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Stability of Coupled Fluctuations in Movement and Visual Attention in Infants

ABSTRACT: *Fluctuations in body movement and visual inspection were measured over minutes in 3-month-old infants to look for evidence of coupling. In Experiment 1, infants (n = 12) looked ad libitum at two identical pictures for an average of 7.3 min. Analysis of the spontaneous fluctuations in movement and inspection revealed that they were inversely coupled: Moment-to-moment changes in movement and inspection occurred in opposite directions. In Experiment 2, after 4 min of free looking, infants (n = 33) were presented with a new pair of stimuli, a temporary change in the stimuli, or no change in stimuli. The inverse coupling between the fluctuations in body movement and visual inspection found in Experiment 1 was present before and after the stimulus changes, even in infants whose body movement decreased transiently in response to the stimulus changes. The reappearance of inversely coupled fluctuations in body movement and visual inspection following the stimulus changes was led by increases in movement. The results demonstrate the stability of the inverse coupling between spontaneous fluctuations in body movement and visual inspection, and suggest that changes in movement may lead changes in inspection.* © 2001 John Wiley & Sons, Inc. Dev Psychobiol 39: 99–106, 2001

Keywords: *movement; visual inspection; cyclic; infants; attention*

In human infants, cyclic movement (CM) begins prenatally (Robertson, 1982) and persists until at least 3 months after birth (Robertson, 1993). These persistent, irregular oscillations in overall body movement occur on a scale of approximately 1 min (Robertson, 1982) and appear to be generated by both spinal and supraspinal sources (Robertson & Smotherman, 1990). The relationships between these sustained fluctuations in body movement and other infant behaviors (e.g., looking, suckling) are unknown.

The fluctuations in body movement may be related to temporal patterns in visual attention (Robertson, 1989). One theoretical basis for this hypothesis is that action and perception are inextricably and reciprocally connected (Bertenthal & Clifton, 1998). This view recognizes the essential contributions of both motor and perceptual systems in the performance of successful action. A second theoretical basis is that attention subserves action systems (Allport, 1989). According to this view, the selectiveness of attention results from the demands of the motor system and the organism's need for behavioral coherence. Thus, attentional behavior especially is likely to be linked to action systems. Therefore, we would expect to find spatial and or temporal relationships between body movement and visual activity.

Not only are there strong theoretical bases for this pursuit, but previous research illustrates several ways in which this connection between action and perception is manifested in early development. For example, eye–head movements and, under some conditions, eye–hand movements are spatially and temporally linked in young infants (Ennouri & Bloch, 1996; van der Meer, van der Weel, & Lee, 1995; von Hofsten, 1984). Additionally, orienting in infants, often following the appearance of a new or unexpected visual stimulus, is characterized by an increase in visual inspection of the stimulus and a transient decrease in body movement (Sokolov, 1963; Stechler & Latz, 1966).

These studies demonstrate that visual attention and body movement are coordinated under some circumstances. Whether the spontaneous fluctuations in overall body movement relate to patterns of visual attention is unknown. However, studies of infant scanning patterns show that infant visual attention toward a target consists of highly variable patterns of discrete fixations and saccades (Banks & Salapatek, 1983; Bronson, 1982, 1990). Temporal aspects of these scanning patterns showed marked developmental and individual variation (Richards, 1989; Braddick & Atkinson, 1988), and any relation between visual attention and ongoing movement may be reflected in these scanning patterns.

Our goals in these experiments were to (a) determine whether fluctuations in body movement and visual inspection are linked, and if so, (b) test the stability of the coupling, and (c) investigate the timing of the return of the coupled fluctuations after orienting to new visual stimuli. In Experiment 1, we investigated the temporal relationship between fluctuations in overall body movement and patterns of infants' visual attention to static stimuli by measuring both movement and attention over minutes. Results indicated that the fluctuations in movement were coupled to fluctuations in visual inspection. In Experiment 2, we investigated the stability of the coupling and relative timing of the return of coupling. The introduction of new visual stimuli after several minutes of observation was designed to elicit an orienting response that would alter ongoing visual inspection and body movement. If the coupling between movement and inspection is stable, then the coupling should be apparent after the orienting that was induced by the change in the visual environment. Evidence for stable coupling between fluctuations in body movement and visual inspection would suggest that this early manifestation of the link between action and attention persists in both static and changing environments.

