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Longitudinal development of attention and inhibitory control during the first year of life

Running Head: Longitudinal infant attention & inhibitory control

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Research Highlights

- This longitudinal study of more than 100 infants investigated the emergence of inhibitory control during the first year, and its relation to early attentional abilities.

- Inhibitory control measures were significantly associated at 9 months, and this was independent of general cognitive development.

- Results indicated some longitudinal stability of individual differences in inhibitory control from as early as 6 months of age.

- Measures of basic attentional abilities at 4 months of age did not predict inhibitory control later during the first year.

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Abstract

Executive functions (EFs) are key abilities that allow us to control our thoughts and actions. Research suggests that two EFs, inhibitory control (IC) and working memory (WM), emerge around 9 months. Little is known about IC earlier in infancy and whether basic attentional processes form the 'building blocks' of emerging IC. These questions were investigated longitudinally in 104 infants tested behaviorally on two screen-based attention tasks at 4 months, and on IC tasks at 6 and 9 months. Results provided no evidence that basic attention formed precursors for IC. However, there was full support for coherence in IC at 9 months and partial support for stability in IC from 6 months. This suggests that IC emerges earlier than previously assumed.

Introduction

Executive functions (EFs) are a set of psychological abilities that allow us to guide our behavior and make adaptive decisions in everyday life. There are many diverse definitions of EFs, but prominent in most accounts is some form of *control* over attention, thought or action. In this respect, EFs can be thought of as a set of abilities that free us from being entirely controlled by our immediate circumstances and automatic response tendencies, and therefore a key requirement for adaptive, flexible and creative behavior.

It should be clear from this description that EFs are relatively immature in infancy. Most caregivers will observe that infants are as yet unable to control many aspects of their behavior, are easily distracted, and often repeat the same behaviors. Nevertheless, it is also clear that infants change substantially during the first year. Their ability to filter out irrelevant information and focus on people and objects of interest improves dramatically. The way a 9-month-old can be deeply engaged with manipulating an interesting toy contrasts with a 4-month-old infant's immediate distraction by any interesting object or person in their visual field.

Studies in adults have defined several differentiated, but also overlapping EFs. One prominent conceptualization that has gained empirical support focusses on three core EFs: working memory (WM), inhibitory control (IC), and shifting / cognitive flexibility (CF) (Miyake et al., 2000). WM involves the process of keeping information in mind and manipulating that information in order to guide thoughts and actions, IC involves overcoming a habitual or other strong response tendency in order to perform an alternative action, and CF is the ability to easily switch between perspectives and activities. More recently, this model has been updated to involve one over-arching function primarily associated with IC ('General

EF'), but still including WM- and CF-specific components (Friedman & Miyake, 2017; Miyake & Friedman, 2012).

A wealth of knowledge already exists on the development of EFs in the preschool period (approx. 2.5-5 years) (Garon, Bryson, & Smith, 2008; Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011). More recently, there has been a renewed interest in the development of EFs and their precursors during infancy and toddlerhood (Hendry, Jones, & Charman, 2016; Johansson, Marciszko, Gredebäck, Nyström, & Bohlin, 2015). Once verbal instruction is possible (usually around 2-2.5 years of age), children can be asked to inhibit actions, maintain and manipulate information in WM, and switch between different tasks (e.g., Garon, Smith, & Bryson, 2014; Mulder, Hoofs, Verhagen, van der Veen, & Leseman, 2014; Zelazo, Frye, & Rapus, 1996). The use of touchscreen devices also allows for a less verbally mediated assessment of toddlers' EF abilities (Holmboe, Fearon, Csibra, Tucker, & Johnson, 2008; Rothbart, Ellis, Rueda, & Posner, 2003; Twomey et al., 2018).

However, research on the development of EFs in infancy (0-12 months) is still relatively sparse, and has primarily focused on the development of WM and IC. The methodology differs compared to research with toddlers and older children, given infants' lack of ability to follow verbal instructions (for discussion, see, Holmboe et al., 2008). To overcome this, infancy researchers have devised methods for encouraging infants to make responses requiring WM and IC by using attractive stimuli and rewards instead of instructions. Some of these infant paradigms have been extensively validated, e.g., linked to brain areas and neurophysiology involved in EF performance later in development (reviewed below). However, it should be noted that whether the nature of these infant EF marker tasks maps neatly onto what we think of as EFs later in childhood and in adulthood, remains to be established.

There is general consensus in the field that EFs are present in some form in infancy

(Diamond, 2002; Garon et al., 2008; Hendry et al., 2016). The prefrontal cortex (PFC), one of

the core brain areas associated with EFs (for review, see Diamond, 2002; Friedman &

Miyake, 2017), is functionally active from at least the second half of the first year of life, and

infants' performance on tasks thought to tap into EFs and related abilities has been

demonstrated to rely on PFC integrity and functioning using a range of methods (Baird et al.,

2002; Cuevas, Swingler, Bell, Marcovitch, & Calkins, 2012; Diamond & Goldman-Rakic,

1989; Holmboe et al., 2010; Werchan, Collins, Frank, & Amso, 2016). Furthermore, more

tasks are now available to assess EFs at the end of the first year of life (Diamond, 1985;

Holmboe et al., 2008; Johansson et al., 2015; Kovács & Mehler, 2009; Wass, Porayska-

Pomsta, & Johnson, 2011), although not all have been validated to the same extent.

At present, it is well established that the basic capacity for inhibitory control (IC) and

working memory (WM) emerges during the second half of the first year of life. Diamond and

others have demonstrated that infants improve on a simple task indexing these functions, the

A-not-B task, between 7 and 12 months of age (Bell & Fox, 1992; Diamond, 1985). In this

task, infants are encouraged to reach to one location (Location A) to retrieve a hidden toy.

After a number of trials at A, the hiding location is switched to a new location, Location B.

Because a delay is typically inserted between the hiding event and the infant's search, the A-

not-B task is thought to have a WM component. The task is also thought to involve IC, as the

prepotent response built up over the A-trials has to be inhibited in order to produce a

successful reach on the B-trial. Performance on the task has been linked to the integrity and

functioning of the PFC in animal and neuroimaging work (Baird et al., 2002; Cuevas et al.,

2012; Diamond & Goldman-Rakic, 1989; Diamond, Zola-Morgan, & Squire, 1989).

Another task, the Freeze-Frame task (Holmboe et al., 2008), has focused more specifically on the development of IC. The task has little WM requirement and can therefore be thought of as a purer measure of IC. In the Freeze-Frame task, infants have to inhibit looking at peripherally presented distractors in order to maintain focus on a more interesting central stimulus. Previous work has established that performance on the Freeze-Frame task is significantly correlated with A-not-B performance at 9 months of age, suggesting that both tasks tap into IC (Holmboe et al., 2008). Furthermore, polymorphic variation in dopamine genes that play a role directly in the brain's EF network has been shown to have an impact on infants' performance on the Freeze-Frame task. Infants carrying a genetic variation associated with more efficient processing in the PFC had a higher level of inhibitory control (Holmboe et al., 2010).

A third line of research that is relevant to understanding emerging EFs during infancy comes from a different tradition, which focuses on the development of attention. Paralleling the findings from studies on emerging WM and IC, this research has suggested the emergence of *endogenous attention* around 8-12 months of age (Colombo, 2001; Colombo & Cheatham, 2006; Courage, Reynolds, & Richards, 2006; Kannass, Oakes, & Shaddy, 2006; Oakes, Kannass, & Shaddy, 2002). Both Colombo and Cheatham (2006) and Richards and colleagues (Courage et al., 2006; Richards, 2010) have noted that across early infancy (0-6 months) there is a decrease in looking time to visual stimuli with age, most likely due to increases in processing speed and improved ability to disengage attention. During the second half of the first year of life, the trend reverses and infants start to look longer at stimuli presented to them, especially if these stimuli are more complex or novel (Colombo & Cheatham, 2006; Courage et al., 2006; Richards, 2010; see also Oakes et al., 2002). This is likely due to infants starting to gain more control over their attention, directing it toward and focusing it on objects in the visual field that they find more engaging.

Supporting the claim that a key development in attention takes place around 9 months of age, Kannass and colleagues (2006) found that differences in focused attention and distractibility become *predictive* of attentional control later in childhood (at 33 months) from 9 months of age (but not from 7 months of age). Similar findings come from Kochanska, Murray and Harlan (2000) and Johansson et al. (2015). Kochanska et al. (2000) found that focused attention at 9 months predicted effortful control (a behavioral construct related to EFs) at 22 months, and Johansson et al. (2015) found that a global index of sustained attention during play at 12 months was predictive of both effortful control and EFs at 24 months. Finally, Papageorgiou et al. (2014) found that the mean duration of fixations during an eye-tracking task at approximately 8 months (range 4-10 months) was positively related to effortful control in childhood.

