Movement–attention coupling in infancy and attention problems in childhood

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Adaptive behavior requires the integration of body movement and attention. Therefore, individual differences in integration of movement and attention during infancy may have significance for development. We contacted families whose 8-year-old children (*n*=26; 16 females, 10 males; mean age 8y 2mo, SD 8mo) participated in a previous study of movement–attention coupling at 1 or 3 months of age, to assess parent-reported attention or hyperactivity problems using the Child Behavior Checklist and Diagnostic and Statistical Manual of Mental Disorders (4th edn) criteria. Parent-reported attention problems at 8 years of age were associated with less suppression of body movement at onset of looking, and greater rebound of body movement following its initial suppression at 3 months, but not at 1 month. Parent-reported hyperactivity was not related to any of the infant movement–attention measures. Results suggests that the dynamic integration of movement and attention early in life may have functional significance for the development of attention problems in childhood.

Adaptive behavior depends on the second-to-second integration of body movement and attention. The nature of this critical relation between mind and body is an age-old issue that continues to stimulate research (Clark 1999). For developmental science, there are at least four questions of fundamental importance to this issue: (1) Are movement and attention integrated very early in development? (2) How does the integration develop? (3) What are the mechanisms responsible for the integration? and (4) What might be the functional significance of individual differences in movement–attention integration?

A recent study reported that during extended periods of free, uncued looking at unchanging objects, very young infants exhibit characteristic patterns of motor quieting and motor activation (Robertson et al. 2001a). At both 1 and 3 months of age, ongoing motor activity decreases rapidly below baseline as gaze locks onto an object and then surges above baseline in the seconds before gaze shifts away. Thus, as early as the first postnatal month, overt attention and general body movement appear to be tightly coupled.

There is evidence of developmental changes in some measures of movement–attention coupling during the first few months after birth (Robertson et al. 2001a). For example, although the suppression of body movement at gaze onset is similar at 1 and 3 months, there are important differences in the burst of body movement at gaze offset. At 1 month, spontaneous gaze shifts are preceded by multiple bursts of motor activation separated by about a second. At 3 months, shifts of gaze are preceded by a single rapid burst in body movement in the final second of the look. It is not known how developmental changes in the control of body movement and gaze interact with covert attention between 1 and 3 months of age to yield tighter integration. However, one possible consequence of tighter integration is that random fluctuations in ongoing motor activity may be less likely to interrupt attention and the perceptual–cognitive processing it facilitates.

The visual system matures rapidly within the first few months of birth. Changes in the visual behavior of infants over this period have been described in detail (Atkinson 2000). However, the extent to which specific neural processes underlying attention and the control of gaze in adults (Hikosaka et al. 2000, Corbetta and Shulman 2002) function in the first few postnatal months is not known. It is possible that general motor activation may play a role in redirecting gaze to a new object or location by releasing the tonic inhibition of saccades exerted by the basal ganglia (Robertson et al. 2001a). Therefore, the suppression of ongoing motor activity at the beginning of a look at an object may facilitate inspection or location of the item by reducing the chance that gaze will be redirected from it.

Although much remains to be learned about the nature of early movement–attention coupling and its rapid development during the first three postnatal months, enough may be known to begin to address questions about the functional significance of individual differences. One interesting question is whether individual differences in movement–attention coupling during early infancy are related to general attentiveness or motor activity during childhood. There have been a few reports that state that some infant measures of visual attention (Auerbach et al. 2001) and motor control (Hadders-Algra and Groothuis 1999) may be associated with an increased risk of attention-deficit–hyperactivity disorder (ADHD) in childhood. However, there has been no report of whether the dynamic integration of movement and attention early in development might be related to attentiveness and motor activity during childhood.

The present study was designed to search for possible links between characteristics of movement–attention coupling in early infancy and attention problems or hyperactivity in childhood. Families who had participated in the infant study of movement and attention (Robertson et al. 2001a) were re-contacted and invited to complete a questionnaire about their child's behavior at approximately 8 years of age. Measures were extracted from infant data to reflect the dynamic integration of attention and motor activity. The relationship between the data in infancy and parent-reported behavior in childhood was examined. Specifically, it was investigated whether the suppression and subsequent rebound of ongoing body movement at gaze onset, or the surge in body movement that accompanies gaze offset at 1 and 3 months of age, predict individual differences in attention problems and hyperactivity reported by parents at 8 years of age.

