23,37,38,41,45,46], has a significant impact on offspring's attention, the underlying mechanisms are still unclear. Previous evidence has shown that the complex and dynamic interactions between multiple biological, psychological and environmental factors contribute to both mothers' mental health and children's attention. For example, based on a reciprocal model, children's attention problems might worsen mothers' mental health, and in return affect mothers' mental health that leads to influencing children's attention[47–49]. Evidence supporting an association between maternal distress and neurological development, more broadly, indicates changes in cortical and subcortical connectivity in human infants[50,51] and children[52], and negative impact on neurogenesis and gene expression in neonates of rodents[53]. From biological and environmental perspectives, while TPH1 enzyme mutations in mothers relating to impaired maternal serotonin production increase in a higher risk of inattention in their children[54], adoption studies demonstrated environmental but genetic factors are associated with children's ADHD symptoms[55,56]. It has also been reported that increased cortisol levels during the 2nd trimester and increased subjective maternal distress in the 3rd trimester are associated with weaker connectivity of the anterior cingulate cortex of neonates[51]. The anterior cingulate cortex has been linked to infant's attention[57], and ADHD in children[58] and adults[59]. Intriguingly, one previous study investigating infants' cognitive development at 12 months of age reported that high cognitive performance is linked to lower maternal cortisol levels in the 2nd trimester and higher cortisol levels in the 3rd trimester[60], suggesting that the link between mother's cortisol levels and children's cognitive development is not linear.

Another layer of the complexity comes from the interactions and/or comorbidity between different aspects of maternal psychological distress at different time points as well as whether the symptoms are chronic or not. In particular, adverse childhood experiences that continue to contribute to psychological distress later in life are common. Previous studies demonstrated that the severity of psychological distress is strongly linked to exposure to traumatic experiences earlier in life[61,62]. Studies also suggested that different types of traumatic events, such as interpersonal and non-interpersonal trauma, have different impacts on mental distress and psychiatric symptoms[63,64]. This moderation effect of adverse childhood experiences on maternal psychological distress might result from the alternation of hypothalamic–pituitary–adrenal axis functioning[65] and increased sensitivity to negative cues[66], in turn, leads to increase anxiety[66,67]. In addition, evidence shows that individual differences contribute to different trajectories related to life satisfaction and well-being after traumatic events[68], some individuals develop higher risks in posttraumatic stress disorder, depression, and anxiety[69]. Thus, when studying the relationships between different aspects of maternal mental health and infants' attention, it is crucial to take maternal adverse childhood experiences into account.

Taken together, compelling evidence has shown that early adverse experiences increase the risks of depression and anxiety later in life[70,71] and during different perinatal phases[72,73]; and maternal psychological distress significantly hinders the development of attention in childhood[23–26]. However, the overarching effect on focused attention in infancy, a time period when the brain is highly plastic, remains less understood. Besides the challenges of assessing infants' attention, it is very difficult to disentangle the effects from different aspects of maternal distress (e.g. types and timing), biological, and environmental factors. The analysis of multiple risk factors together is essential due to the high likelihood of comorbidity and high correlations between risk factors. To distinguish possible interactions between different aspects of maternal mental health on infants' attention will be beneficial for targeted prevention and early intervention. Hence, to better understand the possible underlying mechanisms and examine whether early childhood adverse experiences affect infants' attention, our longitudinal study narrowed down to access the full path of mothers' depressive and anxiety symptoms from the 2nd trimester to 6 months postpartum as well as mothers' childhood traumatic exposure. This time window focused on the in-utero period and the first 6 months postpartum, a period when most infants and mothers share proximal contacts, allowing us to address the maternal-specific factors and to study their associations with infants' focused attention from 6 to 18 months. When relating mothers' mental health to infants' attention, we used a robust focused attention index based on a data-driven method combing fixation data from a wide range of audio-visual tasks. We hypothesize that maternal childhood trauma exposure contributing to maternal distress negatively affects infant's attention.

Results

Multivariate regression analysis. As seen in Table 1, Model A ($F(5, 104) = 4.479$, $R^2 = 0.177$, $p < 0.001$) includes all significant variables systematically selected from Table 2 as described in the Methods. We observed that higher levels of interpersonal traumatic experience in childhood interact with anxiety during the 2nd trimester and a decrease in infants' attention (see Model A in Table 1, $b = -0.038$, $p < 0.001$). We also found two main effects. First, when mothers were exposed to higher levels of non-interpersonal trauma in childhood, there was a decrease in infants' attention to audio-visual stimuli ($b = -0.029$, $p = 0.011$). Second, when mothers reported higher levels of anxiety during the 2nd trimester, infants increased their attention ($b = 0.055$, $p = 0.003$). Unlike the first main effect showing the same direction as in the correlational result ($r = -0.03$, $p = 0.02$), the second main effect is only evident in the presence of the interaction in the model. The second step, Model B ($F(4, 105) = 5.287$, $R^2 = 0.168$, $p < 0.001$) contained only variables that were significant predictors in Model A. All effects remained significant in Model B: the interaction between interpersonal traumatic events and anxiety level during the 2nd trimester ($b = -0.039$, $p < 0.001$), the main effect of non-interpersonal traumatic

Model	Variables	Estimate	SE	Std. Beta	*t* value	*p* value	Model summary
A	(Constant)	0.805	0.022		36.702	< 0.001	F (5, 104) = 4.479, $p < 0.001$, $R^2 = 0.177$
	nIP	−0.029	0.011	−0.235	−2.582	0.011	
	BAI w17	0.055	0.018	0.887	3.024	0.003	
	EPDS w17	−0.008	0.007	−0.131	−1.099	0.274	
	IP	−0.004	0.011	−0.036	−0.389	0.698	
	IP*BAI w17	−0.038	0.011	−0.991	−3.408	< 0.001	
B	(Constant)	0.804	0.022		36.662	< 0.001	F (4, 105) = 5.287, $p < 0.001$, $R^2 = 0.168$
	nIP	−0.029	0.011	−0.237	−2.599	0.011	
	IP	−0.004	0.011	−0.035	−0.378	0.706	
	BAI w17	0.051	0.018	0.832	2.874	0.005	
	IP*BAI w17	−0.039	0.011	−1.023	−3.534	< 0.001	
C	(Constant)	0.820	0.055		14.791	< 0.001	F (8, 99) = 2.888, $p = 0.006$, $R^2 = 0.189$
	nIP	−0.029	0.012	−0.232	−2.495	0.014	
	IP	−0.002	0.012	−0.015	−0.152	0.880	
	BAI w17	0.052	0.018	0.843	2.833	0.006	
	IP*BAI w17	−0.040	0.011	−1.058	−3.572	< 0.001	
	Infant's sex	0.001	0.012	0.005	0.50	0.960	
	Mother's education	0.022	0.014	0.164	1.588	0.115	
	Mother's smoking habit	0.004	0.013	0.028	0.274	0.785	
	Mother's age at birth	−0.002	0.002	−0.129	−1.300	0.197	

Table 1. The final multivariate linear model with infants' look percentage as an outcome measure. Model A includes all significant variables united from Table 2. Model B uses the backward stepwise method to eliminate variables and improve the model. Model C is the final model after adjusting for infant sex, mother's education, smoking habit, and the mother's age birth. SE, Standardized Error; Std. Beta, Standardized Beta; EPDS, Edinburgh Postnatal Depression Scale; BAI, Beck Anxiety Inventory; w17, pregnancy week 17; w32, pregnancy week 32; pv6, postpartum 6 weeks; pm6, postpartum 6 months; IP, interpersonal events; nIP, non-interpersonal events.

Model	Initial included independent variables	Independent variables after backward stepwise elimination	Estimate	Std. Error	Std. Beta	t value	*p* value	Model summary
Non-interpersonal traumatic events and depression	nIP, EPDS w17, EPSD w32, EPDS pw6, EPDS pm6, nIP*EPDS w17, nIP*EPSD w32, nIP*EPDS pw6, nIP*EPDS pm6	(Constant)	0.795	0.018		44.636	< 0.001	$F(3, 106) = 3.602$, $p = 0.015$, corrected $p = 0.04$, $R^2 = 0.0925$
		nIP	−0.029	0.012	−0.233	−2.507	0.014	
		EPDS w17	−0.012	0.006	−0.199	−2.145	0.034	
		EPDS pm6	0.006	0.006	0.098	1.053	0.295	
Interpersonal traumatic events and depression	IP, EPDS w17, EPSD w32, EPDS pw6, EPDS pm6, IP*EPDS w17, IP*EPSD w32, IP*EPDS pw6, IP*EPDS pm6	(Constant)	0.754	0.006		130.371	< 0.001	$F(3, 106) = 2.936$, $p = 0.037$, corrected $p = 0.73$, $R^2 = 0.076$
		EPDS w17	0.026	0.019	0.422	1.415	0.160	
		IP*EPDS w17	−0.025	0.012	−0.634	−2.125	0.036	
Non-interpersonal traumatic events and anxiety	nIP, BAI w17, BAI w32, BAI pw6, BAI pm6, nIP*BAI w17, nIP*EPSD w32, nIP*BAI pw6, nIP*BAI pm6	(Constant)	0.794	0.018		44.241	< 0.001	$F(3, 106) = 2.936$, $p = 0.037$, corrected $p = 0.73$, $R^2 = 0.077$
		nIP	−0.028	0.012	−0.229	−2.445	0.016	
		BAI w17	−0.009	0.006	−0.147	−1.563	0.121	
		BAI pm6	0.006	0.006	0.098	1.046	0.298	
Interpersonal traumatic events and anxiety	IP, BAI w17, BAI w32, BAI pw6, BAI pm6, IP*BAI w17, IP*EPSD w32, IP*BAI pw6, IP*BAI pm6	(Constant)	0.756	0.006		132.995	< 0.001	$F(4, 105) = 3.906$, $p = 0.005$, corrected $p = 0.02$, $R^2 = 0.130$
		BAI w17	0.051	0.018	0.829	2.812	0.006	
		BAI pw6	−0.008	0.005	−0.136	−1.496	0.181	
		IP*BAI w17	−0.039	0.011	−1.001	−3.396	0.001	