The fact that a key development in infants' control of attention coincides with rapid improvements in WM and IC around 9 months of age supports the view that these constructs are highly overlapping in infancy and early childhood, a view that has been put forward by several researchers in the field (Colombo & Cheatham, 2006; Diamond, 2002; Ruff & Rothbart, 1996). In particular, there seems to be general agreement that the ability to focus attention is partly dependent on the ability to exert inhibitory control (Diamond, 2013; Fisher & Kloos, 2016; Oakes et al., 2002; Ruff & Rothbart, 1996).

Despite converging evidence that a key development in controlled attention, WM and IC takes place towards the end of the first year of life, questions remain as to whether these functions exist earlier in infancy. Few studies to date have found support for WM and IC earlier than 8-9 months of age. In the present study, we investigated this question, focusing on the domain of inhibitory control (IC). We chose IC because (1) it is a core aspect of executive functioning in most models, and considered the most fundamental in some (e.g.,

Miyake & Friedman, 2012), and (2) because two well-established tasks suitable for infants are available within this particular domain.

Specifically, we administered a simple IC task, the Freeze-Frame task (Holmboe et al., 2008), at both 6 and 9 months of age, and used an additional IC task, the A-not-B task, at 9 months to look at the stability and coherence of IC from 6 months onwards. Although a factor analysis was not possible, the use of two IC tasks allowed us to evaluate whether findings would generalize across different task designs (a visual task and a manual task). Such generalization would strengthen the argument that effects found were not specific to a single marker task, but to development of and individual differences in IC from the middle of the first year. We also administered the Mullen Scales of Early Learning (MSEL-AGS) at 9 months (Mullen, 1995). This allowed us to control for the effect of general cognitive development on IC functioning, a potentially important confound.

In addition to investigating the possible earlier emergence and stability of IC, we were interested in the question of whether more basic attentional functions in early infancy might form the 'building blocks' of the capacity for IC later during the first year of life. A similar idea has recently been put forward by several researchers in the field, but their hypothesis relates primarily to attention in *late* infancy in relation to toddler and early childhood EFs – there is good evidence for such a link (Garon et al., 2008; Hendry et al., 2016; Johansson et al., 2015). In contrast, little evidence exists so far for a predictive effect of attention in *early* infancy on components of EFs at the end of the first year. The current study sought to address this hypothesis by administering two basic attention tasks at 4 months of age, the Gap-Overlap task (Hood & Atkinson, 1993) and the Visual Expectation Paradigm (here referred to as the Anticipation task) (Canfield, Smith, Brezsnyak, & Snow, 1997; Haith, Hazan, & Goodman, 1988), and relating performance on these two tasks to IC at 6 and 9 months of age.

The Gap-Overlap task provides an index of visual disengagement ability (the ability to move attention from one object to another) across a wide developmental range (Csibra, Johnson, & Tucker, 1997; Csibra, Tucker, & Johnson, 1998; Hood & Atkinson, 1993; Matsuzawa & Shimojo, 1997; Nakagawa & Sukigara, 2013). Being able to flexibly disengage attention can be thought of as a key precursor to, or at least a prerequisite for, more controlled forms of attention and IC. Without such flexibility, it would be hard for the infant to attend to the most relevant and interesting aspects of the environment and to act on these experiences. As an example, imagine that an infant would like to stop being distracted by a salient, but fundamentally uninteresting, visual stimulus, in order to attend to a more interesting object or event. In order to do this, he or she needs to inhibit or ignore the distractor, but in order to inhibit the distractor, he or she also needs to have developed the ability to move his or her gaze with ease and flexibility.

The Anticipation task measures the infant's ability to anticipate visual events in a predictable sequence (Haith et al., 1988). Whereas the Gap-Overlap task is primarily a reactive attention task, the Anticipation task likely requires more endogenous control of attention, because the infant has to move his or her attention in anticipation of a stimulus (but in the absence of any direct visual stimulation). Consistent with this, Jacobson et al. (1992) found that 6.5-month-old infants who anticipated more in the Anticipation task demonstrated more sustained attention during play at 12 months. Furthermore, using a different paradigm with an anticipatory component, Colombo and Richman (2002) found that 4-month-old infants with high levels of sustained attention showed a stronger physiological response (heart rate deceleration) in anticipation of an expected event. Overall, anticipation ability seems closely related to Colombo and Cheatham's (2006) description of endogenous attention as it is expressed later in the first year, and, although assessed earlier here, it could form the foundation for an emerging capacity for basic inhibitory control. As an example, an infant

who is able to expect and respond to predictable events from an early age, may develop a stronger ability to ignore distraction and focus on the most relevant aspects of the environment. We therefore hypothesized that the ability to actively (i.e., endogenously) move attention in expectation of an interesting event would form a precursor for IC later in the first year.

In summary, the present study employed a longitudinal design to investigate whether performance at 4 months on two basic infant attention tasks predicted IC performance later in infancy (Hypothesis A). Despite an expected association between the two attention tasks administered at 4 months (due to overlapping mechanisms involved in eye movement control), we predicted unique effects on later IC from these two tasks, as one task (the Gap-Overlap task) primarily indexes externally driven attentional flexibility, and the other task (the Anticipation task) primarily indexes internally driven endogenous attention. The study also investigated whether stable individual differences in IC emerge earlier than 9 months of age (Hypothesis B). We had five specific predictions with two of these (predictions 2 and 5) relating to the main hypotheses of the study:

Prediction 1: Given that both tasks rely on the control of eye movements, performance on the Gap-Overlap task will be associated with performance on the Anticipation task at 4 months of age.

Prediction 2: Disengagement ability, as assessed by Gap-Overlap performance, and endogenous attention, as assessed by Anticipation performance, at 4 months, will predict Freeze-Frame performance (IC) at 6 months of age. Each attention measure will be a unique predictor of IC at 6 months.

Prediction 3: As found previously by Holmboe et al. (2008), two measures of IC, the Freeze-Frame task and the A-not-B task, will be significantly related at 9 months. Given the

small sample size ($N = 24$) of the original study, a replication in a larger sample is

necessary to reach firm conclusions about IC at 9 months.

Prediction 4: The association between the Freeze-Frame and A-not-B tasks at 9 months will

not be fully accounted for by individual differences in general cognitive development

(performance on the MSEL-AGS).

Prediction 5: Performance on the Freeze-Frame task at 6 months will predict performance on

the Freeze-Frame and A-not-B tasks at 9 months.

These predictions were tested using path analysis within a structural equation modelling

(SEM) framework (Kline, 2016). SEM allowed us to test the predicted concurrent and

longitudinal associations between attention at 4 months, IC at 6 months and 9 months, and

general cognitive development at 9 months.

Method

Participants

Participants were 104 infants (51 boys and 53 girls) recruited from the Greater London area.

To be eligible for the study, infants had to be either full-term (gestation 36 to 42 weeks) or

weigh at least 5 lb (2270 g) at birth, with no major birth complications or health issues.

Approximately three quarters of the sample was of White ethnic background (74%), 20.2%

were of Mixed, 2.9% were of Black and 2.9% were of Asian ethnic origin. Parents were in

their mid-thirties (mothers: M (SD) = 34.4 (5.23) years; fathers: M (SD) = 36.4 (6.52) years).

Families were predominantly of high socio-economic status. This was evidenced by above

average parental education: mothers: M (SD) = 17.9 (3.54) years; fathers: M (SD) = 17.4

(3.41) years. In the current sample, 62.4% of parents had at least 16 years of education

(roughly equivalent to the attainment of a Bachelor's degree) compared to 31% of the general

adult population in London at the time (National Statistics, 2001).