GENERAL METHODS

Experiments were conducted in a sound-attenuated, temperature-controlled laboratory. Auditory white noise (Coulbourn S81-02 noise generator; Realistic SA-150 audio amplifier; two Realistic Minimus-17 speakers on the floor in front of the infant) at approximately 50 dbA at the infant's ears was used to mask equipment noise. Air temperature was $22–24°C$. The three walls visible to the infant were covered by black felt. Lighting was provided by two 40-W, incandescent lamps mounted out of the infant's view and oriented toward the center wall where the visual stimuli were located. Light level at the stimuli was approximately 300 lx. Pacifiers were not used by infants during data collection.

Data Acquisition

Corneal Reflections. Corneal reflections of the visual stimuli were detected by a video camera (Cohu 4815) mounted behind the center wall midway between the two stimuli and recorded (Panasonic AG6300) on videotape. The videotapes were analyzed offline. Each video frame (30 Hz) was assigned a code indicating which stimulus (if any) the infant was looking at. Based on 16 min (28,800 frames) of videotape from 2 infants, intercoder agreement was 91%.

Body Movement. Body movement was detected by two piezoelectric sensors beneath the back and bottom cushion of the infant seat. The sensor output was amplified (Coulbourn S75-01) and then bandpass filtered (Coulbourn S75-34) between 1 and 40 Hz to remove baseline changes and electrical noise. The filtered sensor output was sampled (Data Translation DT2801A) at the beginning of each new video frame of corneal reflections (30 samples/s). The filtered sensor output contained negligible power above 15 Hz.

Breathing Movement. Breathing movements were detected by a thin elastic belt around the infant's abdomen connected to a plethysmograph (Parks Electronics 271). The record of breathing movements was used offline to set thresholds for processing the output of the body movement sensors.

Vocalization. Infant vocalizations, detected by a microphone located near the infant seat, were recorded on videotape along with the corneal reflections. The occurrence of distress vocalizations (in addition to facial expressions and other behavior) was used during offline review of the videotape to determine the end of usable data.

EXPERIMENT 1

In the first experiment, we measured each infant's spontaneous fluctuations in general body movement and the direction of gaze during extended periods of free looking at two visual stimuli. Data analysis focused on the coupling between the fluctuations in body movement and visual inspection.

Subjects

Infants and their families were identified from birth notices in the local newspaper. Usable data were obtained from 12 healthy, full-term, 3-month-old infants (8 males). Postnatal age at the time of study was 86 to 103 days ($M = 95$). The data from 2 additional infants (1 male) could not be used because of excessive fussiness.

Procedure

Sessions were scheduled at a time of day when the parent(s) indicated that the infant was most likely to be alert and not fussy (eight infants were studied between 8:00 am and noon, and none were studied after 4:00 p.m.). After arriving in the laboratory, there was a variable delay until the infant appeared to be comfortable and alert.

Infants were placed in an infant seat equipped with movement sensors and positioned approximately 115 cm from two identical posters (high-contrast color illustrations of humanlike forms; Chwast, 1987). Each poster subtended 14×17-degree visual angle and was centered vertically along the infant's nominal line of sight. The posters were separated horizontally by 19-degree visual angle.

Infants were allowed to look at the posters ad libitum while corneal reflections of the stimuli, along with body movements, breathing movements, and vocalizations, were recorded. Data acquisition continued ($3-20$ min, $M = 7.3$) until the infant became disinterested or fussy.

Data Reduction

The total duration of body movements in each successive 5-s interval of usable data was determined by counting the number of 0.2-s bins in which the filtered movement sensor output exceeded a positive or negative threshold. The thresholds were determined separately for each infant and set to exclude sensor activity due to breathing movements and electrical noise. The total duration of inspection on either of the two stimuli in each of the 5-s intervals was determined from the videotaped record of corneal reflections.