Table 2. Four separated multivariable linear regression models for systematically selecting variables for the final model. Look percentage is the common dependent variable in all four models. Significant variables of each model are included in the united model. Corrected *p* value is calculated based on the Holm-Sidak method. Std. Error, Standardized Error; Std. Beta, Standardized Beta; EPDS, Edinburgh Postnatal Depression Scale; BAI, Beck Anxiety Inventory; w17, antenatal 17 weeks; w32, antenatal 32 weeks; pv6, postpartum 6 weeks; pm6, postpartum 6 months; IP, interpersonal traumatic events; nIP, non-interpersonal traumatic events.

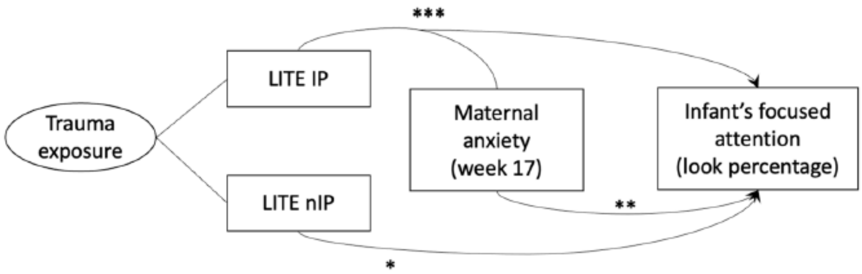

Figure 1. Illustration of the multivariate linear regression after adjusting for the sex of infant, mother's education level, smoking history, and maternal age at birth. Non-interpersonal traumatic experiences in mother's childhood and maternal anxiety in early pregnancy had a direct impact on infants' look percentage in the interaction model. When anxiety at week 17 of pregnancy interacts with interpersonal traumatic exposure in childhood, the negative association with the infants' look percentage is highly significant. *LITE* Life Incidence of Traumatic Events; *IP* interpersonal events; *nIP* non-interpersonal events.

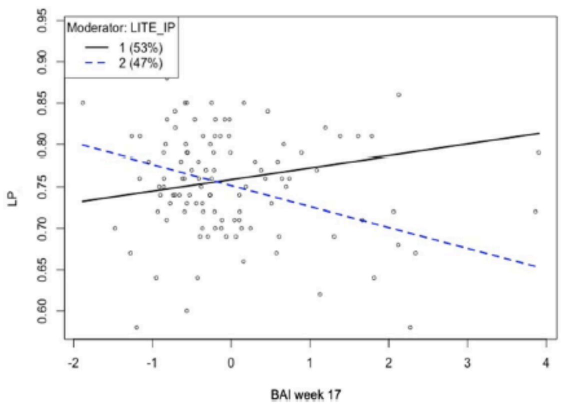

Figure 2. The relationship between maternal anxiety at antenatal 17 weeks (Beck Anxiety Inventory, BAI week 17) and infant's focused attention (look percentage, LP), is moderated by the level of interpersonal traumatic events (IP) in mother's childhood measured by Life Incidence of Traumatic Events (LITE). Level 1 (solid line) represents mothers who exposed to less trauma in childhood compared to those at level 2 (dotted line).

events ($b=-0.029$, $p=0.011$), and the main effect of anxiety level during the 2nd trimester ($b=0.051$, $p=0.005$). After controlling for infant's sex, mother's education, smoking habits, and maternal age at birth, Model C ($F(8, 99)=2.888$, $R^2=0.189$, $p=0.006$) showed that the interaction between interpersonal traumatic experiences and anxiety during the 2nd trimester ($b=-0.040$, $p<0.001$), the main effect of non-interpersonal traumatic events ($b=-0.029$, $p=0.014$), and the anxiety level during pregnancy during 2nd trimester ($b=0.052$, $p=0.006$) all remained significant. Figure 1 visualizes the results of Model C.

Moderation analysis. Following the results described above, exposure to interpersonal traumatic events in childhood was examined as a moderator of the relationship between the anxiety level during the 2nd trimester and the infants' look percentage after adjusting for infant sex and mother's education. Figure 2 displays the slopes for the anxiety level during antenatal 17 weeks and the levels of the exposure to interpersonal traumatic events predicting infants' attention. As indicated by the change in the direction, the effect is moderated by interpersonal traumatic events ($F(5, 103)=2.916$, $R^2=0.124$, $p=0.017$). In other words, the strength of the association between maternal anxiety and infant's focused attention is stronger amongst those with higher maternal exposure to childhood traumatic events compared to those with lower exposure.

Discussion

The primary goal of the current study was to investigate whether maternal distress affects the development of focused attention in infancy. We found that exposure to non-interpersonal and interpersonal traumatic experiences in childhood is associated with infants' focused attention. Moreover, childhood interpersonal trauma experience moderates the maternal anxiety level during the 2nd trimester showing the negative impact on the development of focused attention in infancy. Our results expand our understanding of the impact of maternal adverse childhood experiences on infants' outcomes, and the possible mechanisms driven by maternal anxiety. From the standpoint of prevention, our findings underscore the importance of early screening and intervention for mental health issues to support mothers and infants and prevent long-term consequences, even before the pregnancy starts.

Based on our findings, one critical aspect shows that adverse childhood experiences, in particular the interpersonal traumatic events, might foster the negative impact of maternal anxiety on infants' focused attention. Literature suggests that early traumatic experiences contribute to the change of limbic reactivity[74] and fronto-limbic circuit[75] which are related to dysfunction of emotional regulation[76]. There is also evidence that compared to the exposure to non-interpersonal trauma experience, the exposure to interpersonal trauma is associated with the higher levels of sensitivity to punishment[77], guilt, and shame[64]. Those multiple factors may lead to a long-term cumulative effect of maladaptation and anxiety[78], which in turn, affect infants' outcomes. A recently proposed model in line with the fetal programming framework suggests that fetal life represents a particularly sensitive period when the effects of maternal adverse childhood experiences could be transmitted through psychological, biological, biophysical, and behavioral sequelae[79]. In fact, the fetus's growth of grey matter accounts for the total cerebral growth significantly in the second half of pregnancy[80]. A recent study reported that maternal adverse childhood experiences may lower newborn's intracranial volume and change the trajectory of cortical gray matter growth, suggesting there are structural neurodevelopmental consequences in in-utero resulting from maternal childhood trauma[81].

In our longitudinal data across pregnancy to early infancy, we found a particular vulnerability in the 2nd trimester. One most plausible explanation is that the fetal brain is vulnerable to the in-utero environment due to the critical period of neurogenesis. Especially, the development of neuron connectivity, limbic system, hypothalamic–pituitary–adrenal axis, and prefrontal cortex may be disturbed by antennal anxiety and stress (see review by Van den Bergh et al.)[82]. Compared to the 1st and 3rd trimesters, exposure to ethanol in the 2nd trimester has been reported to cause a great neuronal loss in rodents[83], attenuated cerebral blood flow[84], and long-lasting alternations in synaptic plasticity[85] in the human fetus. In children, a previous study also reported that maternal anxiety during the 2nd trimester, but not later during pregnancy, is associated with gray matter reduction in several brain areas in children (6–9 years old)[86], including the prefrontal lobe, which is a crucial area in cognitive development[87] and controls attention[88].

Another possible explanation is associated with elevated cortisol levels in mothers during the 2nd trimester. Previous studies reported that increased cortisol levels during the 2nd trimester are associated with weaker neural connectivity in the anterior cingulate cortex of neonates[51] and lower cognitive function at 12 months of age[60]. However, increased cortical levels during the 3rd trimester are beneficial for the fetus's brain maturation and cognitive functions at 12 months of age and later in childhood[60,89] suggesting that the maternal cortisol levels affect offspring's cognitive development differently at different time points. More research clarifying the associations might help understand fetal and infant's developmental changes related to the amount and the timing of cortisol exposure.

Interestingly, maternal depression showed no association with infants' attention. However, previous literature has shown that infants of depressed mothers have a less synchronous gaze in the mother-infant interaction[37,90] that may affect the development of attention[38]. Similar to two well-controlled studies investigating cognitive development, maternal depression during pregnancy and infancy did not affect cognitive development at the age of 3 years[91] and 18 months[92], respectively. In the context of the current study, there are several plausible reasons for this finding. First, the association between maternal depression and infants' attention may not exist. However, using the same dataset investigating gaze following, infants of mothers with lower levels of postpartum depression presented better skills in synchronizing visual attention with others based on their gaze direction[42]. Though mutual gaze interaction can predict attention in infancy[38], our data and Astor et al.'s study[42] show that there may be more than one pathway of mother-infant interaction that influences the development of attention. Second, it is possible that the impact of maternal depression on infants' attention is cumulative and becomes significant only in childhood[26]. Third, as maternal depression is complex and heterogeneous in nature[93–95], our four time points may not reflect the complexity and heterogeneity of associations across mothers and infants. Lastly, because of the rigorous nature of the BASIC study, among mothers with depressive symptoms, a higher proportion of those with high functioning/cognitive skills (of which the children might also have good attention) could have filled out the questionnaires, introducing a possible selection bias.