Study overview

Families who had signed up to the lab's volunteer database were contacted and asked if they

were interested in participating in the study. Families who agreed to take part visited the lab

when infants were 4, 6 and 9 months old. Each visit was scheduled within 1 week of the

infant's ideal age for that testing point. At the 4-month visit, infants completed two

behavioral tasks: the Gap-Overlap task (Hood & Atkinson, 1993) and the Anticipation task

(Haith et al., 1988). At 6 months infants completed a simplified version of the Freeze-Frame

task (Holmboe et al., 2008). At 9 months infants completed the full version of the Freeze-

Frame task, the A-not-B task (Diamond, 1985) and Mullen Scales of Early Learning (Mullen,

1995). Parents also completed questionnaires on infant temperament at the 4- and 9-month

visits; these data have been reported previously (Holmboe, Nemoda, Fearon, Sasvari-

Szekely, & Johnson, 2011) and do not form part of the current report. A buccal swab was

collected at 4 months for analysis of genetic polymorphism data; these data have also been

reported previously (Holmboe et al., 2010; Holmboe et al., 2011). The current report focuses

on the behavioral task data collected in this longitudinal cohort at 4, 6 and 9 months of age

and the relations between these variables across age. These results have not been reported

previously. Video clips illustrating the stimuli and infant behavior in each experimental task

can be found in the supplementary materials (Videos S1-S4).

Ethical approval for the study was granted by the Department of Psychological Sciences'

ethics committee at Birkbeck, University of London (ref. no. 2248). The following sections

provide details on the testing protocol at each age. First, the 4-month protocol is described,

followed by the 9-month protocol. The description of the 6-month protocol is provided last

because it involves a simpler version of the original Freeze-Frame task that was used at 9

months. The 6-month Freeze-Frame procedure will therefore be easier to follow after reading

the 9-month Freeze-Frame procedure.

4-month test session

At 4 months, infants were first tested on the Gap-Overlap task and subsequently on the

Anticipation task. The tasks were run on a PC using E-Prime software. The parameters for

the Gap-Overlap task were based on Hood and Atkinson (1993) and Csibra et al. (1998). The

parameters for the Anticipation task were based on Haith et al. (1988) and Csibra et al.

(2001).

The Gap-Overlap task

Apparatus and stimuli. Stimuli were presented on a 51 × 67 cm plasma screen positioned 1 m

from where the parent and infant sat. The stimuli consisted of 14.71 × 14.71 cm colored

squares, subtending 8.41° × 8.41° of visual angle. The stimulus squares were presented on a

black background. The distance between the center of the screen and the nearest edge of the

target square was 21.65 cm (12.30° of eccentricity). Each square was composed of four

colored triangles with the apex pointing towards the center of the square. Adjacent triangles

were of high contrast. On each trial, a new square containing a different set of colored

triangles was presented. The triangles inside the square rotated in a clockwise or anti-

clockwise direction (pseudo-randomized across trials), shifting position every 300 ms. This

gave the square an animated appearance, with the triangles rotating inside the square. A video

of the infant's face with the stimuli superimposed in the top-right corner was recorded for

offline coding. Brief attractor sounds were used to regain or maintain the infant's attention.

An example of the stimulus presentation can be seen in the top-right corner of Video S1.

Procedure. Infants sat in their parent's lap. Parents were asked to close their eyes during testing in order to avoid movement cues. The experimenter controlled the experiment from behind a gray screen. Each trial started with the colorful, animated square being presented in the center of the screen. As soon as the infant fixated the central stimulus, the experimenter presented an identical target on the left or right side of the screen. In the Overlap condition, the central stimulus stayed on while the target was presented for 3 s, which allowed the infant enough time to reorient to the target. In the Gap condition, the central stimulus disappeared, leaving the screen blank for 200 ms, before the target appeared (again for 3 s). When the target appeared in the Gap condition, the triangle rotation had moved to the next position in order to keep the rotation continuous. A short gap of 200 ms was used because this gap duration has been shown to be effective for eliciting the Gap-Overlap effect, i.e., a difference in saccadic reaction time (SRT) between the two conditions (Csibra et al., 1998; Hood & Atkinson, 1993). At longer gap durations, more incorrect refixations (saccades to other locations than the target) and slightly increased SRTs have been found (Hood & Atkinson, 1993; Matsuzawa & Shimojo, 1997), resulting in a reduced Gap-Overlap effect.

Forty-eight trials were presented in a pseudo-random sequence. The sequence was created in such a way that no more than two consecutive trials presented the same condition (Gap or Overlap), side of target (right or left) or rotation direction inside the square (clockwise or anti-clockwise). Extra trials were run by restarting the experiment if the infant looked away from the screen on a large proportion of trials during the session. Video S1 shows a 4-month-old infant performing the Gap-Overlap task.

Video coding. Trial validity and saccadic latencies were coded offline on a frame-by-frame basis (the smallest unit was 1 half-frame, equivalent to 20 ms). SRT was coded as the time between target onset and the first visible eye movement towards the target. If the infant did

not look at the central stimulus during the last 200 ms preceding target presentation, the trial

was considered invalid. Saccades that had a latency of 120 ms or less were considered

anticipatory (Csibra et al., 2001) and were also excluded from the analyses (this was rare in

the Gap-Overlap task). In addition, the trial was considered invalid if the infant looked from

the central stimulus to some other location than the target, or if the infant's eyes were out of

view during target presentation. Trials where infants remained fixated on the central stimulus

throughout target presentation were very rare (0.6% of all trials), and were excluded from

subsequent SRT analyses. Inter-coder reliability for trial validity was good ($\kappa = .78$, based on

all trials, $N = 240$, from 5 participants), and the correlation between SRTs for trials coded as

valid by both coders was very high ($r = .987$, $p < .001$). When the validity coding was

inconsistent between coders, the final coding of the trial was determined by the first author.

Individual performance measure. In order to calculate an index of each infant's

disengagement ability, the median SRT for the Overlap condition was divided by the median

SRT for the Gap condition. The two medians were divided, not subtracted, in order to cancel

out as much as possible of the overall effect of the infant's baseline saccadic reaction time.

The higher a score was above 1, the poorer the disengagement ability, i.e., the slower the

infant was on Overlap trials compared to Gap trials.

The Anticipation task

Apparatus and stimuli. The general setup was the same as for the Gap-Overlap task. Stimuli

consisted of animated cartoons presented sequentially in two 27.39 × 26.53 cm black squares

positioned on each side of the screen. Each black square subtended 15.60° × 15.11° of visual

angle. The distance between the two black squares was 13.95 cm (7.98° of visual angle). The

black squares were positioned at an equal distance from the top and bottom of the screen and

were presented on a gray background. An example of the stimulus presentation can be seen in

the top-right corner of Video S2.

Procedure. In a similar fashion to Haith et al. (1988), the experiment consisted of stimuli presented alternating between the left and right side of the screen. The stimuli were brief animated cartoons. Each switch in side constituted a new trial, with a new animation being used on each trial. At the beginning of the experiment, the first frame of the first animation blinked at a rate of 200 ms in the stimulus location on the right. As soon as the infant looked at this location, the experimenter pressed a key to start the animation. Each animation was presented for 1200 ms at a frame rate of 100 ms (i.e., 12 frames per animation). This is slightly longer than Haith et al. (1988) because piloting indicated that the animations would otherwise be too brief for the infants to find them engaging. Each animation was followed by an inter-stimulus interval of 800 ms where no animations were present in the two target locations. This inter-stimulus interval was based on Csibra et al. (2001), who found that this interval was optimal for 4-month-old infants. Each animation was accompanied by a varying, pleasant sound. These sounds were always presented in synchrony with the onset of a new animation. The experimenter could also attract the infant's attention by pulling a string attached to a small bell positioned behind the stimulus monitor. A session consisted of 60 trials. Video S2 shows a 4-month-old infant performing the Anticipation task.

Coding. Trial validity and saccadic latencies were coded offline using the same setup as described for the Gap-Overlap task. Trials were only considered valid if the infant looked from the previous target location to the new target location, but the trial was still coded as valid if the infant moved his or her eyes to the new target location in several smaller saccades (this looking pattern was common). SRT was coded as the time between the first frame of the target (target onset) and the first visible eye movement towards the new target. Negative SRTs indicated anticipatory eye movements. Inter-coder reliability for trial validity was

acceptable ($\kappa = .69$, based on all trials, $N = 540$, from 5 participants). The correlation between SRTs for trials coded as valid by both coders was high ($r = .830$, $p < .001$). When the validity coding was inconsistent between coders, the final coding of the trial was determined by the first author.

Individual performance measure. SRTs from all valid trials were categorized as either reactive or anticipatory. In accordance with previous research (Canfield et al., 1997; Csibra et al., 2001), a conservative cut-point for anticipatory saccades was adopted: SRT $\leq$ 120 ms (including negative SRTs). This was based on evidence that 120 ms is the limit for how fast infants can respond to the presentation of a visual stimulus (Canfield et al., 1997). The remaining saccades were considered reactive. Anticipation performance was calculated as number of anticipatory trials divided by number of valid trials. Because the number of anticipatory saccades was positively correlated with the number of valid trials ($N = 103$, $r = .295$, $p = .003$), variance in the number of valid trials was partialled out of the anticipation measure used in the final analyses.