Method

PARTICIPANTS

Participants were 26 children (16 females, 10 males; mean age 8y 2mo [SD 8], range 7 to 9y) who were studied as infants at either 1 month (nine females, four males) or 3 months (seven females, six males) of age by Robertson et al. (2001a). The 26 children were from a sample of 44 children with useable infant data. All were healthy at birth, with birthweight between 2.72 and 4.51kg (mean 3.64kg, SD 0.42), and gestational ages between 39 and 42 post-menstrual weeks (mean 40wks, SD 1).

Data from three children studied at 1 or 3 months were not used: one had trisomy 21, one had a brain tumor, and one was an extreme outlier on the child measures (>4SD above the mean on both Child Behavior Checklist [CBCL; Achenbach 2001] measures and >2.5SD above the mean on both measures of the Diagnostic and Statistical Manual of Mental Disorders – 4th edition [DSM-IV; American Psychiatric Association 1994] measures). Twenty-nine other children did not have usable infant data because they cried or fussed, 10 because they were too tired, three because they did not look at the stimuli, and three because of technical problems. Infants without usable data did not differ from the study sample on birthweight (mean 3.46kg, SD 0.46) or gestational age (mean 40wks, SD 1). Fifteen children with usable infant data and 17 without usable infant data could not be located at follow-up or did not complete the follow-up.

Infants who were lost to follow-up did not differ from the study sample on birthweight (mean 3.69kg, SD 0.51) or gestational age (mean 40wk, SD 1). The original infant study and follow-up were approved by the Cornell University Committee on Human Subjects, and informed consent was obtained from a parent or guardian at both time-points. Parents volunteered to participate in the original study by responding to a letter distributed to all parents whose child was born at a local hospital in Ithaca, NY, USA.

INFANT STUDY

Infants participated in a free looking task at 1 or 3 months after birth (Robertson et al. 2001a). Four identical, static, three-dimensional objects (commercially available Big Bird toys with a bright yellow head and body, orange feet, pink eyelids, blue eyelashes, and large black pupils) were mounted on a black background in a rectangular arrangement approximately 100cm in front of the infant. Each object subtended 7° of visual angle in the horizontal direction and 9° in the vertical direction. The two objects were separated by 21° of visual angle in the horizontal direction. Infants sat in a commercial infant car seat while they looked freely at the objects. The seat was fitted with a loose safety strap, which did not interfere with

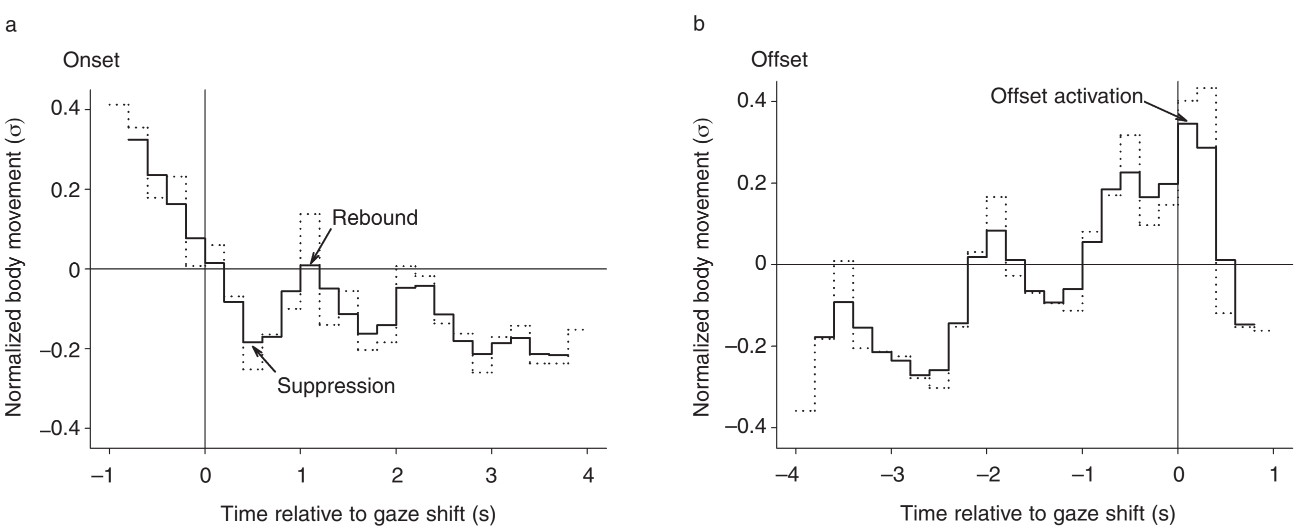

Figure 1: *Primary measures of movement–attention coupling during free looking in an infant at 3 months of age. (a) Movement Suppression and Rebound immediately following gaze onset. (b) Offset Movement Activation, i.e. body movement at gaze offset. Dotted lines are mean body movement during 200ms intervals around gaze onset and offset for 23 looks that lasted at least 4s, (expressed as σ) from baseline calculated from entire period of data collection. Solid lines are three-term weighted moving averages based on mean body movement in an interval (weighted 0.50) and mean body movement in the immediately preceding and following intervals (each weighted 0.25). Vertical reference lines indicate gaze onset and offset.*