Keeping these alternatives in mind, we cautiously propose another reason. Given the high comorbidity of depression and anxiety in our data (Table 4) and the literature[96,97], we propose that anxiety may be the driving force behind peripartum depression. For example, when we examined depressive and anxiety symptoms separately (Table 2), they showed a unique effect during the 2nd trimester. When we further combined all dimensions and examined the effect while simultaneously controlling others, anxiety dominated the effect. To the best of our knowledge, maternal depression and anxiety are rarely combined and related to child development, meaning that the importance of maternal anxiety may have been interpreted as an effect of depression in prior work. However, the complexity and dynamics between traumatic experiences, depression, and anxiety and how the dynamics change over time are beyond the scope of the current study. Future studies are needed to help us understand how maternal mental health affects infants' attention. Most importantly, it will provide us with more knowledge on promoting maternal mental health and infant development.

Finally, and especially due to our limited sample size, our results must be interpreted in light of some limitations. For the focused attention measure, we applied a data-driven method to explore and establish the focused attention index (look percentage). Theoretically, this index mimics measuring the duration of time an infant spends on targeted tasks. Our method included a great amount of fixation data from several audio-visual tasks and examined the looking behavior at the micro-level. We excluded very few trials where no fixations were present, ensuring that all trials where infants provide valid fixation data are included while avoiding making assumptions about the reason why some trials lack data altogether (e.g. lack of data = poor attention). Combining fixation data across multiple tasks increases the resolution of individual differences though we did not examine the success rate of each trial. Future research might want to investigate the associations between a global focused attention index, such as our look percentage, and looking patterns, success rate, and others that are more task-specific to understand different aspects of the cognitive operation. Another limitation with regard to the attention measure is that we used a composite score. In our results, high internal consistency of the development of focused attention from 6, 10 to 18 months motivated us to create the focused attention as a single construct. Thus, a composite score was calculated. Though this provided us with a straightforward way to explain our results, we might lose some information related to developmental changes. Future longitudinal studies might be interested in emphasizing the developmental trajectories within and between different constructs of attention and investigating their relationships to maternal mental health.

With regard to maternal measures, overall, we focused on the period between pregnancy and the first 6 months postpartum to possibly eliminate partial mother–child reciprocal influences often observed in studies in childhood. Admittedly, in the first year postpartum, there is also evidence demonstrating, for example, that infants' temperament[98], has a reciprocal influence on both mother's mental health and infant's development. Yet, evidence related to infants' attention is still scarce.

Another limitation is that we could not focus on clinically severe cases due to the relatively small number of severely depressed mothers. To deal with the relatively small sample size and the significant collinearity between depression and anxiety, we calculated factor scores for depression and anxiety separately at four different time points. This may prevent interactions at different stages and different levels to impact the results in unforeseeable ways.

In addition, we used a dichotomous distinction to separate groups of mothers with low- vs high-traumatic exposure. There are advantages and disadvantages to this strategy. We are aware that using dichotomic variables reduces variability in the data. At the same time, our data showed a low rate of different frequencies, dichotomization made it simpler to study and interpret interaction effects. Alternatively, future studies might use the raw scores or convert them to other continuous values.

Moreover, our sample is limited to a homogenous population in Uppsala (Sweden), with more than half of participating mothers having education levels of university or higher. Furthermore, we did not control for the possible influence of partners' mental health on mothers' well-being and infants' attention. As our results indicate the important influence of interpersonal traumatic experiences, future studies should consider this interpersonal aspect and its dynamics with regard to mothers' well-being.

Our findings add to the growing body of research, suggesting that prevention and intervention should start before pregnancy for both mothers and infants. Lastly, the findings describe a previously undocumented connection between maternal early trauma, anxiety, and the development of focused attention in infants. Treating pregnant women's anxiety, especially if she has experienced traumatic events in the past, may not only improve the lives of mothers but also support the positive development of their children from infancy onwards.

Methods

Participants. The final data included 118 mother-infant dyads from the BASICchild cohort as part of a longitudinal study (the BASIC Child Project)[99] of a subsample of the population-based BASIC study "Biology, Affect, Stress, Imaging, and Cognition (BASIC)"[100] collected from 2014 to 2018. Characteristics of the mother-infant dyads are shown in Table 3. Only healthy pregnant women > 18 years old who received a routine examination at Uppsala University Hospital were invited to participate in the projects. Mothers who consented to participate were invited to fill out a series of questionnaires online at 17 and 32 gestational weeks, and postpartum at 6 weeks, 6 months, and 12 months. Mothers and infants who took part in the BASIC Child Project visited the Uppsala Child and Baby Lab when the infants were aged 6 (n = 118; mean = 185 days, SD = 7.5 days, 59 boys), 10 (n = 110; mean = 302 days, SD = 9.2 days, 53 boys), and 18 months (n = 104; mean = 544 days, SD = 12.1 days, 53 boys). All infants were reported healthy. Sixty-five percent of the mothers held a university degree. All procedures in the study were conducted in accordance with the 1964 Declaration of Helsinki ethical standards and approved by the Regional Ethical Review Board in Uppsala, Sweden (EPN). Mothers who agreed to participate in the online surveys returned their written informed consent prior to the study. For participating infants, all legal guardians provided written informed consent during each visit prior to the experiment. Participants received a gift voucher worth approximately 30 euros after each visit to the lab.

Measures of maternal distress. Symptoms of depression were measured using the Swedish version of the Edinburgh Postnatal Depression Scale (EPDS)[101,102]. The EPDS includes 10 questions scored from 0 to 3. Thus, the total score ranges from 0 to 30, with higher scores indicating more severe symptoms. The reliability and validity of the EPDS have been shown to be adequate[103,104]. Symptoms of anxiety were measured using the Beck Anxiety Inventory (BAI)[105]. The scale consists of 21 items, with participants indicating the extent to which they were bothered by each item. The total score for each item ranges from 0 to 63, with higher scores indicating more server symptoms[106]. A high level of internal consistency and a good test–retest correlation have been reported[105]. Mothers in the study completed the online version of both EPDS and BAI at 17 and 32 weeks of pregnancy and 6 weeks and 6 months of the first postnatal year. Childhood traumatic exposure was measured using the Swedish version of the Life Incidence of Traumatic Events (LITE)[107,108]. The LITE is a self-reported checklist that consists of 15 fixed items and one optional item. Each item enquires whether the event has occurred, how many times, the age of the first occurrence, and how inconvenient it remains now. The first eight items ask whether different types of non-interpersonal traumatic events (nIP) have occurred, whereas the remaining items ask whether the seven types of events regarding interpersonal traumatic events (IP) occurred. Interpersonal events are defined

Characteristic	Mother-infant dyad ($n = 118$)
Maternal age, years	30.54 (3.92)
Country of origin	
Scandinavian	93.1%
Other	6.9%
Maternal education	
University or higher	65.0%
Other	35.0%
Cohabitating with the second caregiver	99.2%
With smoking history	36.4%
Employment	
Full-time	61.2%
Part-time	18.1%
Student	9.5%
Sick leave	4.3%
Unemployed	6.9%
Length of gestation, days	280 (8.09)
Infant sex, female	59%
Infant birth weight, g	3,664 (481)
Infant's Apgar score at 5 min	
7	0.9%
8	2.6%
9	6.0%
10	90.6%

Table 3. Demographic characteristics of 118 mother-infant dyads. Data are given as the proportion of dyads or mean (SD).

as events dependent on a conscious act of another human being, such as physical harm, divorce, or separation of parents, etc. Non-interpersonal events include natural disasters, accidents, or illness of others, etc. The sums of occurrences of nIP and IP were used as two variables in the analysis. Acceptable test–retest reliability and validity have been reported[109]. Mothers in the current study were invited to complete the LITE online during postpartum 12 months.

Measure of infants' focused attention. Infants' focused attention was measured by the look percentage (defined as the total fixation duration of the stimuli divided by the total duration of all tasks within the same age group) across a variety of free-looking tasks at the age of 6, 10, and 18 months (see Supplementary Table S1). All tasks were presented as dynamic audio-visual stimuli. During each visit, infants were invited to watch a serial of videos that were divided into 3 to 4 blocks. Each block lasted between 5 to 7 min. Conceptually, focused attention is the ability to focus and spend a period of time on targeted tasks[2,8,110]. In the current study, we applied a data-driven method and determined the measure, look percentage, that mimics the theoretical concept to evaluate focused attention. Overall, there were ca. 0.51 million fixations included in the final analysis (further information about the missing trials across tasks at different age points please see Supplementary Table S2). There are a few reasons for our choice to combine a theoretical-based and a data-driven method. First, data-driven methods are regularly applied in the field. They provide the opportunity to explore data while relaxing theory-driven constraints with more freedom and allowing new knowledge to merge[111]. We believe that the field can benefit from examining looking data from a different perspective. Second, previous studies have demonstrated that individual looking or fixation duration is stable and consistent[112,113] across stimuli types in early development[113,114]. Third, when we preprocessed the mean and variance of fixation duration across tasks with the same age group, we observed consistency in the results (see Supplementary Figure S1). Taken together, we aggregated all fixation data from different tasks within the same age point for further analysis. Outliers were removed using a z-score. The age-appropriate tasks are listed in Supplementary Table S1. A series of videos depicting the stimuli presented to participants can be viewed on Databary as following https://nyu.databrary.org/volume/828.