9-month test session

At the 9-month test session, infants were first tested on the Freeze-Frame task (Holmboe et al., 2008), followed by the A-not-B task (Diamond, 1985). After the two experimental tasks, the Mullen Scales of Early Learning were administered (Mullen, 1995).

The Freeze-Frame task

The version of the Freeze-Frame task presented at 9 months of age has been published previously (Holmboe et al., 2008; Holmboe et al., 2010). Further details can be found in these papers. The following is a brief summary of the task.

Procedure. Infants sat in their parent's lap while watching stimuli on a 19-in (48.3-cm)

monitor. Attractor sounds were used to regain and maintain infants' attention to the screen during the task. The aim was for infants to complete at least 80 trials, but the session was stopped if an infant became fussy. On each trial, the infant was presented with an animated cartoon in the center of the screen, subtending between 2.1° and 5.1° in height, and between 1.2° and 4.9° in width. Once the infant looked at the central animation, a white distractor square was presented either on the right or the left side of the screen. The distractor subtended 3.2° of visual angle at 13.5° eccentricity from the center. The central animation was frozen during distractor presentation and for 600 ms after the distractor. If the infant made a saccade towards the distractor stimulus, the experimenter froze the animation for a further 2400 ms to discourage the infant from looking to the distractors (i.e., to encourage inhibitory control). On even numbered trials, the infant was presented with constantly changing and colorful cartoon animations (interesting trials), and on odd numbered trials, the infant was presented with a rotating orange star animation (boring trials). Video S3 shows a 9-month-old infant performing the Freeze-Frame task.

The beginning of the experiment was used as a calibration phase. During calibration, the distractor duration was increased in 40-ms steps until distractors reliably elicited saccades from the infant. The initial distractor duration was 200 ms. Distractor duration was fixed once the infant reached the calibration criterion: looking to the distractor on two consecutive trials. If the infant did not reach the calibration criterion, distractor duration was fixed once it reached 1200 ms.

Coding. Video recordings of each infant's looking behavior were coded offline. A trial was considered invalid if the infant was not looking at the central stimulus at distractor onset. The trial was also considered invalid if the infant blinked (i.e., the pupils were fully covered) during distractor presentation. In addition, the trial was considered invalid if these behaviors

occurred during the 1000 ms following distractor presentation. On rare occasions, a trial was excluded because the infant's eyes were out of view; such trials were considered invalid if the eyes were out of view for more than 2 frames (80 ms) during distractor presentation or within the 1000 ms following distractor presentation. Finally, trials where a saccade to the distractor was initiated earlier than 3 frames (120 ms) after distractor onset were also considered invalid (see above). Inter-coder reliability was good for both looking behavior (i.e., look or no look to distractor, $\kappa = .94$) and validity ($\kappa = .86$), based on all trials from 10 participants ($N = 750$ trials).

Individual performance measure. Based on findings from previous research (Holmboe et al., 2010), and in order to match the Freeze-Frame data collected at 6 months (see below), the proportion of looks to the distractor in interesting trials across the whole experiment was used to index inhibitory performance (calculated for all interesting trials from two trials prior to the calibration trial). A lower proportion of looks to the distractors in interesting trials was considered to indicate higher IC.

The A-not-B task

The setup and procedure was identical to the setup and procedure used by Holmboe et al. (2008). The following is a brief summary of the protocol.

Apparatus and stimuli. Infants sat in their parent's lap in front of a table containing two wells. The wells were 11.2 cm in diameter and positioned 18 cm apart. The distance between each well and the edge of table closest to the infant was 18.5 cm. The experimenter was seated across the table, facing the child. A collection of small toys was available for the hiding events. Two brown cardboard squares were used as covers for the wells. The infant's behavior was video-recorded. A second experimenter hid behind a divider in the room, from where she monitored the infant's performance and indicated the next hiding location to the

first experimenter via a computer monitor placed behind the infant and parent.

Procedure. A trial began with the experimenter drawing the infant's attention to a toy. When the infant was focused on the toy, the experimenter put the toy into one of the wells and covered the wells simultaneously. The initial hiding location was counterbalanced across participants. A trial was only considered valid if the infant saw the toy being hidden in the well and if the toy was completely hidden in the well (if this was not the case, the trial was re-administered). When the wells had been covered, the delay period started. During the delay period, infants were distracted to prevent them from looking at the correct well. The distraction consisted of the experimenter talking in an exaggerated voice, saying the infant's name, waving, etc. Furthermore, parents were asked to hold their infants back during the delay to prevent premature reaching. At the end of the delay period, the experimenter said, "Okay", and this was the signal to the parent to let the infant reach.

The initial delay was set to 2 s and adjusted depending on the infant's performance. At the 0 s delay, infants were allowed to reach immediately without any attempt to distract them. If the infant reached to the correct well, he or she was praised and allowed to play with the toy briefly as a reward. If the infant reached to the incorrect well, the experimenter drew the infant's attention to the toy in the correct well and started a new trial without letting the infant touch the toy. If the infant reached to both wells simultaneously, did not reach at all, or if it was otherwise difficult to establish whether the response was correct, the trial was repeated. The experimenter continued to hide the toy in the same well until the infant reached to the correct well on two consecutive trials. At this point, the toy was hidden in the other well (change trial), and then was repeatedly hidden in that well until the infant had completed another two successful trials consecutively. If two consecutive trials ended in failure, the delay period was decreased by 2 s. If two consecutive change trials ended in success, the

delay period was increased by 1 s. Infants were encouraged to complete 40 A-not-B trials.

Video S4 shows a 9-month-old infant performing the A-not-B task.

Performance measure. A previous study indicated that the maximum delay that infants could

sustain on change trials as recorded by the computer (controlled by the second experimenter

during testing) was highly correlated with a detailed cumulative index coded offline after

testing ($r = .933$, $p < .001$; Holmboe et al., 2008). It was therefore decided to use the

computer recorded maximum delay on change trials as the individual performance measure

in the current study. A higher delay indicates higher WM and IC. Infants had to complete a

minimum of 10 trials to be included in the analyses (97% inclusion). Infants who did not pass

any change trials, including trials with no delay ($n = 2$ infants), were excluded from the

analyses.

The Mullen Scales of Early Learning, AGS Edition

The Mullen Scales of Early Learning, AGS Edition (MSEL-AGS), is an individually

administered test battery developed to assess motor and cognitive abilities in infants and

young children. The MSEL-AGS consists of five scales: Gross Motor, Visual Reception, Fine

Motor, Receptive Language, and Expressive Language. The latter four scales are defined as

cognitive scales. A measure combining the standardized scores from these four scales, and

referred to as the Early Learning Composite, is considered a measure of general cognitive

development. Details on the standardization and psychometric properties of the MSEL-AGS

can be found in the manual (Mullen, 1995).

6-month test session

At 6 months, infants performed a single IC task. The task was a simplified version of the

Freeze-Frame task, which has previously only been used with older infants. Infants

performed the task while EEG (electroencephalogram) data were recorded from the scalp for the purpose of event-related potentials (ERP) analysis. The ERP data is the topic of a separate report. Most aspects of the 6-month version of the Freeze-Frame task were identical to the original 9-month version, including trial timings and the calibration procedure. These details can be found above, under the description of the 9-month version of the task. The 6-month and 9-month versions of the Freeze-Frame task differed in the following ways: (1) The 6-month version only had interesting trials. This decision was made to reduce the number of conditions for the ERP analysis. (2) In the 6-month version, the central animation was not frozen for an additional 2400 ms if infants looked to a distractor, the animation simply froze on all trials during distractor presentation and for the 600 ms after distractor presentation (regardless of the infant's looking behavior). This modification was made to be able to administer trials faster, which again was important for the ERP data collection. Infants should still be motivated to remain focused on the more engaging central stimulus compared to the relatively boring distractor. (3) A different set of interesting animations was used in the 6-month and 9-month versions in this study in order to avoid familiarity effects. Previously reported data have indicated that the specific set of animations used in the Freeze-Frame task does not significantly change the results (Holmboe et al., 2010). (4) The task was continued for as long as possible to obtain as many trials as possible for the ERP analysis, however, only 80 trials were included in the behavioral analysis reported here. The number of trials was limited to 80 in order to make the Freeze-Frame measure at 6 months comparable to the Freeze-Frame measure at 9 months.