body movement. Motor activity was measured by piezoelectric sensors in the seat and digitized online at 30Hz. Corneal reflections of the stimuli were recorded with a video camera located in the center of the stimulus array and synchronized with the sampling of the movement sensors. Spontaneous shifts of gaze were determined off-line to the nearest video frame (1 per 30s).

Infant measures

Analysis of infant data focused on the changes in spontaneous body movement that occurred at the onset and offset of looks that lasted at least 4s. The number of looks greater than 4s ranged from 8 to 41 (mean 18, SD 11) at 1 month, and from 8 to 41 (mean 24, SD 10) at 3 months. Mean length of looks greater than 4s ranged from 11.5 to 23.4s (mean 16s, SD 3.4) at 1 month and from 6.8 to 23.6s (mean 11.3s, SD 4.7) at 3 months. The periods of free looking lasted 4.3 to 14 minutes (mean 7.2min, SD 2.8) at 1 month and 6.6 to 16 minutes (mean 11.1min, SD 3.2) at 3 months.

For each infant, the magnitude of movement sensor activity was averaged during each 200ms interval in the 1s preceding and 4s following gaze onset, and in the 4s preceding and 1s following gaze offset. The 200ms movement data were then averaged across looks and normalized using the overall mean and standard deviation for the infant.

Three primary measures of the dynamic coupling between movement and attention were extracted from the three-term weighted moving average of each infant's normalized movement data (based on the mean body movement in an interval, weighted 0.50 and the mean body movement in the immediately preceding and following intervals, each weighted 0.25; Fig 1): (1) Movement Suppression is the first minimum in body movement that occurs immediately following gaze onset, and reflects the extent to which ongoing motor activity is suppressed when the infant begins to visually inspect an object. (2) Movement Rebound is the next maximum in body movement, and reflects the level to which spontaneous motor activity returns immediately following its initial suppression. (3) Offset Movement Activation is the first maximum in body movement following the last minimum before gaze offset, and reflects the extent to which motor activity increases at the end of a look.

In addition to the primary measures of movement–attention coupling, the following two measures were used to describe more general characteristics of looking and motor activity during free looking. (1) Look Duration is the median duration of all looks during the experiment (including those less than 4s); (2) Motor Activity is the percentage of time during the experiment that movement sensor activity exceeded thresholds set to exclude respiratory movements. Both Look Duration and Motor Activity reflect overall properties of looking and body movement explicitly defined without reference to each other.

Table I: Infant and child measures

Measures	*1 month of age, (n=13) Mean (SEM)*	*3 months of age, (n=13) Mean (SEM)*
Infant measures		
Movement Suppression (σ)	–0.20 (0.02)	–0.18 (0.05)
Movement Rebound (σ)	–0.06 (0.03)	–0.06 (0.06)
Offset Movement Activation (σ)	0.58 (0.09)	0.18 (0.08)[a]
Look Duration, s	2.56 (0.65)	1.32 (0.16)
Motor Activity, %	38.8 (3.2)	53.2 (1.4)[b]
Child Measures		
DSM-IV Inattention	2.5 (0.7)	1.9 (0.5)
DSM-IV Hyperactivity	2.8 (0.6)	2.7 (0.5)
CBCL-Attention Problems	2.2 (0.5)	1.8 (0.6)
CBCL-ADHD	2.2 (0.5)	1.6 (0.5)

Student's *t*-test. [a]$p<0.01$; [b]$p<0.001$. DSM-IV, Diagnostic and Statistical Manual of Mental Disorders – 4th edition (American Psychiatric Association 1994); CBCL, Child Behavior Checklist (Achenbach 2001); ADHD, attention-deficit–hyperactivity disorder.