In this study, the mean look percentage at 6, 10, and 18 months was 73.63% (SD = 9.84), 73.47% (SD = 9.36), and 79.24% (SD = 6.86), respectively. The Pearson's correlation coefficients (Table 4) of attention, look percentage, between different ages were 0.33 (6–10 months, $n = 110$, $p < 0.001$), 0.21 (6–18 months, $n = 103$, $p = 0.04$), and 0.31 (10–18 months, $n = 100$, $p < 0.01$), suggesting the stability and internal consistency of attention during the course of development. In the current study, the composite score of look percentage was calculated by averaging each participant's look percentage measured at three time points and used as the dependent variable. There are two reasons that a composite score is used. First, from the correlational results, look percentages between different age points are very consistent, suggesting the individual difference is stable across three time points

	Timing of measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. LP (6 months)	Postpartum	–													
2. LP (10 months)	Postpartum	0.33***	–												
3. LP (18 months)	Postpartum	0.21*	0.31**	–											
4. LP composite	Postpartum	0.76***	0.79***	0.62***	–										
5. EPDS w17	Antenatal	–	–	–	–	–									
6. EPDS w32	Antenatal	–	–	–	–	0.75***	–								
7. EPDS pw6	Postpartum	–	–	–	–	0.47*****	0.58***	–							
8. EPDS pm6	Postpartum	–	–	–	–	0.54***	0.57****	0.63***	–						
9. BAI w17	Antenatal	–	–	–	–	0.74***	0.60***	0.40***	0.37***	–					
10. BAI w32	Antenatal	–	–	–	–	0.57***	0.68***	0.41***	0.41***	0.76***	–				
11. BAI pw6	Postpartum	–	–	–	–	0.43***	0.49***	0.62***	0.54***	0.53***	0.54***	–			
12. BAI pm6	Postpartum	–	–	–	–	0.37***	0.49***	0.40***	0.59***	0.52***	0.53***	0.66***	–		
13. LITE IP	Postpartum	–	–	–	–	0.22*	0.24*	0.25**	0.25*	0.21*	0.19*	0.34***	–	–	
14. LITE nIP	Postpartum	–	−0.17⁺	−0.35***	−0.26**	–	–	–	–	–	–	–	–	0.34***	–
Skewness	–	−0.87	−0.52	−0.85	−0.47	0.95	0.97	0.79	0.95	1.47	1.06	1.45	1.57	0.95	0.97
Kurtosis	–	1–52	−0.16	1.09	−0.03	0.68	1.33	0.01	0.88	2.46	1.12	1.90	2.40	0.68	1.33
VIF 1	–	NA	NA	NA	NA	5.24	3.95	2.50	2.86	4.23	2.83	2.78	2.98	1.24	1.23
VIF 2	–	NA	NA	NA	NA	2.05	1.43	1.40	1.54	2.01	1.47	1.50	1.50	1.13	1.07
MSA	–	NA	NA	NA	NA	0.70	0.71	0.76	0.77	0.72	0.72	0.77	0.77	0.42	0.43

Table 4. Pearson's zero order correlations between all variables using raw scores. ⁺ $p<0.1$, * $p<0.05$, ** $p<0.01$, *** $p<0$ .001 with Benjamini–Hochberg correction. Abbreviations: LP, look percentage; LP composite, mean look percentage of three age points; EPDS, Edinburgh Postnatal Depression Scale; BAI, Beck Anxiety Inventory; LITE, Lifetime Incidence of Traumatic Events; VIF, variance inflation factor (using LP as an outcome, other 10 variables as predictors; VIF 1 is calculated all with raw scores; VIF 2 is calculated with factor scores of EPDS and BAI and composite scores of LITE); MSA, measure of sampling adequacy according to Kaiser–Meyer–Olkin test; w17, pregnancy week 17; w32, pregnancy week 32; pv6, postpartum 6 weeks; pm6, postpartum 6 months; IP, interpersonal events; nIP, non-interpersonal events; NA: not applicable, as LP 6, 10, and 18 months were used as dependent variables.

and it is reasonable to create a single construct. Second, to answer our research question, we used the focused attention measure to relate to 10 maternal variables. Reducing the number of variables is helpful to reduce the complexity of regression analysis and to better interpret the results. All tasks were recorded using an eye-tracker with a sampling rate of 60 Hz following a 5-point calibration (Tobii TX300, Tobii Technology AB, Sweden).

Statistical analysis. *Maternal psychological distress.* We used multivariate linear regression models and a moderator analysis to examine the association between multiple predictors across different time points and the outcome measure. To assess the reliability of the maternal scale instruments, we calculated the internal consistency coefficient, Cronbach's alpha for each tool: EPDS, 0.87, good; BAI, 0.81, good; and LITE, 0.9, excellent. Before adjusting their scores, the zero-order Pearson correlations (with Benjamini–Hochberg correction), skewness, and kurtosis of all variables were calculated (Table 4). The variance inflation factor (VIF) was calculated based on the assumption that infants' look percentage is predicted by 10 variables from the EPDS (4 time points), BAI (4 time points), and LITE (1 time point). For the10 maternal variables, we performed a test of Missing Completely at Random for multivariate data with missing value[115]. Given the p-value for the chi-squared statistic was 0.82, we can conclude that maternal variables are missing completely at random. As seen in Table 4, raw scores for anxiety symptoms during antenatal 17 weeks and postpartum 6 weeks are not in the acceptable range of the kurtosis index. The raw scores of the EPDS, BAI, and LITE did not reach the range of approximate symmetric distribution (kurtosis index acceptable range, -2 to $+2$; skewness index acceptable range -0.5 to $+0.5$)[116]. In addition, the literature has shown that comorbidity of depression and anxiety is common[96,97], so we expected to detect potential multicollinearity from the raw data. As seen in Table 4, the raw scores of the EPDS and the BAI during antenatal 17 weeks fit the strict criteria for multicollinearity (VIF1 > 4) with other variables[117,118]. Considering the non-normal distribution and multicollinearity of the EPDS and BAI, the Kaiser–Meyer–Olkin test was used to examine the sampling adequacy (MSA) and transformed all raw scores from four time points into factor scores (MSA > 0.65)[119]. The percentage of missing values in EPDS and BAI at 4 different time points are–0.8, 0, 8, 12, and 8, 3, 5, 13.5–, respectively. Missing values were imputed using predictive mean matching[120]. Individual factor scores of the EPDS and BAI at four time points were calculated using the imputed values. The LITE raw scores, including IP and nIP, were the frequency of the occurrences. To be consistent in the analysis using the comparable values that can represent different levels, they were transformed into dichotomic variables based on the median of the raw scores to interpret the interaction. This choice was made due to (1) the asymmetrical distribution of the raw scores (see Table 4, the value of skewness of nIP and IP); (2) the infrequent occurrence of extremely high numbers; (3) low rate of different frequencies; and (4) the lack of a standardized scoring system to distinguish clinically significant levels. To examine differences in high versus low levels of exposure, a dichotomic categorization splitting based on median permitted the comparison between the subgroup never or rarely exposed to trauma and the subgroup that appeared to be frequently exposed to trauma[121,122]. There were 8 data points missing in LITE. Unlike EPDS and BAI covering multiple time points and considering the unknown mechanisms of how trauma is related to other factors, deleting missing data was considered not to over-interpret the data. More details are presented in Supplementary Table S3. The outcome measure was infants' look percentage composite.

Variable elimination and model fitting. Initially, there was a theoretical selection of 10 predictors included in the current data set that evaluated trauma exposure (one time point of previous IP and nIP), depressive symptoms (four time points), and anxiety symptoms (four time points) in the main analysis to predict infants' look percentage. No other variables except those listed here have been evaluated as part of the analysis. In step 1, considering that maternal trauma exposure prior to pregnancy (both IP and nIP) may interact with depression or anxiety, we separated variables into four groups as listed in Table 2 and analyzed four linear regression models independently. Applying a backward stepwise method, the number of variables in each model was reduced (3rd column, Table 2). In step 2, we performed Holm-Sidak correction to adjust the p values of all models[123,124]. Based on the statistical selection shown in Table 2, we combined the significant variables and 2-degree interaction from two significant models to assess how they jointly predict infants' focused attention (measured by look percentage; see Model A, Table 1). Based on Model A, we selected significant variables for Model B (see Table 1). In the third step, we added the sex of infants[125,126], mothers' smoking habits[127], education[128], and the maternal age at birth[129] to the analysis (Model C, Table 1). All tests were two-sided tests with $p < 0.05$ considered significant. All statistical analyses were performed using R 4.0.3[130].

