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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

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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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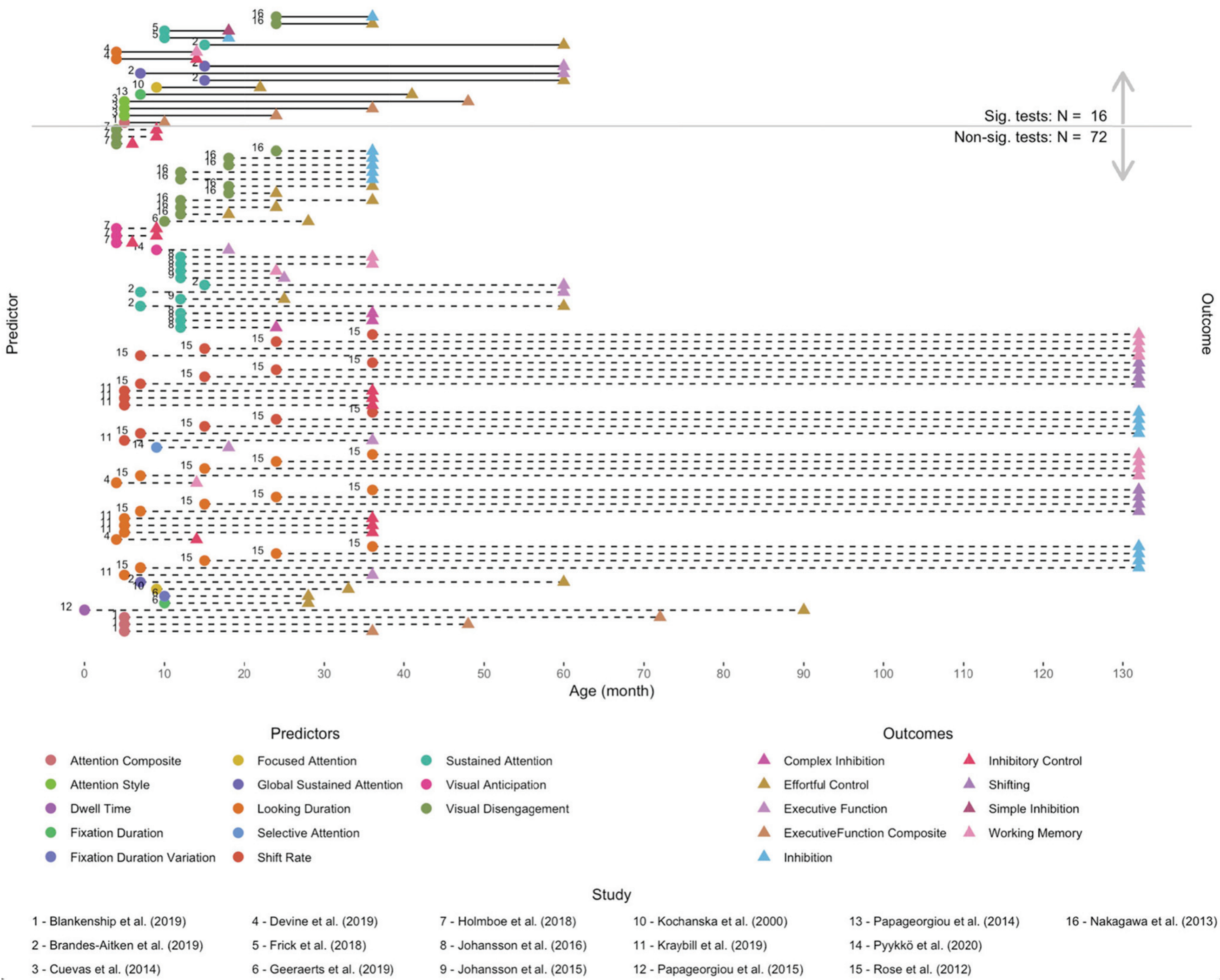
Figure 1