The movement and inspection time series were smoothed (see Figure 1) with a Tukey cosine window (weights $= 1 + \cos(\pi j/5)$, $j = 0, \pm 1, \ldots, \pm 4$; Jenkins & Watts, 1968) to remove fluctuations faster than typical CM (i.e., faster than 2 cycles/min). All subsequent analyses in Experiment 1 were conducted on the smoothed time series.

Data Analysis

The extent to which the directions of change in body movement and visual inspection were coupled was quantified in two ways: (a) *Periods* of increasing movement were defined as periods during which the first derivative of the smoothed movement time series was positive (Dadisp 4.0, 1995). Similarly, periods of decreasing movement were defined as periods during which the first derivative of the smoothed movement time series was negative. For each of these periods, the percentage of 5-s intervals that inspection was changing in the opposite direction (i.e., the derivative of the smoothed movement time series and the derivative of the smoothed inspection time series had opposite signs) was determined. (b) *Points of transition* between periods of increasing movement and periods of decreasing movement (or the reverse), and points of transition between periods of increasing inspection and periods of decreasing inspection (or the reverse) were identified. For transitions in movement and inspection that occurred close in time (within 5 s), the percentage of transitions that were in the opposite direction was calculated.
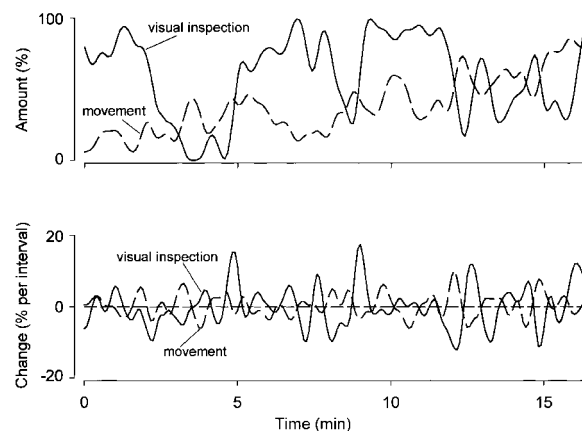

FIGURE 1 Movement and visual inspection time series (percent of each successive 5-s interval, top) and their derivatives (bottom) for 1 infant during a period of free looking. Both time series have been smoothed with a Tukey cosine window (see Methods).

Results

Periods of Increasing (or Decreasing) Movement.
During periods when body movement was increasing
(or decreasing), visual inspection was changing in the
opposite direction $61 \pm 3\%$ (mean $\pm$ *SEM*) of the
time, which is greater than the expected value (50%)
if the direction of changes in movement and inspe-
ction were not coupled, $t(11) = 3.9$, $p = .003$.

***Transitions Between Increasing and Decreasing
Movement.*** For transitions between periods of in-
creasing movement and periods of decreasing move-
ment (or the reverse), $80 \pm 9\%$ of the transitions in
visual inspection occurring within 5 s were in the
opposite direction, which is greater than the expected
value of 50% in the absence of coupling, $t(11) = 3.2$,
$p = .009$.

EXPERIMENT 2

Experiment 1 demonstrated that the fluctuations in
body movement and visual inspection were inversely
coupled. In the second experiment, the appearance of
new visual stimuli was used to alter ongoing visual
inspection and body movement to test the stability of
the coupling. Analyses focused on the existence of the
coupling before and after the presentation of the new
visual stimuli and on the relative timing of the re-
emergence of the fluctuations in movement and inspe-
ction following orienting.

Subjects

Infant subjects were identified from birth notices in
the local newspaper. Usable data were obtained from
33 healthy, full-term, 3-month-old infants (18 males).
Postnatal age at the time of testing was 80 to 91 days
($M = 85$). Most infants ($n = 26$) were studied between
8:00 a.m. and noon; the remaining infants were stud-
ied between noon and 2:30 p.m. Data from an addi-
tional 25 infants could not be used due to inattention
or excessive fussiness.