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Author contributions

H.T.: drafting the article, data analysis and interpretation, final approval of the version to be published. A.S.: design and data collection of the longitudinal maternal data, critical revision of the article, interpretation, and final approval of the version to be published. M.L.: data collection of infants' longitudinal data, critical revision of the article, final approval of the version to be published. G.G.: data collection of infants' longitudinal data, data analysis and interpretation, critical revision of the article, final approval of the version to be published.

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3. General Discussion and Outlook

Attention has been investigated for several decades and it is often considered a cornerstone of cognitive development and learning. Extensive evidence has focused on its developmental changes, the role as a precursor of the development of self-regulation, as well as the early risk factors that lead to its impairment. However, due to inconsistent or insufficient results, many questions remain open about how different aspects of attention develop and support self-regulation or other cognitive skills, and what the risk factors that possibly hinder infants' attention are, etc. In this thesis, I aimed to answer whether attention in infancy is related to self-regulation in toddlerhood; and whether maternal psychological distress affects infants' attention. In this thesis, based on a longitudinal dataset, I (1) showed a high degree of stability and internal consistency in two aspects of attentional control from 6 to 18 months using a data-driven method; (2) observed a lack of significant associations between attentional control in infancy and self-regulation in toddlerhood which failed to support a widely assumed link, at least in toddlerhood; and (3) pinpointed the significant impact of maternal psychological distress related to maternal adverse childhood experiences on infants' sustained attention. While taking the systematic steps in answering these overarching questions, my results have also raised few several more questions at the conceptual and neurobiological levels with regard to the development of self-regulation and the cross-generational impact over the course from pregnancy to infancy and toddlerhood. Although the findings are extensively discussed in the publications, in the following sections, I would like to discuss several implications, specific questions, as well as the optimization of future work.

3.1 Implications and Questions from the Experimental Work

To examine the relationships between attention and self-regulation, I first focused on establishing robust attention measures. The results in Publication 1, I showed that the multifaceted attention control–information processing and sustained attention–in infancy is a steady construct. Given the stable continuity from infancy to early toddlerhood of attention, I was able to relate two attention measures in infancy to later development, early risk factors, and other cognitive skills. In practice, using robust measures can reduce statistical errors or noise caused by unreliable independent variables. Meanwhile, by exploring eye-tracking data using a data-driven method, I also demonstrated the stability of fixation durations across a variety of tasks. This suggests that processing information at the micro-level is universal in different tasks.

In other words, the individual difference in fixation duration might be generalizable across different tasks. At the macro-level, I used the total looking time of tasks as a proxy of sustained attention. Together, I was able to directly observe both attentional processes. Interestingly, those two processes did not show any significant correlation, suggesting that the underlying mechanisms might arise from two different networks. In sum, my methods of establishing robust measures can support future studies in investigating the underlying mechanisms and be beneficial to the evaluation of developing children and children at risk. However, the results of attention measures in the current thesis are limited to two types of processes. As the literature shows, attention contains other processes such as alerting, orienting, filtering, etc. Additionally, there are multiple measures of different attention abilities (e.g., selective attention, visual anticipation, visual disengagement, etc.). Similar to this thesis, future work might gain benefit from the application of a data-driven approach when investigating different attentional processes and their relationships to other cognitive abilities.

After establishing the robust attention measures based on a longitudinal dataset, the relationships between attention and self-regulation were examined. As reported in Publication 1, I was unable to find any significant association between attention in infancy and self-regulation in toddlerhood measured using several marker tasks (see Figure 5). There are several possible explanations which lead to questions for future studies. First, the link between attentional control in infancy and later self-regulation may not exist. Second, the associations may exist but they are too weak to be captured reliably and may be influenced by other factors (e.g., motor control, communication, maternal scaffolding, maternal sensitivity, postnatal growth, the level of parents' education, etc.) as other studies suggested (Aarnoudse-Moens, Weisglas-Kuperus, Duivenvoorden, Oosterlaan, & van Goudoever, 2013; Bibok, Carpendale, & Müller, 2009; Gottwald, Achermann, Marciszko, Lindskog, & Gredebäck, 2016; Hammond, Müller, Carpendale, Bibok, & Liebermann-Finestone, 2012; Hughes, Roman, Hart, & Ensor, 2013; Kuhn et al., 2014; Marciszko et al., 2020). Third, due to the neurological immaturity, the associations might be captured later in childhood or during teenage years. In addition to those possible reasons, current tasks measuring self-regulatory functions in infants and children are largely based on the framework of executive functions in adults. Moreover, besides studies indicating the lack of coherence in self-regulatory constructs in the early years of life (Frick et al., 2018; Miller & Marcovitch, 2015) and in adults (I. W. Eisenberg et al., 2019), ongoing debates in the field also show the urge to better understand the underlying mechanisms, to unify the terminology, and perhaps to explore new frameworks (Hendry et al., 2016; Nigg, 2017;

Tiego et al., 2020; Zhou et al., 2012). Hence, it remains questionable in the field whether the developmental changes of self-regulatory functions can be reliably captured by the tasks we commonly use. With the current and past results in mind, the field might also need to more cautiously examine the body of work that claims and promotes the positive effects of attention training in infants or young children on other cognitive development or skills. More specifically, theories of early self-regulation and executive functions might consider toning down or revising their claims that attention is the driving force behind self-regulatory functions. Otherwise, a hypothesis that has not been supported by evidence might become the basis of further research. Thus, it repeats the weak evidence and reinforces itself as result. For instance, evidence that does not confirm the association might be dismissed and stay unreported. Perhaps at the moment, it is essential to gain a clearer understanding of how dynamic and putative factors of self-regulation interact and merge. In particular, more longitudinal studies that explore robust measures and their relations are necessary.

Nevertheless, attention plays a role in cognitive development. Research that supports the development of attention in the early years has been one of the cornerstones in the developmental literature. While previous evidence shows that the development of attention in childhood is affected by maternal mental health, our results also showed similar effects in infancy. Using the robust attention measure, our findings described a previously undocumented connection between maternal early trauma, anxiety, and the development of sustained attention in infants. Treating pregnant women's anxiety, especially if she has experienced traumatic events in the past, may not only improve the lives of mothers but also support the positive development of their children from infancy onwards. In Publication 2, I systematically examined different dimensions of maternal distress bringing clear and specific distinctions among anxiety, depression, and early exposure to trauma. From mothers' childhood to pregnancy and postpartum, our attempt to construct the pathway of the cross-generational impact highlights the critical and vulnerable time in the 2nd trimester. This potentially supports the defining of a time window for early screening and optimizing prevention programs. What remains unknown here are (1) to what extent the complexity of maternal psychological distress interacts with genetic, biological (e.g., hormones) and/or social factors over the course of pregnancy and affect infants' attention; (2) what are the underlying mechanisms that might explain how maternal childhood trauma intertwines with anxiety and/or depression; and (3) how different trajectories of maternal distress, including their timing, duration, frequency, severity, comorbidity (for instance, depression combined anxiety), receiving treatments, or recovering, etc. play a role in infants' attention and cognitive development. Besides, the small number of participants with a high degree of homogeneity (e.g., education, ethnicity) in our results and the lack of clinical severe cases also limit the aspect of generalization. Due to the high percentage of women who experience mental distress during pregnancy (Meaney, 2018; Okagbue et al., 2019; Wikman et al., 2020), I also want to emphasize the importance of prevention as well as the urge to have more in-depth investigations of supportive factors.

3.2 Optimizing the Design of Future Studies

This thesis demonstrates the continuity of the development of attention from infancy to toddlerhood and challenges the purported claim that attention is fundamental to self-regulatory functions. It also emphasizes the cross-generation effect of maternal mental health on infants' attention. To move forward, as several critical questions arose in the previous section, I would like to propose some possible optimizations in the following paragraphs that future studies might gain benefit from.

First, though I included as much data as possible when employing a data-driven method to identify attention measures, it is important to bear in mind that we have very little understanding of what happened during the few trials where no data existed (for the number of missing trials of eye-tracking data, please see Supplementary Information Table S1). In those trials, infants might have failed to look, created excessive movements, or other factors that contributed to no data being captured. I believe that it would not be optimal to simply assume that infants all show poor attention when no data exist. With advancing technology, perhaps in the future eye-trackers that might allow a great degree of movements or combinations with other physiological measures (e.g., EEG) might help distinguish the behaviors and those unknown trials.

Second, my results of attention measures are limited to two types of processes. As literature shows, attention contains other processes such as alerting, orienting, filtering, etc., and several other measures of different attention abilities (e.g., selective attention, visual anticipation, visual disengagement, etc.). Similar to this current work, future work might gain benefits from the application of a data-driven approach when investigating different attentional processes and their relationships to other cognitive abilities.

Third, while the field might be focusing on revising the framework of self-regulation, it is important to explore the stability of self-regulation measures and to re-examine their associations. Similar to the attention measures addressed in this thesis, having robust measures of self-regulation can help us better capture the developmental trajectories of self-regulation as well as gaining more insight about the underlying mechanisms.

Fourth, when addressing the impact of maternal mental health on infants' development, future studies perhaps can focus more on the complexity of depression, anxiety, and lifetime adverse experiences and trauma exposures. In this thesis, I only emphasized 4 time-points of depression and anxiety, as well as the traumatic exposure in childhood. This is not enough to reflect the interactions between different risk factors and how the impact accumulates while time unfolds. In addition, it is also very important to consider the biological and genetic factors that might be the underlying mechanisms of maternal mental health which contribute to the cognitive development of their offspring. Meanwhile, to include more clinical cases, (e.g., depression and/or anxiety history, chronic cases, or new-onset only due to pregnancy, etc.), as well as to investigate whether different paths of recovery play a role in supporting their infants' development will help to understand the dynamics of cross-generational impact and provide us valuable insight for prevention and intervention.