Child measures

Child measures were constructed from the DSM-IV (American Psychiatric Association 1994) diagnostic criteria for ADHD, and two scales taken from the CBCL (Achenbach 2001). The DSM-IV is designed for clinical application and each symptom is scored as present or absent. To be consistent with other items on the questionnaire, parents were asked to respond 'not true'; 'somewhat/sometimes true'; or 'very/often true' to all questions. DSM-IV responses were then recoded to yes (somewhat/sometimes true and very/often true) or no (not true), and the number of yes responses were summed. Results did not change if DSM-IV responses were coded 0 (not true), 1 (somewhat/sometimes true), or 2 (very/often true).

The DSM-IV assesses inattention and hyperactivity as criteria for ADHD. 'DSM-Inattention' was the total score for the nine DSM-IV items assessing symptoms of inattention, and 'DSM-Hyperactivity' was the total score for the nine DSM-IV items assessing symptoms of hyperactivity/impulsivity. 'CBCL-Attention Problems' was the total score for the 10 items on the CBCL Attention Problems scale, and 'CBCL-ADHD' was the total score for the seven items on the CBCL Attention-Deficit–Hyperactivity Disorder scale. For each measure, higher scores indicate more parent-reported inattention or hyperactivity.

ANALYSES

Group differences were analyzed using the Student's *t*-test and the Mann–Whitney *U* test. Correlations between measures were analyzed using Pearson's *r* and Spearman's rho. Results were considered significant at $p<0.05$. In all cases, results were the same for the parametric and nonparametric tests. Therefore, only results of the parametric tests are reported.

Results

Table I shows the means and standard errors for the infant and child measures. Tables II and III show the intercorrelations among the infant and child measures respectively.

PRIMARY INFANT MEASURES AND DSM-IV AND CBCL AT 8 YEARS

For children studied at 1 month after birth, there was no significant correlation between Movement Suppression, Rebound or Offset Movement Activation and any of the child measures.

For children studied at 3 months after birth, there was a clear pattern of correlations between the primary infant measures of movement–attention coupling and child ADHD and attention measures (see Fig. 2). Less suppression of ongoing body movement at gaze onset during free looking of infants was associated with greater parent-reported ADHD indicators

(CBCL-ADHD, $r=-0.69, p=0.008$), attention problems (CBCL-Attention Problems, $r=-0.57$, $p=0.041$), and inattention (DSM-Inattention, $r=-0.56, p=0.049$) during childhood. Similarly, greater rebound of body movement following initial suppression after gaze onset during free looking of infants was associated with greater parent-reported ADHD indicators (CBCL-ADHD, $r=0.62, p=0.025$) and attention problems (CBCL-Attention Problems, $r=0.57, p=0.044$), and marginally associated with parent-reported inattention (DSM-Inattention, $r=0.48, p=0.095$), during childhood.

The increase in body movement that accompanies gaze offset during infant free looking was not related to any of the child measures. None of the infant measures of movement–attention coupling was related to parent-reported hyperactivity in childhood (DSM-Hyperactivity). Because of the limited sample size, only the main result (correlation between infant movement suppression and child attention problems) remains significant when the significance criterion is adjusted for multiple tests.

There was no significant correlation between the general measures of infant looking or motor activity (Look Duration and Motor Activity) at 1 or 3 months of age and any of the child measures.

A two-way analysis of variance (age×excluded for fussiness) indicated that children who were excluded as infants for fussiness ($n=29$) had higher scores on the DSM-Inattention scale (mean 3.8, SD 0.6) compared with children with usable infant data (mean 2.2, SD 0.5), $F(1, 51)=4.28$, $p=0.044$. There was no main effect of age, $F(1,51)=0.44$, $p=0.51$, and no interaction between age and exclusion for fussiness, $F(1,51)=0.01$, $p=0.91$. There was no main or interaction effect of infant age or exclusion for fussiness on the DSM-Hyperactivity, CBCL-ADHD, or CBCL-Attention Problems scales. Children who were excluded as infants for fussiness did not differ from the study sample on birthweight (mean 3.43kg, SD 0.49) or gestational age (mean 40wks, SD 1).

Discussion

Less suppression and greater rebound of motor activity at the *onset* of looking at 3 months of age predicted more parent-reported inattention, attention problems, and indicators of ADHD at 8 years of age. Motor activation at the *offset* of looking was not correlated with child measures. Neither of the more general measures of infant looking and motor activity was correlated with the child measures. While childhood attention problems were highly correlated with infant measures, childhood hyperactivity was not correlated with either the dynamic integration of movement and attention, or with more general movement or looking behaviour, at 1 or 3 months of age.