Procedure

Infants were randomly assigned to one of three
conditions: (a) no change (noc) or (no change) in
the visual environment, $n = 11$, (b) temporary change
(temp), $n = 10$, or (c) permanent change (perm),
$n = 12$. In the two change conditions, the two visual
stimuli (stuffed toys) were replaced with a new pair
after 4 min of data acquisition. In the temp condition,

the second pair of stimuli was displayed briefly (3–
9 s), and then the original pair was redisplayed for the
remainder of the session (4 min). In the perm condit-
ion, the second pair of stimuli was displayed for the
rest of the session (4 min). Given the time required to
rotate the new stimuli into position and then rotate the
original stimuli back into position, the stimuli in the
temp condition were in motion twice as long as in the
perm condition. Infants had to provide at least 7 min
of continuous data to be included in the analyses.

Infants faced a black central screen; the two stimuli
were visible through holes in the screen. The visual
stimuli were identical, 3-D toys (Big Birds or
dalmation dogs). Each Big Bird toy was mounted
back-to-back with a dog toy on a horizontal bar. The
bar was rotated by hand to reveal the pair of toys on
the reverse side of the first pair presented. Infants
could see the toys move as the bar was rotated. In the
two change conditions, half of the infants were
presented with Big Bird in Phase 1. In the no change
condition, half of the infants were presented with Big
Bird toys and half with the dog toys. Infants were
randomly assigned to toy sequence (dog first or Big
Bird first). Toys were presented 91 to 102 cm from the
infant's face and were centered vertically along the
infant's nominal line of sight. The toys subtended
12×14-degree (Big Bird) and 12×12-degree (dog)
visual angle and were separated (center to center) by
27-degree visual angle.

Data Reduction

The duration of body movements in each successive
1-s interval was determined by counting the number
of 0.1-s bins in which the filtered movement sensor
output exceeded a positive or a negative threshold.
Thresholds were determined separately for each
infant. The duration of inspections on either of the
two stimuli in each of the 1-s intervals was determined
by counting the number of 0.1-s units in each second
in which the infant was looking at either toy. Shorter
intervals were used in Experiment 2 to increase the
temporal resolution of some of the analyses. For some
analyses (indicated later), the movement and inspec-
tion time series were smoothed as in Experiment 1 to
remove fluctuations faster than typical CM.

Data Analysis

Coupling Between Movement and Inspection. As in
Experiment 1, evidence for coupling between the
directions of change in body movement and visual
inspection in the data of Phases 1 and 2 was sought by

examining periods of increasing (or decreasing) movement defined as periods during which the derivative of the smoothed movement time series was positive (or negative). For each of these periods, the percentage of 1-s intervals that inspection was changing in the opposite direction (i.e., the derivatives of the smoothed time series had opposite signs) was calculated.

Effects of the Change in Visual Stimuli on Movement and Inspection. Body movement and visual inspection immediately before and after the presentation of the new stimuli were compared across conditions to assess the effects of the manipulation on motor and visual activity. It was hypothesized that the introduction of the new visual stimuli would elicit an orienting response characterized by initially high levels of visual inspection of the stimuli and a brief cessation or significant decrease in movement (Graham, Anthony, & Zeigler, 1983; Spinks & Siddle, 1983). Evidence of orienting following the presentation of the new stimuli would indicate that the change in the visual environment effectively altered the infant's current patterns of inspection and body movement.

The movement and visual inspection data used in the analysis of short-term responses to the new stimuli were the unsmoothed time series of duration of activity per second. The average level of activity in the 5 s preceding the appearance of the new stimuli was compared to the average in the 5 s after the stimulus change was initiated. These two 5-s periods were contiguous. Data from 1 infant were excluded from this analysis because the time (within 1 s) of the appearance of the new stimuli could not be determined accurately.

Return of Fluctuations in Movement and Inspection After Orienting. This analysis examined the relative timing of the return of coupled fluctuations in movement and inspection following orienting. To be included in this analysis, infants had to meet both an inspection criterion and a movement criterion of orienting to the new stimuli. Of the 21 infants in the temp and perm conditions, 19 met the looking criterion (at least 2 consecutive s of visual inspection in the first 5 s after the new stimuli appeared). Of these 19 infants, 15 also met the movement criterion (cessation of body movement for at least 1 s in the first 5 s after the new stimuli appeared). To determine whether any systematic changes in movement preceded the eventual *decrease* in looking following orienting (Bornstein, 1985), we examined movement in the seconds before the point at which inspection fell to 50%. Ten infants provided at least 7 s of movement data for this analysis.