Fifth, one interesting factor—infants' gaze-following ability—has been linked to maternal depression (Astor et al., 2020) and it predicts the development of attention (Niedźwiecka et al., 2018). In the current thesis, infants' performance of gaze-following was included but not isolated as an independent parameter. Future studies can address how gaze-following ability is moderated by maternal mental health and linked to attentional control in infancy and childhood.

Sixth, this thesis attempted to identify the risk factors for maternal mental health to infants' attention. Besides highlighting the importance of prevention and early intervention in mothers' mental psychological distress and infants' development, some supportive factors that might buffer against the negative impact of maternal psychological distress will be certainly crucial for further research. However, related literature is scarce. Future studies might want to explore those aspects using a longitudinal design.

Lastly, the studies included in the thesis have a general limitation due to the high degree of homogeneity of the sample from a university town with more than half of the mothers holding a university degree or higher. Meanwhile, it was not possible to collect information on race or ethnicity, this essentially limited the generalization of the results. Different experiences (such as homogenous contexts, collectivistic contexts, individualistic contexts) and variations in socioeconomic status community access might already show significant impacts on development early in life. In short, it will be very meaningful that future studies can ensure the increase of the heterogeneity of participants and prevent bias or underrepresentation of minorities in research.

4. Summary

Zusammenfassung der Arbeit

Dissertation zur Erlangung des akademischen Grades Dr. rer. med.

"The Longitudinal Investigation of Infants' Attentional Control and Its Associations with Self-regulatory Functions in Toddlerhood and Maternal Mental Distress"

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Einreichung:	Mai, 2022

4.1 English Summary

Attention is an important cognitive operation involving several processes including alertness, orienting, filtering and processing input, maintaining focus, and endogenous control (Colombo, 2001; Hendry et al., 2019). It is assumed that attention can support the allocation of cognitive resources, prioritization, updates of incoming information, and regulation of behavior in early development (Colombo et al., 2011; Esterman & Rothlein, 2019). Attentional control in the early years is often considered crucial to the later development of self-regulation (Posner et al., 2016; Rueda, Posner, et al., 2005) which is linked to academic performance and learning later in life (Best et al., 2011; Morgan et al., 2019). Impairments of attention and self-regulation are often related to neurodevelopmental disorders, such as attention-deficit/hyperactivity disorder (Barkley, 1997; Sjöwall, Roth, Lindqvist, & Thorell, 2013; Sonuga-Barke, Bitsakou, & Thompson, 2010) and autism spectrum disorder (Gilotty, Kenworthy, Sirian, Black, & Wagner, 2002; Matson et al., 2013; Samson et al., 2014).

Looking onwards– from infancy to toddlerhood

In developmental literature, measurements of attentional control have heavily relied on various looking behavior (Bornstein, 1985; Colombo et al., 1999; Gredebäck et al., 2009). Different parameters of looking behavior have been used to assess different aspects of attentional control, such as the latency of orienting to stimuli (Pyykkö et al., 2020), the duration of looking at stimuli (Johansson et al., 2015), or the speed of processing visual stimuli (Blankenship et al., 2019), etc. Though it has been reported that different aspects of the development of attentional

control are stable across the first 2 years of life (Brandes-Aitken et al., 2019; Colombo et al., 2004; Rose & Feldman, 1987; Rose et al., 2001), most results were based on a single and brief period of observation (e.g. 5 minutes). In this thesis, I employed a data-driven method to explore a longitudinal dataset that contains looking behavior from 6, 10, to 18 months of age. This allows us to observe the developmental changes of attentional control from a different perspective. More importantly, it enables us to identify and establish stable and robust measures that can be used to relate to other variables from other domains, for instance, self-regulation and maternal mental health in the current thesis. Attention in infancy is often used as an earlier marker or a predictor of self-regulatory functions. Self-regulatory functions, commonly emphasizing effortful control and executive functions (Posner & Rothbart, 2000; Rothbart & Rueda, 2005; Rothbart, Sheese, et al., 2011), correlate with an individual's academic achievement, life satisfaction, and labor market success (Ahmed et al., 2019; Best et al., 2011; Brock et al., 2009; Morgan et al., 2019). It is suggested that attention might be fundamental to the development of self-regulatory functions (Colombo & Cheatham, 2006; Posner & Rothbart, 2009; Rueda, Posner, et al., 2004). Based on this, several recent studies have claimed a positive association between attention and self-regulation in the early years (Blankenship et al., 2019; Cuevas & Bell, 2014; Geeraerts et al., 2019; Papageorgiou et al., 2014). In this thesis, I reviewed the body of literature that claims this association exists and examined the overall evidence. However, although empirical evidence exists to support this claim, the findings are not consistent. Furthermore, following the same assumption, I presented the experimental findings examining this association between attention measures in infancy (established based on the data-driven method) and measures of self-regulatory functions at 18 and 30 months of age. Our findings, like our review, did not support the purported claims of the association between attention and self-regulation, at least, in toddlerhood.

Looking retrospectively–from infancy back to pregnancy and mothers' childhood

Given the importance of attention in infancy and its role in later development addressed above, studies in infancy and childhood have attempted to identify the early risk factors that might hinder the development of attention. This brings the focus retrospectively to the in-utero period and even maternal childhood experiences. There is substantial evidence showing that maternal distress can change cortical and subcortical connectivity (Rifkin-Graboi et al., 2013; Scheinost et al., 2020) in infants and has negative impacts on children's cognitive development (Keim et al., 2011; Kingston et al., 2015; Laplante et al., 2004; Tarabulsy et al., 2014). Furthermore, recent studies also reported that maternal adverse childhood experiences may have cumulative effects on maternal mental health (Sacchi et al., 2020; Weltz et al., 2016), and in turn, lead to structural neurodevelopmental consequences in *in-utero* (Andescavage et al., 2017; Moog et al., 2018). In line with these findings, several large scale studies have demonstrated the negative associations between maternal distress and childhood trauma, attention-related problems (Ross et al., 2020; Wang & Dix, 2017), attention-deficit/hyperactivity disorder symptoms (Moon et al., 2021; Mulraney et al., 2019; Vizzini et al., 2019), and an elevated risk for autism (Roberts et al., 2013) in their children. Even though extensive literature has shown that maternal distress affects children's attention, underlying mechanisms are still unknown. In this thesis, I reviewed the theoretical rationales and empirical evidence supporting the connection between maternal distress and offspring's attention. Next, to better understand the possible underlying mechanisms, I investigated different aspects of maternal mental health (e.g. depressive symptoms, anxiety symptoms, and maternal adverse childhood experiences) and their associations with infants' attention based on the same sample from attention measures and included the maternal data from pregnancy to 12 months postpartum in this thesis.

Taken together, there are three main aims of this thesis corresponding to two publications. First, I investigated the development of attention from 6, 10, to 18 months using approx. 0.5 million fixations from eye-tracking measures and examined the data based on a data-driven method. Only when the stable and robust attention measures were identified, I moved on to the second aim to analyze their associations with self-regulatory functions. Third, using the robust attention measures, I retrospectively examined whether maternal childhood adverse experiences and maternal distress during pregnancy and infancy affected infants' attention (Tu et al., 2021). In our findings, I (1) showed a high degree of stability and internal consistency in two aspects of attentional control from 6 to 18 months using a data-driven method; (2) observed the lack of significant associations between attentional control in infancy and self-regulation in toddlerhood which failed to support widely assumed link, at least in toddlerhood; and (3) pinpointed the significant impact of maternal psychological distress related to maternal adverse childhood experiences on infants' sustained attention.

To summarize, this thesis provides a deeper insight into the development of attention in infancy and adds to the growing body of research, suggesting that prevention and intervention should start before pregnancy for both mothers and infants. Meanwhile, this thesis also highlights the urge that the field needs further investigations of the developmental pathways that lead to self-regulation, emphasizing the multi-phased nature of development. To date, there is little evidence that attention early in infancy is strongly and uniquely associated with self-regulation during childhood. Theory and testable models specifically designed to assess early emerging foundations of self-regulation are essential models that acknowledge the complexity of the task at hand.

Articles included in this thesis:

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4.2 Deutsche Zusammenfassung

Aufmerksamkeit ist eine wichtige kognitive Operation, die mehrere Prozesse betrifft, zu welchen Konzentration, Orientierung, Filterung und Verarbeitung von Inputs, das Aufrechterhalten des Fokus und endogene Kontrolle gehören (Colombo, 2001; Hendry et al., 2019). Es wird angenommen, dass Aufmerksamkeit die Allokation von kognitiven Ressourcen, die Priorisierung und Aktualisierung eintreffender Informationen und die Regulierung von Verhalten in der frühkindlichen Entwicklung unterstützen kann (Colombo et al., 2011; Esterman & Rothlein, 2019). Die Fähigkeit zur Steuerung von Aufmerksamkeit in frühen Jahren wird häufig als entscheidend für die spätere Entwicklung von Selbstregulation angesehen (Posner et al., 2016; Rueda, Posner, et al., 2005), welche verbunden ist mit der akademischen Leistung und Lernleistung im späteren Leben (Best et al., 2011; Morgan et al., 2019). Beeinträchtigungen von Aufmerksamkeit und Selbstregulation sind oft mit neurologischen Entwicklungsstörungen verbunden, wie beispielsweise einer Aufmerksamkeitsdefizits- oder einer Hyperaktivitätsstörung (Barkley, 1997; Sjöwall et al., 2013; Sonuga-Barke et al., 2010) oder einer Autismus-Spektrum-Störung (Gilotty et al., 2002; Matson et al., 2013; Samson et al., 2014).