Coding. The coding procedure was identical to the procedure used for data collected at 9 months. Inter-coder reliability was excellent for both looking behavior ($\kappa = .97$) and validity ($\kappa = .92$), based all trials from 5 participants ($N = 526$ trials).

Individual performance measure. Based on findings from previous research (Holmboe et al., 2010), the proportion of looks to the distractor in interesting trials (i.e., all 80 trials at this age) across the whole experiment was used to index inhibitory performance. A lower proportion of looks to the distractors in interesting trials was considered to indicate higher IC.

SEM analyses

The final data set, including individual performance indices from 4, 6 and 9 months, was analyzed using structural equation modelling (SEM). Goodness-of-fit of a model with predictive relationships between attention at 4 months and IC at 6 months (Hypothesis A), and between IC at 6 months and IC at 9 months (Hypothesis B), was evaluated against the thresholds recommended by Hooper, Coughlan and Mullen (2008) and Morin, Marsh and Nagengast (2013). The fit was considered excellent if the comparative fit index (CFI) and the Tucker Lewis index (TLI) > .95 and the root mean square error of approximation (RMSEA) < .07. In addition, for adequate model fit, the Chi-square (χ^2) test was expected to be non-significant (p > .05). All analyses were performed using Mplus version 7.4 (Muthén & Muthén, 2015). The estimation method was maximum likelihood estimation with robust standard errors (MLR), although we also ran the analysis using Bayesian estimation (see Results below). Data from all 104 infants were included in the model; missing data were accounted for using full information maximum likelihood (FIML). A two-tailed alpha level of p < .05 was used to assess significance of the paths in the model.

Results

Descriptive statistics and replication of previously reported group-level effects

Table 1 presents means and standard deviations for each performance measure, as well as

details on replication of previous effects in the literature. These group-level effects are not the

topic of this paper, which focuses on the development of individual differences, but a few

points deserve mention. The Gap-Overlap effect (Hood & Atkinson, 1993) was replicated: as

expected, infants took significantly longer to disengage from the central stimulus in the

Overlap condition compared to the Gap condition. Infants also showed clear signs of

anticipation ability at 4 months, making anticipatory eye movements on approximately a

quarter of all trials (26%) in the Anticipation task (consistent with Canfield, Wilken,

Schmerl, & Smith, 1995; and Haith et al., 1988; 27% and 22%, respectively). The main

Freeze-Frame effect originally reported by Holmboe et al. (2008), i.e., a lower rate of looking

to the distractors in the interesting trials compared to the boring trials, was also replicated. It

is worth noting that the proportion of looks to the distractors in the interesting trials at 9

months was about half (22%) of that seen at 6 months (43%). Although the two versions were

not identical (the 6-month version included only interesting trials and no additional freezing),

and are therefore not directly comparable, this suggests that infants have better IC during the

latter half of the first year, consistent with previous evidence (Bell & Fox, 1992; Colombo &

Cheatham, 2006; Diamond, 1985; Oakes et al., 2002).

Overall, these group-level results indicate that the tasks chosen for the study worked as

intended, measuring the effects we were interested in.

[INSERT TABLE 1]

Further descriptive statistics can be found in the supplementary materials to this article.

Supplementary Table 1 provides information on the number of trials and the number of valid

trials completed in each of the experimental tasks and in each condition within tasks.

Supplementary Table 2 provides data on the covariance coverage, i.e., the percentage of data

available within and across the variables used in the path analysis. Supplementary Table 3

provides further descriptive statistics for these same variables, including the median, range,

skewness and kurtosis. Finally, Supplementary Table 4 provides individual means and

standard deviations for saccadic reaction times in both conditions of the Gap-Overlap task

(these data have been fully anonymized).

Missing data

The path model assumed that any missing data were missing at random. To test this

assumption, we carried out analyses investigating whether there were (1) any systematic

patterns in which variables had data missing, (2) whether there were sex-differences in data

missingness, (3) whether individual differences in willingness to be tested had an effect on

missingness (this was based on whether infants were willing to participate in the EEG study

at 6 months, as this assessment had the highest attrition rate), and (4) whether maternal level

of education (as a proxy for SES) had an influence on data missingness. None of these

analyses indicated significant effects of demographic or other variables on data missingness

or outcomes, and, although it is not possible to exclude bias completely, we therefore

conclude that data were missing at random. Full details on the missingness analyses can be

found in Supplementary Information.

Zero-order correlations

Table 2 presents the zero-order correlations between all variables in the path analysis. It is

clear from the table that measures at 6 and 9 months were more strongly correlated, both

within age (at 9 months) and longitudinally, than measures taken at 4 months. The pattern of correlations therefore broadly suggested significant associations between IC measures at 6 and 9 months (Hypothesis B), with some influence of general development as well. However, the zero-order correlations provided limited support for the idea that the basic attention measures at 4 months were predictive of later IC (Hypothesis A).

[INSERT TABLE 2]

SEM results

The model was specified according to the predictions outlined in the Introduction. The model had an excellent fit, $\chi^2(6) = 6.25$, $p = .40$; RMSEA = .02 (CI: .00-.13); CFI = .99; TLI = .98. Figure 1 presents a diagram of the model.

[INSERT FIG 1]

As can be seen from Figure 1, Prediction 2 was not confirmed. Performance on the two basic attention tasks (Gap-Overlap and Anticipation) at 4 months was not predictive of IC at 6 months. Predictions 1, 3 and 4 were fully confirmed. At 4 months, there was a significant association between the two basic attention tasks: infants who were slower at disengaging in the Gap-Overlap task anticipated less in the Anticipation task (Prediction 1). We also replicated a significant association between performance on the Freeze-Frame task and the A-not-B task at 9 months (Prediction 3). The association between the Freeze-Frame task and the A-not-B task remained significant even when accounting for the association between A-not-B performance and general cognitive development in the model (Prediction 4).

Prediction 5 was partially confirmed. Freeze-Frame performance at 6 months significantly predicted Freeze-Frame performance at 9 months, demonstrating longitudinal stability in this IC measure between the two ages. The path between Freeze-Frame performance at 6 months

and A-not-B performance at 9 months was marginal ($p = .09$), suggesting a longitudinal trend

in the same direction as the within-age relationship between the two tasks at 9 months.

To ensure that the estimation method did not bias the results, we re-ran the analysis using

Bayesian estimation. Model estimates from this analysis are presented in Supplementary

Table 5. Although the estimates varied slightly in magnitude compared to the original

estimation, no paths that were non-significant in the model estimated with MLR became

significant in the Bayesian model. Likewise, all significant and marginally significant paths

in the MLR model remained significant or marginal in the Bayesian model.

Finally, we also tested an alternative model that included performance in the boring Freeze-

Frame trials at 9 months. Proportion of looks to the distractor in the boring trials could

potentially be an index of more basic attentional orienting at this later age, and it seemed

worthwhile to test whether this index had an impact on IC at 9 months. However, the

alternative model had a poorer fit to the data than the original model, and there was no

indication that performance on the boring Freeze-Frame trials was associated with indices of

IC at 9 months (ps > .2). The original model was therefore retained.

Discussion

The current study set out to investigate whether basic attentional abilities in early infancy

form the building blocks for IC towards the end of the first year of life (Hypothesis A), and

whether IC shows stability earlier in infancy than previously demonstrated (Hypothesis B).

We found good evidence for Hypothesis B, and most of the five specific predictions we made

(each equivalent to a path in the model in Fig. 1), but little evidence for Hypothesis A. In the

following, we discuss these findings, starting with the lack of support for the 'building block'

hypothesis, and then moving on to the finding of emerging stability in IC from 6 months.

There was a significant, although modest (β = -.201), association between the two basic

attention tasks at 4 months (Prediction 1), indicating modest overlap in function. However,

performance on these two tasks did not predict inhibitory performance (Prediction 2); that is,

neither disengagement ability nor early endogenous attention predicted IC later during the

first year. There are several possible explanations for this negative finding. It is of course

possible that disengagement and anticipation abilities are not precursors for IC. In looking for

'building blocks', we may simply have chosen the wrong measures. Although we have

provided justification for the potential mechanisms linking these two early attention indices

to later IC, it is possible that other basic functions, not investigated here, form stronger

precursors.