Results

Inverse Coupling. During periods when body movement was increasing (or decreasing), visual inspection was changing in the opposite direction in $58 \pm 2\%$ of the 1-s intervals in Phase 1, which exceeds the expected value in the absence of coupling (50%), $t(32) = 3.7$, $p = .001$. The results were similar in Phase 2: $61 \pm 2\%$ of the 1-s intervals in no change, $t(10) = 5.1$, $p < .001$; $56 \pm 1\%$ of the 1-s intervals in temp, $t(9) = 4.1$, $p = .003$; and $62 \pm 2\%$ of the 1-s intervals in perm, $t(11) = 5.5$, $p < .001$. A Condition (No Change, Temp, Perm) $\times$ Phase (1,2) ANOVA with repeated measures on phase revealed no effect of condition, $F(2, 30) = -2.8$, $p = .08$, or phase $F(1, 30) = .75$, $p = .39$, and No Condition $\times$ Phase interaction, $F(2, 30) = .04$, $p = .96$, on the degree of coupling.

Effects of the Change in Visual Stimuli. For both movement and visual inspection, infants' responses to the appearance of the new stimuli were examined using Condition $\times$ Phase (No Change, Temp, Perm $\times$ 1, 2) ANOVAs with repeated measures on phase. For movement, there were main effects of condition, $F(2, 29) = 5.2$, $p = .01$, and phase, $F(1, 29) = 6.7$, $p = .01$. The Condition $\times$ Phase interaction was not significant, $F(2, 29) = 2.9$, $p = .07$. The decrease in movement in the temp condition differed from the increase in the no change condition, $t(19) = 2.7$, $p = .02$. However, the decrease in movement in the perm condition did not differ from the slight increase in the no change condition, $t(21) = 1.5$, $p = 0.2$, nor were the decreases in movement in the temp and perm conditions different from each other, $t(19) = -.98$, $p = .34$ (Figure 2).

Similarly, for visual inspection there were main effects of condition, $F(2, 29) = 7.9$, $p = .002$, and phase, $F(1, 29) = 12.1$, $p = .002$, and the Condition $\times$ Phase interaction was not significant, $F(2, 29) = 2.6$, $p = .09$. The increase in inspection in the temp condition was greater than that in the no change condition, $t(18) = -2.3$, $p = .03$. However, the increase in inspection in the perm condition was not greater than that in the no change condition, $t(21) = -.52$, $p = .61$. In addition, the increases in inspection in the temp and perm conditions did not differ from each other, $t(19) = 1.7$, $p = .11$.

Return of Fluctuations in Movement and Inspection After Orienting. To determine whether systematic changes in movement preceded the decrease in looking after orienting, we analyzed movement in the seconds before the point at which inspection fell to
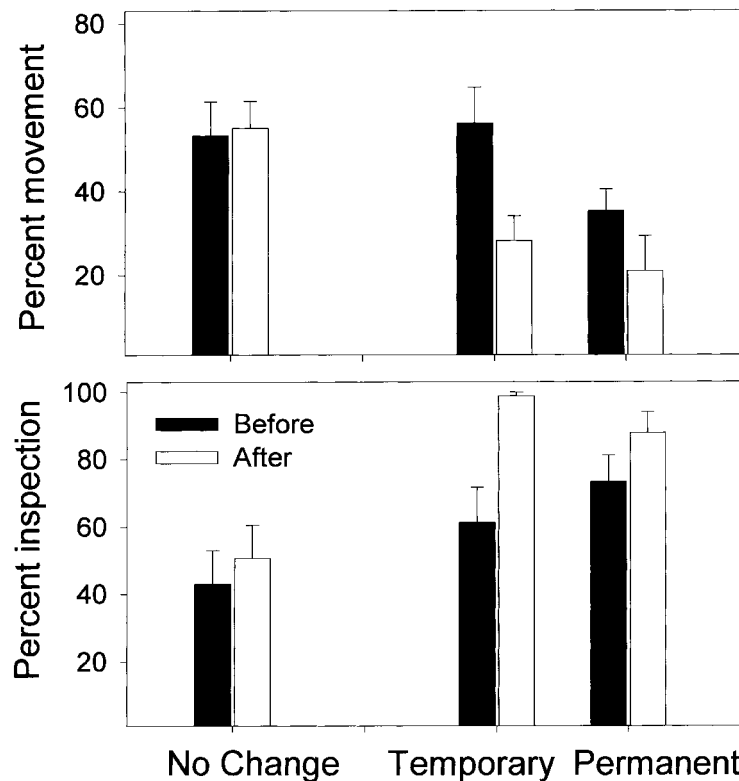
FIGURE 2 (Top) Percent movement during the 5 s before (filled bars) and 5 s after (open bars) the change in visual stimuli. (Bottom) Percent inspection during the 5 s before and 5 s after the change in visual stimuli. Data from the No Change condition is the last 5 s at the end of Phase 1 and the first 5 s of Phase 2. Error bars depict standard errors.