Der Blick nach vorn – vom Säugling zum Kleinkind

Die Entwicklungsliteratur verlässt sich zur Messung der Aufmerksamkeitssteuerung stark auf die Messung unterschiedlichen Blickverhaltens (Bornstein, 1985; Colombo et al., 1999; Gredebäck et al., 2009). Verschiedene Parameter des Blickverhaltens wurden verwendet, um unterschiedliche Aspekte der Aufmerksamkeitssteuerung zu erfassen, wie beispielsweise die

Latenz der Ausrichtung zu Stimuli (Pyykkö et al., 2020), die Blickdauer auf Stimuli (Johansson et al., 2015) oder die Verarbeitungsgeschwindigkeit visueller Stimuli (Blankenship et al., 2019). Obwohl berichtet wurde, dass verschiedene Aspekte der Entwicklung der Aufmerksamkeitssteuerung über die ersten 2 Lebensjahre stabil sind (Brandes-Aitken et al., 2019; Colombo et al., 2004; Rose & Feldman, 1987; Rose et al., 2001), basieren die meisten Ergebnisse auf einem einzelnen und kurzen Beobachtungszeitraum (z. B. 5 Minuten). In dieser Arbeit wird eine datengetriebene Methodik eingesetzt, um einen longitudinalen Datensatz zu untersuchen, der Daten zum Blickverhalten im Alter von 6, 10 und 18 Monaten enthält. Auf diese Weise sind wir im Stande, Entwicklungsänderungen der Aufmerksamkeitssteuerung aus verschiedenen Perspektiven zu beobachten. Vor allem konnte auf diese Weise eine stabile und robuste Messgröße identifiziert und etabliert werden, die verwendet werden kann, um zu anderen Variablen in Bezug gesetzt zu werden, beispielsweise in der vorliegenden Arbeit zur Selbstregulation und zur mütterlichen psychischen Gesundheit. Aufmerksamkeit im Säuglingsalter wird oft als Frühindikator oder Prädiktor für Selbstregulationsfunktionen genutzt. Selbstregulationsfunktionen wiederum, häufig unter Betonung von Effortful Control und exekutiven Funktionen (Posner & Rothbart, 2000; Rothbart & Rueda, 2005; Rothbart, Sheese, et al., 2011), korreliert mit individuellen akademischen Leistungen, der Lebenszufriedenheit und dem Arbeitsmarkterfolg (Ahmed et al., 2019; Best et al., 2011; Brock et al., 2009; Morgan et al., 2019). Es wurde vorgeschlagen, dass Aufmerksamkeit grundlegend für die Entwicklung von Selbstregulationsfunktionen ist (Colombo & Cheatham, 2006; Posner & Rothbart, 2009; Rueda, Posner, et al., 2004). Auf dieser Basis haben mehrere jüngere Studien einen positiven Zusammenhang zwischen Aufmerksamkeit und Selbstregulation in den frühen Lebensjahren festgestellt (Blankenship et al., 2019; Cuevas & Bell, 2014; Geeraerts et al., 2019; Papageorgiou et al., 2014). In der vorliegenden Arbeit wurde die Literatur gesichtet, die diesen Zusammenhang aufstellt, und die Gesamtevidenz geprüft. Obwohl zwar empirische Hinweise darauf existieren, die diese Feststellung unterstützen, sind die Ergebnisse nicht konsistent. Des Weiteren werden basierend auf den gleichen Annahmen experimentelle Ergebnisse präsentiert, welche den Zusammenhang zwischen Messgrößen der Aufmerksamkeit im Säuglingsalter (auf Basis der datengetriebenen Methodik) und der Selbstregulationsfunktionen im Alter von 18 und 30 Monaten untersuchen. Die vorliegenden Resultate, ebenso wie der Literaturüberblick unterstützen die Behauptung eines Zusammenhangs zwischen Aufmerksamkeit und Selbstregulation nicht, zumindest nicht im Kleinkindalter.

Der Blick zurück – vom Säugling zu Schwangerschaft und Kindheit der Mutter

Vor dem Hintergrund der Wichtigkeit von Aufmerksamkeit im Säuglingsalter und der zuvor beschriebenen Rolle in der späteren Entwicklung haben Studien zu Säuglingsalter und Kindheit versucht, diejenigen Risikofaktoren zu identifizieren, welche die Aufmerksamkeitsentwicklung beeinträchtigen könnten. Dies legt den nachträglichen Fokus der Betrachtung auf die In-Utero-Periode und sogar Kindheitserfahrungen der Mutter. Es existieren substantielle Hinweise darauf, dass mütterliche Stressfaktoren kortikale und subkortikale Verknüpfungen von Säuglingen beeinflussen (Rifkin-Graboi et al., 2013; Scheinost et al., 2020) und negative Auswirkungen auf die kognitive Entwicklung von Kindern haben kann (Keim et al., 2011; Kingston et al., 2015; Laplante et al., 2004; Tarabulsy et al., 2014). Des Weiteren wurde in jüngeren Studien berichtet, dass negative mütterliche Kindheitserfahrungen einen kumulativen Effekt auf die mütterliche psychische Gesundheit haben kann (Sacchi et al., 2020; Weltz et al., 2016) und wiederum zu strukturellen Konsequenzen für die neuronale Entwicklung *in-utero* führen kann (Andescavage et al., 2017; Moog et al., 2018). Im Einklang mit diesen Ergebnissen haben mehrere umfangreiche Studien einen negativen Zusammenhang zwischen mütterlichem Stress und Kindheitstraumata, aufmerksamkeitsbezogenen Problemen (Ross et al., 2020; Wang & Dix, 2017), Aufmerksamkeitsdefizits-/Hyperaktivitätssymptomen (Moon et al., 2021; Mulraney et al., 2019; Vizzini et al., 2019) und einem erhöhten Autismusrisiko (Roberts et al., 2013) ihrer Kinder gezeigt. Obgleich eine umfangreiche Literatur zeigt, dass mütterlicher Stress die Aufmerksamkeit von Kindern beeinflusst, sind die zugrundeliegenden Mechanismen weiterhin unbekannt. In der vorliegenden Arbeit wurden die theoretischen Erklärungsansätze und die empirische Beweislage zum Zusammenhang von mütterlichen Stressfaktoren und Aufmerksamkeit des Nachwuchses untersucht. Im nächsten Schritt wurden, um ein besseres Verständnis für die zugrundeliegenden Mechanismen zu entwickeln, verschiedene Aspekte der mütterlichen psychischen Gesundheit (z. B. depressive Symptome, Symptome von Angstgefühlen und negative mütterliche Kindheitserfahrungen) und ihr Zusammenhang mit der Aufmerksamkeit von Säuglingen untersucht, basierend auf der gleichen Stichprobe anhand der Aufmerksamkeitsmessgrößen und unter Hinzufügen mütterlichen Daten von der Schwangerschaft bis 12 Monate nach der Geburt.

Im Gesamten behandelt die vorliegende Arbeit drei Hauptthesen, welche in zwei verbundenen Veröffentlichungen untersucht werden. Erstens wurde die Entwicklung von Aufmerksamkeit im Alter von 6, 10 und 18 Monaten unter Verwendung von etwa 0,5 Millionen Fixierungen von Eye-Tracking-Messungen untersucht und mittels einer datengetriebenen Methode analysiert. Nach der Entwicklung von stabilen und robusten Aufmerksamkeitsmessgrößen, wurde das zweite Ziel umgesetzt, den Zusammenhang mit Selbstregulationsfunktionen zu untersuchen. Drittens wurde unter Verwendung der robusten Aufmerksamkeitsmessgrößen untersucht, ob rückblickend negative mütterliche Kindheitserfahrungen und mütterliche Stressfaktoren während der Schwangerschaft die Aufmerksamkeit von Säuglingen beeinflussen (Tu et al., 2021). Im Ergebnis zeigt sich (1) ein hoher Grad an Stabilität und interne Konsistenz zweier Aspekte der Aufmerksamkeitssteuerung von 6 bis 18 Monaten unter Verwendung einer datengetriebenen Methodik; (2) die Abwesenheit eines signifikanten Zusammenhangs zwischen Aufmerksamkeitssteuerung im Säuglingsalter und Selbstregulation im Kleinkindalter, welche eine weithin angenommene Verbindung zumindest im Kleinkindalter nicht bestätigt; und (3) einen signifikanten Einfluss von mütterlichen psychologischen Stressfaktoren, die in Verbindung zu negativen mütterlichen Kindheitserfahrungen stehen, auf die dauerhafte Aufmerksamkeit von Säuglingen.