Motor suppression at the onset of looking in infants was clearly related to later attention problems, but general measures of infant motor activity and looking were not. This suggests that further investigation of the dynamic integration of movement and attention in infancy may provide insight into the development of childhood attention problems. Furthermore, the absence of any correlation between the infant measures and parent-reported hyperactivity is consistent with the standard clinical model of ADHD that distinguishes between inattention and hyperactivity (Lahey et al. 1988, American Psychiatric Association 1994, Chhabildas et al. 2001). However, our sample did not include any children diagnosed with ADHD, and the sample size limited power to detect more subtle associations which might include general measures of movement (e.g. the measure of motor activity) or attention (e.g. the measure of look duration) in infancy and hyperactivity in childhood.

The pattern of findings suggests that the extent to which

Table II: Intercorrelations for infant measures at 1 and 3 months of age

	Movement Suppression	*Movement Rebound*	*Offset Movement Activation*	*Look Duration*
1 month of age ($n=13$)				
Movement Rebound	0.17			
Offset Movement Activation	0.01	–0.48		
Look Duration	0.16	–0.34	0.25	
Motor Activity	0.38	–0.10	–0.28	0.56[a]
3 months of age ($n=13$)				
Movement Rebound	0.90[b]			
Offset Movement Activation	0.45	0.42		
Look Duration	–0.44	–0.55	–0.54	
Motor Activity	0.08	–0.02	–0.25	0.16

Values are Pearson's correlations. [a]$p<0.05$; [b]$p<0.001$.

Table III: Intercorrelations for child measures

	DSM-Inattention	*DSM-Hyperactivity*	*CBCL-Attention Problems*
DSM-Hyperactivity	0.57[a]		
CBCL-Attention Problems	0.78[b]	0.35	
CBCL-ADHD	0.76[b]	0.51[a]	0.90[b]

Pearson's r, $n=26$. [a]$p<0.01$; [b]$p<0.001$. DSM, Diagnostic and Statistical Manual of Mental Disorders – 4th edition (American Psychiatric Association 1994); CBCL, Child Behavior Checklist (Achenbach 2001); ADHD, attention-deficit–hyperactivity disorder.

ongoing body movement is suppressed at gaze onset during free looking at 3 months of age may reflect differences in early movement–attention integration. This integration has important implications for the subsequent development of adaptive behavior. In view of the evidence that bursts of motor activity may unlock gaze from targets of attention in young infants (Robertson et al. 2001a), less suppression of ongoing body movement at the onset of looking may leave attention more vulnerable to disruption by the normal background fluctuations in motor activation (Bacher and Robertson 2001, Robertson et al. 2001b). Thus, individual differences in motor suppression at the onset of looking in infants may reflect differences in the vulnerability of attention to disruption. If disrupted attention persists as a moderately stable individual difference, this could account for some of the differences in attention problems during childhood.

There are a number of reasons to suspect that the neural substrate of dynamic movement–attention coupling includes the basal ganglia, and that individual differences in dynamic coupling may reflect differences in basal ganglia structure or function. The central role played by the basal ganglia in the adaptive regulation of ongoing behavior, including gaze and attention, is well-documented (Graybiel et al. 1994, Hikosaka et al. 2000, Casey et al. 2004). Maturation of basal ganglia circuits is thought to play a key role in the normal development of visual behavior in the first few months after birth (Johnson 1995). Perinatal hypoxic-ischemic damage to the basal ganglia disrupts normal visual function at 5 months of age, particularly gaze shifts, which in turn predicts neuromotor outcome at 2 years of age (Mercuri et al. 1997). Furthermore, structural and functional abnormalities in the basal ganglia have been implicated in the pathophysiology of ADHD, including altered control of visual behavior (Castellanos et al. 2002, Munoz et al. 2003).

There are changes in the control of gaze in the first few months after birth that may account for the absence of any relation between childhood attention problems and measures of movement–attention coupling at 1 month, despite a