For example, a reasonable amount of evidence exists linking infants' look duration (typically

to static images), often referred to as habituation, to childhood cognitive functioning. The

general finding from this literature is that shorter look duration in infancy is associated with

better cognitive outcomes later in childhood and even in adolescence (for review, see Kavšek,

2004). This includes significant associations between indices of infants' look duration and

later EFs (Cuevas & Bell, 2014; Sigman, Cohen, & Beckwith, 1997; but see, Rose, Feldman,

& Jankowski, 2012, for a negative finding as regards look duration). It should be noted that

this predictive relationship covers a very broad range of cognitive functions, including

general intelligence, speed of information processing (later in development) and language

and motor skills (e.g., Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; Sigman et al.,

1997), and it is therefore as yet unclear whether any particular aspect of infant looking time

relates specifically to later EFs.

As regards these findings, our study did not specifically investigate the predictive effect of early infancy habituation on IC later during the first year of life. Basic parameters from our 4-month measures that could be considered indices of processing speed (e.g., Canfield et al., 1995; Dougherty & Haith, 1997), such as median SRT in the Gap condition of the Gap-Overlap task and in non-anticipatory trials in the Anticipation task, did not predict later IC (all $ps > .10$). It is, however, a possibility that the predictive effect of early infancy processing speed, as well as possibly of the basic attentional mechanisms studied here, on IC and other EFs kick in later in development (e.g., Cuevas & Bell, 2014).

An alternative explanation for the lack of longitudinal prediction between 4-month attention measures and later IC could be that 4 months is simply too early to assess stable individual differences in attentional abilities. Previous studies have sometimes failed to find longitudinal stability in Gap-Overlap and Anticipation task performance before 6 months of age, although this has typically been in much smaller samples (Butcher, Kalverboer, & Geuze, 2000; Canfield et al., 1997; Canfield et al., 1995; Ns between 13 and 24). Nevertheless, a longitudinal predictive relationship has been found between infant Anticipation performance at 3.5 months and IQ later in childhood (Dougherty & Haith, 1997), suggesting that meaningful individual variation in attentional abilities can indeed be assessed this early. Furthermore, in the present study, we observed an unexpected significant zero-order correlation ($p < .05$) between Gap-Overlap performance at 4 months and general cognitive development (MSEL-AGS performance) at 9 months. These findings seem to go counter to measurement reliability being the issue.

A clear limitation of the current study is that attentional abilities were only assessed at 4 months of age. Given the extensive development of more controlled endogenous attention during the second half of the first year of life (Colombo, 2001; Colombo & Cheatham, 2006;

Courage et al., 2006; Kannass et al., 2006; Oakes et al., 2002; Richards, 2010), an association between attentional mechanisms and IC may well *emerge* as infants' control over their attention improves across this key developmental period. Future research should therefore investigate the co-development of these two important cognitive functions across the first year.

As regards the emergence of IC from around the middle of the first year, we found good evidence for this hypothesis. Firstly, we solidly replicated the association between the Freeze-Frame task and the A-not-B task at 9 months in a large sample of infants (Prediction 3), originally reported by Holmboe et al. (2008) in a smaller sample. Not only did the association replicate, it was also the strongest path in the model (β = -.331). According to Cohen (1992), effect sizes over .30 constitute a moderate or medium-sized effect, with effects under .10 classified as small and effects over .50 classified as large. Our model controlled for all other associations between variables when estimating each path; therefore, this result indicates that performance on two very different IC tasks was moderately associated at the end of the first year, even when other factors were taken into account and despite the general noisiness of infant data. Replication was important for our hypothesis, as a substantial number of psychology studies have recently failed replication (Open Science Collaboration, 2015), casting doubt on hitherto accepted conclusions. This is a particular issue in infant research, where sample sizes tend to be small (Oakes, 2017). Our replication confirmed that infants who are less distractible on engaging trials in the Freeze-Frame task can sustain longer delays without perseverating in the A-not-B task, implicating inhibitory control as the shared function.

Importantly, and substantially adding to what has previously been demonstrated, our findings also showed that, although there was some association between A-not-B performance and

general cognitive development as assessed by the MSEL-AGS (as would be expected given the complex and interactive nature of the A-not-B task), the relation between the two IC tasks remained moderate and highly significant when controlling for general cognitive development in our model (Prediction 4). This is in agreement with findings from the adult EF literature, showing some overlap between EFs and general intelligence, but also separability, especially as regards IC (Friedman & Miyake, 2017). Importantly, this finding establishes that infants who have strong IC abilities across tasks are not simply more developmentally advanced.

In addition to showing significant and independent association between our two IC measures at 9 months, the current study adds to existing knowledge by demonstrating that some stability in IC exists already from 6 months of age (Prediction 5). Performance on the Freeze-Frame task at 6 months directly and significantly predicted performance on the same task 3 months later. That is, infants who demonstrated higher inhibitory control at 6 months, by looking less to the distractors while engaged, also demonstrated higher inhibitory control at 9 months. The size of this effect was small-to-moderate (β = .287). It was nevertheless the second strongest path in the model, providing significant evidence for longitudinal stability. Given the large developmental changes in attention and IC occurring across this period (6 to 9 months), as highlighted in the literature (Colombo & Cheatham, 2006; Diamond, 1985; Richards, 2010), it is remarkable that individual differences in Freeze-Frame performance at 6 months were already predictive of later performance on the same task.

In contrast, Freeze-Frame performance at 6 months only marginally predicted A-not-B performance at 9 months, and the effect was comparatively small (β = -.195). Clearly, early performance on the Freeze-Frame task was substantially less associated with A-not-B performance than within age at 9 months. Nevertheless, the fact that we saw a predictive

association, albeit weak, in the same direction as found at 9 months suggests at least some emerging longitudinal stability in this cross-task relationship.

Overall, our results suggest that stability in IC is emerging from around 6 months of age. This is encouraging in terms of studying the emergence of individual differences in IC earlier in infancy and its development into the childhood years. This finding also argues against a phase-like shift in IC abilities around 9 months of age, something suggested by the heavy focus on this age in the literature. Although there is significant coherence in IC abilities measured by our two tasks at 9 months, these abilities likely develop gradually from at least the middle of the first year.

It should be noted that we do not know the exact relationship between the IC tasks we have used in this study at 6 and 9 months and more fully fledged, instruction-based, IC tasks for older children. The Freeze-Frame task and the A-not-B task have both been successfully linked to the neural substrates involved in executive functioning at later ages (e.g., Diamond & Goldman-Rakic, 1989; Holmboe et al., 2010), but it remains to be established whether these simple IC tasks predict performance on traditional IC tasks later in childhood. Apart from overcoming the limitation of using single tasks to identify early markers of executive functioning, an important avenue for future research is therefore to establish the exact relation between purported markers of EFs in infancy and well-established EF tasks for toddlers and young children. Longitudinal research spanning the transition between infancy and early childhood is needed to achieve this.

In conclusion, our study did not find that two basic attention measures in early infancy form the building blocks of IC later in the first year. However, we did find that stability in IC starts to emerge from around 6 months, and that IC performance on two established tasks is coherent and relatively independent of general development by 9 months. Strengths of the

study include the relatively large sample size for a longitudinal infant study involving

behavioral tasks, and the use of well-validated paradigms for measuring infant attention and

inhibitory control. The study also had limitations. SEM requires particularly large sample

sizes, and although we were able to successfully specify and test a simple model of the

longitudinal development of attention and IC during the first year of life, a larger sample

would be needed to investigate a more comprehensive and complex model. As more infant

EF tasks become available, a factor analysis would be an ideal avenue for future research,

reducing the reliance on single tasks each with their own idiosyncratic measurement error. It

would also be beneficial in the future to include repeated measures of both attention and IC,

as well as other measures of basic functioning, such as processing speed. The current study

was confined to a relatively high-SES sample, and it did not include measures of social

interaction variables that have recently been shown to have potentially important effects on

sustained attention and related functions in infancy (Yu & Smith, 2016). Finally, as discussed

above, it is a clear limitation that the current study was confined to the first year of life. In

order to establish full stability of EFs across development, a longer-term longitudinal study

would be needed. Nevertheless, the present findings are encouraging in terms of the prospect

of investigating developmental trajectories in executive functioning, in particular inhibitory

control, from an earlier age than previously considered feasible.