Zusammenfassend bietet die vorliegende Arbeit tiefere Einblicke in die Entwicklung von Aufmerksamkeit im Säuglingsalter und trägt zu einer wachsenden Literatur bei, die nahelegt, dass Prävention und Intervention sowohl für Mütter als auch für Säuglinge bereits vor der Schwangerschaft ansetzen sollten. Gleichzeitig zeigt die vorliegende Arbeit auf, dass das Forschungsfeld dringend weitere Untersuchungen zu den Entwicklungspfaden benötigen, die zu Selbstregulation führen. Dies unterstreicht die mehrstufige Natur von Entwicklungsprozessen. Zum jetzigen Zeitpunkt besteht nur wenig Evidenz, dass Aufmerksamkeit im frühen Säuglingsalter stark und auf besondere Weise mit Selbstregulation in der Kindheit in Zusammenhang stünde. Eine Theoriebasis und überprüfbare Modelle, die spezifisch für die Bewertung von früh entstehenden Grundlagen der Selbstregulation entwickelt werden, wären essenzielle Modelle, die der Komplexität der Aufgabe gerecht werden können.

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Appendix

A.1 Supplementary Information

Supplementary Table S1

The number of trials and missing trials in each task by age

Age (month)	Task	Nr. of trials	Nr. of average missing trials
6	Action evaluation rational	6	0.20
	Action evaluation irrational	6	0.15
	Approximate number system	6	0.11
	Face perception (3 emotions)	12	0.31
	Biological motion	4	0.10
	Gaze following	6	0.19
	Small forms discrimination	8	0.23
	Pupillary light response	8	0.00
	Action prediction	2	0.00
	Coherent motion task	4	0.13
	Associative learning	2	0.01
10	Action evaluation rational	6	0.33
	Actional evaluation irrational	6	0.25
	Approximate number system	6	0.15
	Biological motion	4	0.15
	Gaze following	6	0.25
	Small forms discrimination	8	0.65
	Pupillary light response	8	0.00
	Action prediction	2	0.07
	Coherent motion task	4	0.30
	Associative learning	2	0.02
	Gravity	8	0.37
	Face perception (4 emotions)	24	2.75
	Visual sequence task	15	0.01
18	Reaching	8	0.13
	Face perception (4 emotions)	24	2.24
	Approximate number system	6	2.23
	Visual sequence task	15	0.02

A.2 Author Contributions to the Publications

Author Contribution to the Publications 1

"Attentional control is a stable construct in infancy but not steadily linked with self-regulatory functions in toddlerhood" by Hsing-Fen Tu* **(HFT)**, Marcus Lindskog **(ML)**, Gustaf Gredebäck **(GG)**; Developmental Psychology 2022;
*Corresponding author

Principle investigator:	ML, GG
Conception and design of the paper:	HFT, GG
Literature review:	HFT
Data acquisition:	ML, GG
Data interpretation:	HFT, ML, GG
Figure creation:	HFT, ML
Drafted manuscript:	HFT
Critical revision:	HFT, ML, GG

Signatures

Leipzig, den	30-04-2022	Hsing-Fen Tu	Hsing-Fen Tu
Uppsala, den	27/4-22	Marcus Lindskog	[signature]
Uppsala, den	26/4-22	Gustaf Gredebäck	[signature]

Author Contribution to the Publication 2

"*Maternal childhood trauma and perinatal distress are related to infants' focused attention from 6 to 18 months*" by Hsing-Fen Tu* **(HFT)**, Alkistis Skalkidou **(AS)**, Marcus Lindskog **(ML)**, Gustaf Gredebäck **(GG)**; Scientific Reports December 2021;
*Corresponding author

Principle investigator:	GG
Conception and design of the paper:	HFT, GG, AS
Literature review:	HFT
Data acquisition:	AS, ML, GG
Data interpretation:	HFT, GG, AS
Figure creation:	HFT
Drafted manuscript:	HFT
Critical revision:	HFT, AS, ML, GG

Signatures

Leipzig, den	20. Dec. 2021	Hsing-Fen Tu	Hsing-Fen Tu
Uppsala, den	14 jan 2022	Alkistis Skalkidou	ASkalkidou
Uppsala, den	27/4 -22	Marcus Lindskog	[signature]
Uppsala, den	26/4-22	Gustaf Gredebäck	[signature]

A.3 Declaration of Authenticity

Erklärung über die eigenständige Abfassung der Arbeit

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und ohne unzulässige Hilfe oder Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Ich versichere, dass Dritte von mir weder unmittelbar noch mittelbar eine Vergütung oder geldwerte Leistungen für Arbeiten erhalten haben, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen, und dass die vorgelegte Arbeit weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde zum Zweck einer Promotion oder eines anderen Prüfungsverfahrens vorgelegt wurde. Alles aus anderen Quellen und von anderen Personen übernommene Material, das in der Arbeit verwendet wurde oder auf das direkt Bezug genommen wird, wurde als solches kenntlich gemacht. Insbesondere wurden alle Personen genannt, die direkt an der Entstehung der vorliegenden Arbeit beteiligt waren. Die aktuellen gesetzlichen Vorgaben in Bezug auf die Zulassung der klinischen Studien, die Bestimmungen des Tierschutzgesetzes, die Bestimmungen des Gentechnikgesetzes und die allgemeinen Datenschutzbestimmungen wurden eingehalten. Ich versichere, dass ich die Regelungen der Satzung der Universität Leipzig zur Sicherung guter wissenschaftlicher Praxis kenne und eingehalten habe.

26.04.2022
....
Datum

....
Unterschrift

A.4 Curriculum Vitae

Personal Data

Name	Hsing-Fen Tu
Date and place of birth	1980/01/14 in Tainan, Taiwan
Address	Von Kraemers allé 1C, 752 37 Uppsala, Sweden
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Education

2018/02 – 2022/12	Doctoral Researcher at the Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany Thesis: "The longitudinal investigation of infants' attentional control and its associations with self-regulatory functions in toddlerhood and maternal mental distress" (Supervisors: Prof. Dr. Arno Villringer & Prof. Dr. Gustaf Gredebäck)
2003/09 – 2006/06	Master of Science (1.3), School of Occupational Therapy, College of Medicine, National Taiwan University, Taipei, Taiwan Thesis: "Performance on spatial attention tests by adults with and without unilateral stroke: Functional implications of spatial neglect" (Prof. Dr. Keh-Chung Lin, ScD, OTR/L)
1998/09 – 2003/06	Bachelor of Science (1.7), School of Occupational Therapy, College of Medicine, National Cheng Kung University, Tainan, Taiwan

Work Experience

Since 2021/08	Lab Coordinator at the Uppsala Child & Baby Lab, Department of Psychology, Uppsala University, Uppsala, Sweden
Since 2020/10	Scientific Project Assistant at the Uppsala Child & Baby Lab, Department of Psychology, Uppsala University, Uppsala, Sweden
2019/07 – 2019/10	Visiting PhD Student at the Visual Attention Lab, Brigham & Women's Hospital, Harvard Medical School, Boston, United State (Prof. Dr. Jeremy Wolfe)

Work Experience (continued)

2007/02 – 2009/07	Board Certified Lecturer at the Department of Early Childhood Development and Education, Southern Taiwan University of Science and Technology, Tainan, Taiwan
2006/04 – 2009/07	Board Certified Occupational Therapist in Child and Adolescent Psychiatry Division, Jianan National Psychiatric Center, Tainan, Taiwan
2001/07 – 2002/09	Research Assistant at the Department of Occupational Therapy, National Cheng Kung University, Tainan, Taiwan

Research School

2018/09 – 2022/12	International Max Planck Research School on Neuroscience of Communication: Function, Structure, and Plasticity, Leipzig, Germany

Memberships

Since 2019	International Congress of Infant Studies (ICIS)
2022	OHBM Student and Postdoc Student Interest Group (SIG) International Online Mentoring Program (as an online mentor)
Since 2023	Member of COST Actions (European Cooperation in Science and Technology), Working Group: Research Innovation and Sustainable Pan-European Network in Perinatal Depression Disorder (Riseup-PPD)
Since 2023	Member of Cochrane Translator (Traditional Mandarin, Cochrane Taiwan)

A.5 List of Publications

Paper:

Tu, HF., Lindskog, M., & Gredebäck, G. (2022). Attentional control is a stable construct in infancy but not steadily linked with self-regulatory functions in toddlerhood. *Developmental Psychology*, 2022 Apr 21. https://doi.org/10.1038/s41598-021-03568-2 Epub ahead of print

Tu, HF., Skalkidou, A., Lindskog, M. *et al.* Maternal childhood trauma and perinatal distress are related to infants' focused attention from 6 to 18 months. *Sci Rep* **11,** 24190 (2021). https://doi.org/10.1038/s41598-021-03568-2

A.6 Conference Contributions

2018/06 Tu, H. F. "Seeing in time: an investigation of entrainment and visual processing in toddlers." In *10th ACM Symposium on Eye Tracking Research and Applications, ETRA*, Warsaw, Poland. https://doi.org/10.1145/3204493.3207418

2020/07 Tu, H.F. & Fritz, T. "Modulation of visual search performance by acoustic concurrent stimulation in early childhood." Poster presented at the *International Congress of Infant Studies (v-ICIS 2020)*.

2022/08 Tu, H.F. "Attention in infancy: a data-driven perspective." Verbal presentation in ECVP Symposium: "From vision to attention: the development of visual perception in early childhood" at the *European Conference on Visual Perception, ECVP 2022*, Nijmegen, the Netherlands.

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