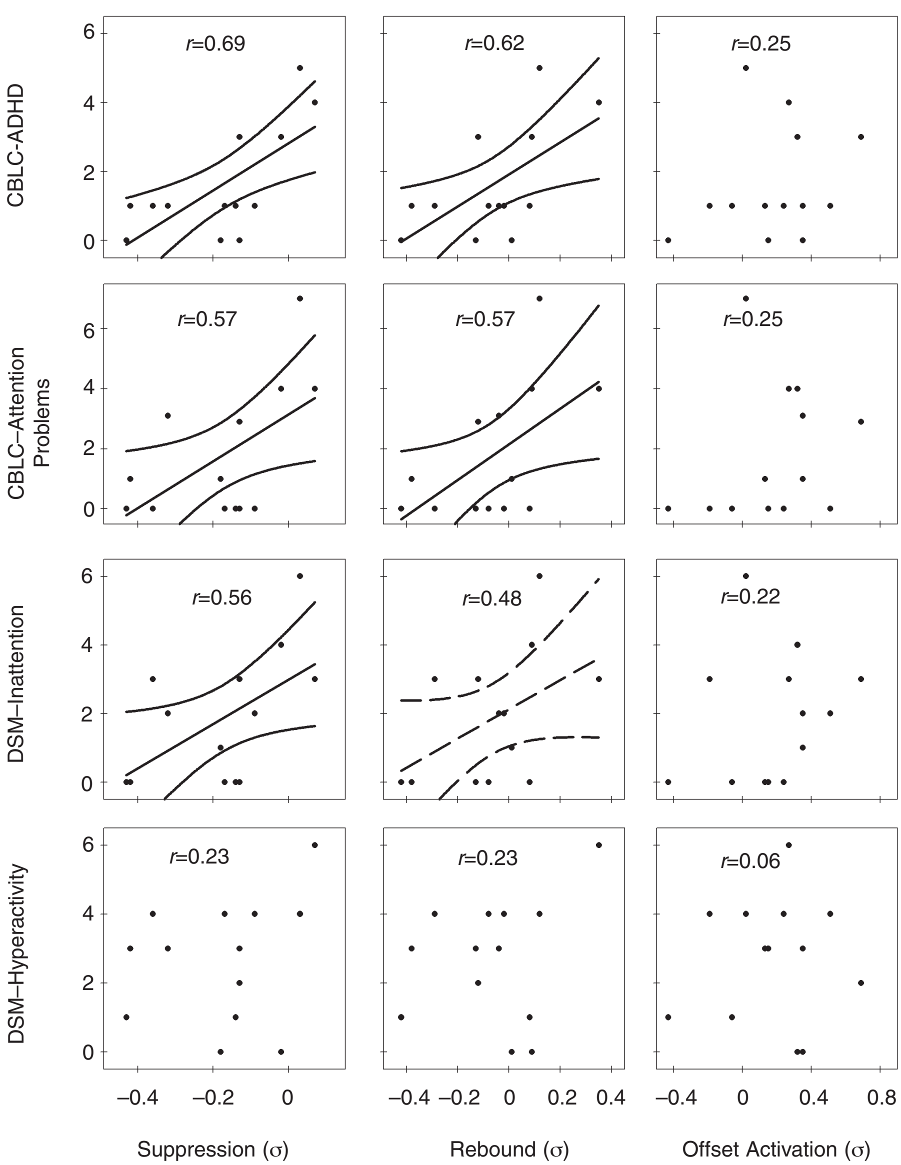

Figure 2: *Scatter plots of three primary measures of infant movement–attention coupling and child measures of attention and hyperactivity. Pearson's correlations are shown for each bivariate relation. Linear regression of child measure on infant measure, and 95% confidence limits, are shown as solid lines if $p<0.05$ and as broken lines if $p>0.05$ but <0.10. DSM, Diagnostic and Statistical Manual of Mental Disorders (4th edn; American Psychiatric Association 1994); CBLC, Child Behavior Checklist. (Achenbach 2001). ADHD, attention-deficit–hyperactivity disorder.*

clear relation at 3 months of age. For very young infants, gaze has been described as 'obligatory' or 'sticky' because they sometimes have difficulty looking away from visual stimulus (Atkinson et al. 1992). It is thought that stickiness occurs because pathways that suppress the tonic inhibition of eye movements have not yet matured (Johnson 1995). It is likely that the change in movement–attention coupling between 1 and 3 months of age reflects the maturation of circuits involved in overriding the tonic inhibition of saccades (Robertson et al. 2001a). Individual differences in movement–attention coupling after this period of rapid developmental change is more likely to reflect stable differences in the disruption of attention by bursts of motor activity.

The dynamic integration of brain function, motor activity, and the stimulation and constraints of the physical world is the basis of adaptive behaviour. Its disruption is a major concern of clinicians. The current findings provide empirical support for the significance of individual differences in one aspect of this dynamic integration – the coupling of body movement and visual attention in young infants – as a predictor of later attention problems. More generally, our findings suggest that a fuller understanding of attention problems and other forms of maladaptive behavior during childhood might be achieved by focusing on the details of how the dynamic integration of brain, body, and world develops from early in life.

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