References

Baird, A. A., Kagan, J., Gaudette, T., Walz, K. A., Hershlag, N., & Boas, D. A. (2002).
Frontal lobe activation during object permanence: Data from near-infrared
spectroscopy. *Neuroimage, 16*, 120-126. doi:10.1006/nimg.2002.1170

Bell, M. A., & Fox, N. A. (1992). The relations between frontal brain electrical activity and
cognitive development during infancy. *Child Development, 63*, 1142-1163.
doi:10.1111/j.1467-8624.1992.tb01685.x

Butcher, P. R., Kalverboer, A. F., & Geuze, R. H. (2000). Infants' shifts of gaze from a
central to a peripheral stimulus: A longitudinal study of development between 6 and
26 weeks. *Infant Behavior & Development, 23*(1), 3-21. doi:10.1016/S0163-
6383(00)00031-X

Canfield, R. L., Smith, E. G., Brezsnyak, M. P., & Snow, K. L. (1997). Information
processing through the first year of life: A longitudinal study using the visual
expectation paradigm. *Monographs of the Society for Research in Child Development,
62*(2). doi:10.2307/1166196

Canfield, R. L., Wilken, J., Schmerl, L., & Smith, E. G. (1995). Age-related change and
stability of individual differences in infant saccade reaction time. *Infant Behavior &
Development, 18*, 351-358. doi:10.1016/0163-6383(95)90023-3

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*(1), 155-159.

Colombo, J. (2001). The development of visual attention in infancy. *Annual Review of
Psychology, 52*, 337-367. doi:10.1146/annurev.psych.52.1.337

Colombo, J., & Cheatham, C. L. (2006). The emergence and basis of endogenous attention in
infancy and early childhood. In R. Kail (Ed.), *Advances in Child Development and
Behavior* (Vol. 34, pp. 283-322).

Colombo, J., & Richman, W. A. (2002). Infant timekeeping: Attention and temporal

estimation in 4-month-olds. *Psychological Science, 13*(5), 475-479.

doi:10.1111/1467-9280.00484

Colombo, J., Shaddy, D. J., Richman, W. A., Maikranz, J. M., & Blaga, O. M. (2004). The

developmental course of habituation in infancy and preschool outcome. *Infancy, 5*(1),

1-38. doi:10.1207/s15327078in0501_1

Courage, M. L., Reynolds, G. D., & Richards, J. E. (2006). Infants' attention to patterned

stimuli: Developmental change from 3 to 12 months of age. *Child Development,

77*(3), 680-695. doi:10.1111/j.1467-8624.2006.00897.x

Csibra, G., Johnson, M. H., & Tucker, L. A. (1997). Attention and oculomotor control: A

high-density ERP study of the gap effect. *Neuropsychologia, 35*(6), 855-865.

doi:10.1016/S0028-3932(97)00016-X

Csibra, G., Tucker, L. A., & Johnson, M. H. (1998). Neural correlates of saccade planning in

infants: A high-density ERP study. *International Journal of Psychophysiology, 29*,

201-215. doi:10.1016/S0167-8760(98)00016-6

Csibra, G., Tucker, L. A., & Johnson, M. H. (2001). Differential frontal cortex activation

before anticipatory and reactive saccades in infants. *Infancy, 2*(2), 159-174.

doi:10.1207/S15327078IN0202_3

Cuevas, K., & Bell, M. A. (2014). Infant attention and early childhood executive function.

Child Development, 85(2), 397-404. doi:10.1111/cdev.12126

Cuevas, K., Swingler, M. M., Bell, M. A., Marcovitch, S., & Calkins, S. D. (2012). Measures

of frontal functioning and the emergence of inhibitory control processes at 10 months

of age. *Developmental Cognitive Neuroscience, 2*(2), 235-243.

doi:10.1016/j.dcn.2012.01.002

Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by

infants' performance on AB. *Child Development, 56*, 868-883. doi:10.2307/1130099

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young

adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T.

Knight (Eds.), *Principles of Frontal Lobe Function*. Oxford: Oxford University Press.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135-168.

doi:10.1146/annurev-psych-113011-143750

Diamond, A., & Goldman-Rakic, P. S. (1989). Comparison of human infants and rhesus

monkeys on Piaget's A-not-B task: Evidence for dependence on dorsolateral

prefrontal cortex. *Experimental Brain Research, 74*, 24-40. doi:10.1007/BF00248277

Diamond, A., Zola-Morgan, S., & Squire, L. (1989). Successful performance by monkeys

with lesions of the hippocampal formation on AB and object retrieval, two tasks that

mark developmental changes in human infants. *Behavioural Neuroscience, 103*(3),

526-537. doi:10.1037//0735-7044.103.3.526

Dougherty, T. M., & Haith, M. M. (1997). Infant expectations and reaction time as predictors

of childhood speed of processing and IQ. *Developmental Psychology, 33*(1), 146-155.

doi: 10.1037//0012-1649.33.1.146

Fisher, A., & Kloos, H. (2016). Development of selective sustained attention: The role of

executive functions. In J. A. Griffin, P. D. McCardle, & L. S. Freund (Eds.),

Executive Function in Preschool-Age Children: Integrating Measurement,

Neurodevelopment, and Translational Research. Washington, DC: American

Psychological Association.

Friedman, N. P., & Miyake, A. (2017). Unity and diversity of executive functions: Individual

differences as a window on cognitive structure. *Cortex, 86*, 186-204.

doi:10.1016/j.cortex.2016.04.023

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A

review using an integrative framework. *Psychological Bulletin, 134*(1), 31-60.

doi:10.1037/0033-2909.134.1.31

Garon, N., Smith, I. M., & Bryson, S. E. (2014). A novel executive function battery for

preschoolers: Sensitivity to age differences. *Child Neuropsychology, 20*(6), 713-736.

doi:10.1080/09297049.2013.857650

Haith, M. M., Hazan, C., & Goodman, G. S. (1988). Expectation and anticipation of dynamic

visual events by 3.5-month-old babies. *Child Development, 59*, 467-479.

doi:10.2307/1130325

Hendry, A., Jones, E. J. H., & Charman, T. (2016). Executive function in the first three years

of life: Precursors, predictors and patterns. *Developmental Review*.

doi:10.1016/j.dr.2016.06.005

Holmboe, K., Fearon, R. M. P., Csibra, G., Tucker, L. A., & Johnson, M. H. (2008). Freeze-

Frame: A new infant inhibition task and its relation to frontal cortex tasks during

infancy and early childhood. *Journal of Experimental Child Psychology, 100*(2), 89-

114. doi:10.1016/j.jecp.2007.09.004

Holmboe, K., Nemoda, Z., Fearon, R. M. P., Csibra, G., Sasvari-Szekely, M., & Johnson, M.

H. (2010). Polymorphisms in dopamine system genes are associated with individual

differences in attention in infancy. *Developmental Psychology, 46*(2), 404-416.

doi:10.1037/a0018180

Holmboe, K., Nemoda, Z., Fearon, R. M. P., Sasvari-Szekely, M., & Johnson, M. H. (2011).

Dopamine D4 receptor and serotonin transporter gene effects on the longitudinal

development of infant temperament. *Genes Brain and Behavior, 10*(5), 513-522.

doi:10.1111/j.1601-183X.2010.00669.x

40

Hood, B. M., & Atkinson, J. (1993). Disengaging visual attention in the infant and adult. *Infant Behavior and Development, 16*, 405-422. doi:10.1016/0163-6383(93)80001-O

Hooper, D., Coughlan, J., & Mullen, M. R. (2008). Structural equation modelling: Guidelines for determining model fit. *Electronic Journal of Business Research Methods, 6*(1), 53-60.

Jacobson, S. W., Jacobson, J. L., O'Neill, J. M., Padgett, R. J., Frankowski, J. J., & Bihun, J. T. (1992). Visual expectation and dimensions of infant information processing. *Child Development, 63*(3), 711-724. doi:10.1111/j.1467-8624.1992.tb01656.x

Johansson, M., Marciszko, C., Gredebäck, G., Nyström, P., & Bohlin, G. (2015). Sustained attention in infancy as a longitudinal predictor of self-regulatory functions. *Infant Behavior & Development, 41*, 1-11. doi:10.1016/j.infbeh.2015.07.001

Kannass, K. N., Oakes, L. M., & Shaddy, D. J. (2006). A longitudinal investigation of the development of attention and distractibility. *Journal of Cognition and Development, 7*(3), 381-409. doi:10.1207/s15327647jcd0703_8

Kavšek, M. (2004). Predicting later IQ from infant visual habituation and dishabituation: A meta-analysis. *Applied Developmental Psychology, 25*(3), 369-393. doi:10.1016/j.appdev.2004.04.006

Kline, R. B. (2016). *Principles and Practice of Structural Equation Modelling* (4th ed.). New York: The Guilford Press.