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

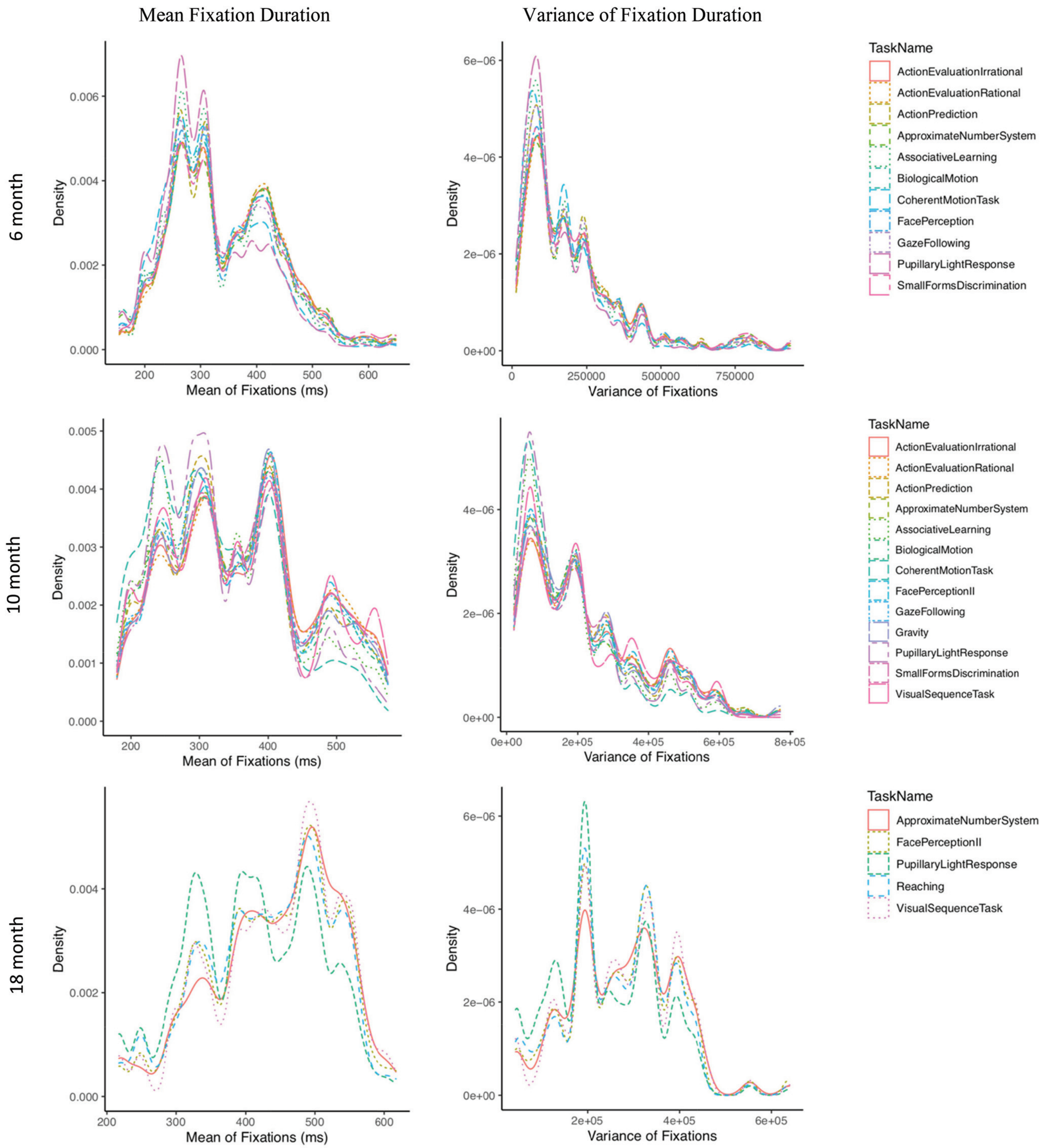
The analyses of the relations between the attention measures and the measures of self-regulatory functions are summarized in Table 4. None of the analyses showed significant correlations between attentional control (measured by short fixation ratio and look percentage) and self-regulatory function at 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

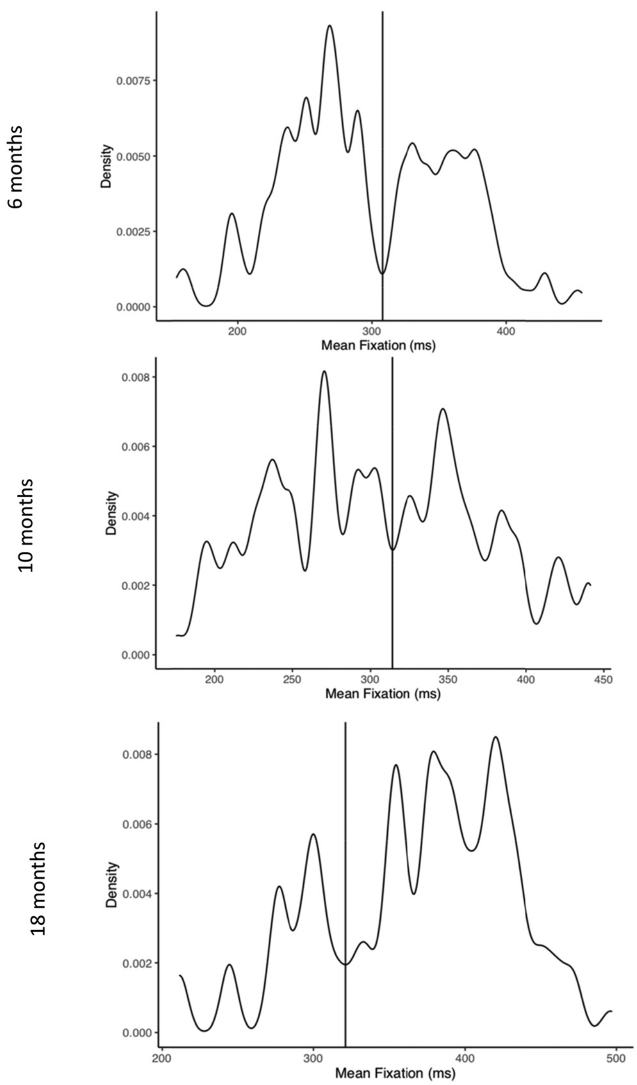
Illustration of the Distributions of Mean (Left Column) and Variance (Right Column) of Fixation Durations at Three Different Age Points Across Different Age-Appropriate Tasks



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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