Kochanska, G., Murray, K. T., & Harlan, E. T. (2000). Effortful control in early childhood: Continuity and change, antecedents, and implications for social development. *Developmental Psychology, 36*(2), 220-232. doi:10.1037/0012-1649.36.2.220

Kovács, Á. M., & Mehler, J. (2009). Cognitive gains in 7-month-old bilingual infants. *Proceedings of the National Academy of Sciences, 106*(16), 6556-6560. doi:10.1073/pnas.0811323106

Matsuzawa, M., & Shimojo, S. (1997). Infants' fast saccades in the gap paradigm and development of visual attention. *Infant Behavior & Development, 20*(4), 449-455. doi:10.1016/S0163-6383(97)90035-7

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science, 21*(1), 8-14. doi:10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49-100. doi:10.1006/cogp.1999.0734

Morin, A. J. S., Marsh, H. W., & Nagengast, B. (2013). Exploratory structural equation modeling. In G. R. Hancock & R. O. Mueller (Eds.), *Structural Equation Modeling: A Second Course* (2nd ed.). Greewich, Connecticut: IAP.

Mulder, H., Hoofs, H., Verhagen, J., van der Veen, I., & Leseman, P. P. M. (2014). Psychometric properties and convergent and predictive validity of an executive function test battery for two-year-olds. *Frontiers in Psychology, 5*(733), 1-17. doi:10.3389/fpsyg.2014.00733

Mullen, E. M. (1995). *Mullen scales of early learning* (AGS ed.). Circle Pines, Minnesota: American Guidance Service, Inc.

Muthén, L. K., & Muthén, B. O. (2015). Mplus Version 7.4. Los Angeles: Muthén & Muthén.

Nakagawa, A., & Sukigara, M. (2013). Individual differences in disengagement of fixation and temperament: Longitudinal research on toddlers. *Infant Behavior & Development, 36*(4), 728-735. doi:10.1016/j.infbeh.2013.08.001

Oakes, L. M. (2017). Sample size, statistical power, and false conclusions in infant looking-time research. *Infancy, 22*(4), 436-469. doi:10.1111/infa.12186

Oakes, L. M., Kannass, K. N., & Shaddy, D. J. (2002). Developmental changes in endogenous control of attention: the role of target familiarity on infants' distraction latency. *Child Development, 73*(6), 1644-1655. doi:10.1111/1467-8624.00496

Office for National Statistics (2001). Census 2001- Population of England and Wales grows 2.5 per cent. Retrieved from

http://www.statistics.gov.uk/census2001/profiles/commentaries/people.asp

Open Science Collaboration (2015). Estimating the reproducibility of psychological science. *Science, 349*(6251), aac4716. doi:10.1126/science.aac4716

Papageorgiou, K. A., Smith, T. J., Wu, R., Johnson, M. H., Kirkham, N. Z., & Ronald, A. (2014). Individual differences in infant fixation duration relate to attention and behavioral control in childhood. *Psychological Science, 25*(7), 1371-1379. doi:10.1177/0956797614531295

Richards, J. E. (2010). The development of attention to simple and complex visual stimuli in infants: Behavioral and psychophysiological measures. *Developmental Review, 30*(2), 203-219. doi:10.1016/j.dr.2010.03.005

Rose, S. A., Feldman, J. F., & Jankowski, J. J. (2012). Implications of infant cognition for executive functions at age 11. *Psychological Science, 23*(11), 1345-1355. doi:10.1177/0956797612444902

Rothbart, M. K., Ellis, L. K., Rueda, M. R., & Posner, M. I. (2003). Developing mechanisms of temperamental effortful control. *Journal of Personality, 71*(6), 1113-1143. doi:10.1111/1467-6494.7106009

Ruff, H. A., & Rothbart, M. K. (1996). *Attention in Early Development: Themes and Variations*. Oxford: Oxford University Press.

Sigman, M., Cohen, S. E., & Beckwith, L. (1997). Why does infant attention predict

adolescent intelligence? *Infant Behavior & Development, 20*(2), 133-140.

doi:10.1016/S0163-6383(97)90016-3

Twomey, D. M., Wrigley, C., Ahearne, C., Murphy, R., De Haan, M., Marlow, N., &

Murray, D. M. (2018). Feasibility of using touch screen technology for early

cognitive assessment in children. *Archives of Disease in Childhood, Epub ahead of

print: [13 March 2018]*. doi:10.1136/archdischild-2017-314010

Wass, S., Porayska-Pomsta, K., & Johnson, M. H. (2011). Training attentional control in

infancy. *Current Biology, 21*(18), 1543-1547. doi:10.1016/j.cub.2011.08.004

Werchan, D. M., Collins, A. G., Frank, M. J., & Amso, D. (2016). Role of prefrontal cortex

in learning and generalizing hierarchical rules in 8-month-old infants. *Journal of

Neuroscience, 36*(40), 10314-10322. doi:10.1523/JNEUROSCI.1351-16.2016

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to

understand executive control in preschool children: I. Latent structure. *Developmental

Psychology, 44*(2), 575-587. doi:10.1037/0012-1649.44.2.575

Wiebe, S. A., Sheffield, T., Nelson, J. M., Clark, C. A., Chevalier, N., & Espy, K. A. (2011).

The structure of executive function in 3-year-olds. *Journal of Experimental Child

Psychology, 108*(3), 436-452. doi:10.1016/j.jecp.2010.08.008

Yu, C., & Smith, L. B. (2016). The social origins of sustained attention in one-year-old

human infants. *Current Biology, 26*(9), 1235-1240. doi:10.1016/j.cub.2016.03.026

Zelazo, P. D., Frye, D., & Rapus, T. (1996). An age-related dissociation between knowing

rules and using them. *Cognitive Development, 11*, 37-63. doi:10.1016/S0885-

2014(96)90027-1

Table 1. Descriptive statistics for individual performance measures and replication of previously found group-level effects for each task.

Task	N	Mean (SD) of performance measure[a]	Original effect	Key references to original effect	Replication of original effect
Gap-Overlap	104	1.16 (0.18)	Longer SRT on Overlap trials compared to Gap trials	Hood & Atkinson (1993)	Yes ($p <. 001$, $\eta_p^2 = .45$)
Anticipation	103	0.00 (0.20)[b]	Infants anticipate the target (SRT $\leq$ 120 ms) on approx. 1/4 of trials	Haith, Hazan, & Goodman (1988); Canfield, Wilken, Schmerl, & Smith (1995)	Yes, mean anticipation rate across all trials = 26%
Freeze-Frame, 6 months	79	0.43 (0.18)	N/A (only 1 condition)	N/A	N/A
Freeze-Frame, 9 months	86	0.22 (0.14)	Infants look less to distractors in interesting trials than in boring trials	Holmboe, Fearon, Csibra, Tucker, & Johnson (2008)	Yes ($p <. 001$, $\eta_p^2 = .45$)
A-not-B	87	1.35 (1.44)	Large variability in performance, but few 9-month-olds can sustain long delays on change trials	Diamond (1985); Bell & Fox (1992); Holmboe et al. (2008)	Yes, only 15.7% of infants could sustain a delay that was longer than 2 s on change trials
MSEL-AGS	94	112 (10.30)	N/A (no specific hypothesis)	N/A	N/A

Note. SRT = saccadic reaction time. [a] Measure used in the structural equation model in Fig. 1. [b] For the Anticipation measure, variance in the number of valid trials was controlled for. This was done to avoid confounds caused by the number of trials that each infant viewed in this free-viewing paradigm.

Table 2. Zero-order correlations between performance measures at 4, 6 and 9 months.

		4 months		6 months	9 months		
		Gap-Overlap	Anticipation	Freeze-Frame	Freeze-Frame	A-not-B	MSEL-AGS
4 months	Gap-Overlap	1					
	Anticipation	-.201*	1				
6 months	Freeze-Frame	.101	-.149	1			
9 months	Freeze-Frame	.006	-.039	.290**	1		
	A-not-B	-.189†	.147	-.186†	-.396***	1	
	MSEL-AGS	-.194*	.146	.016	-.185†	.252**	1

Note. Correlation coefficients (r) from Mplus, p-values calculated on https://www.danielsoper.com/statcalc/calculator.aspx?id=44#. Full information maximum likelihood (FIML) was used to account for missing data, therefore the full sample ($N = 104$) was used in the analyses. ***$p < .001$, **$p < .01$, *$p < .05$, †$p < .10$, two-tailed p-values.

Figure 1. Path analysis of the relationship between attention at 4 months, inhibitory control at 6 and 9 months, and general development at 9 months. The standardized solution is shown in bold typeface, with unstandardized estimates, followed by standard errors, presented in brackets. Gray lines indicate non-significant or marginal paths. ***$p < .001$, **$p < .01$, *$p < .05$, †$p < .10$, two-tailed.