50% using a Condition × Time (Temp, Perm × 7 1-s intervals) ANOVA with repeated measures on time. There was a main effect of time, $F(6, 48) = 3.8$, $p = .004$ ($p = .03$ with the Greenhouse–Geisser correction), but no effect of condition, $F(1, 8) = .02$, $p = .90$, or a Time × Condition interaction, $F(6, 48) = .58$, $p = .75$. Post hoc, paired comparisons (Fischer PLSD) indicated significant differences ($p < .05$) between movement 7 s before the decrease in looking and movement 3, 2, and 1 s before the decrease in looking (Figure 3).

A one-way, repeated measures ANOVA of percent visual inspection indicated that looking decreased significantly over the period prior to and including the point at which the criterion was met, $F(7, 63) = 44.4$, $p < .001$. Post hoc, paired t tests indicated that the drop in inspection occurred primarily in the last second before the criterion was met. The comparison of percent inspection means from Second 1 to Second 0 indicated a significant drop in percent looking, $t(9) = -12.\ 7$, $p < .001$; all other comparisons of

adjacent means were not statistically significant ($p > .05$) (Figure 3).

The duration of the first bout of sustained inspection after the change in visual stimuli ranged from 5 to 88 s (18.6 ± 21.4). Infants in the temp and perm conditions did not differ in the duration of sustained looking, $t(18) = -.13$, $p = .90$.

DISCUSSION

Existence of Coupling

The results of Experiment 1 demonstrated that fluctuations in spontaneous body movement and visual attention were coupled in an inverse manner: During periods of increasing movement, visual inspection tended to be decreasing and vice versa. The inverse coupling between the directions of change means that while infants can move and look at the same time, changes in movement or inspection
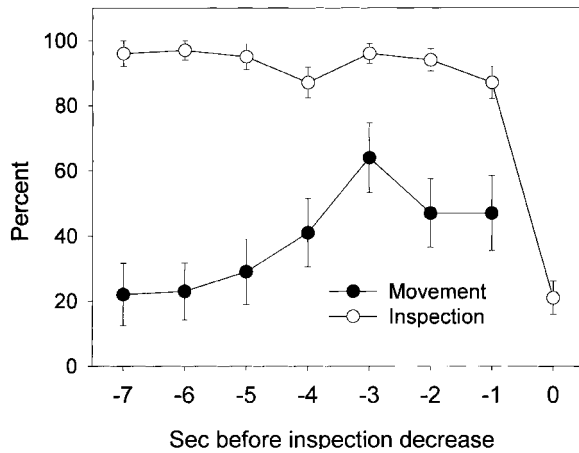
FIGURE 3 Percent movement and inspection for each second preceding the first decrease in inspection following the presentation of the new stimuli ($n = 10$). Error bars depict standard errors.

tended to be accompanied by opposite changes in the other.

Stability of Coupling

The results of Experiment 2 demonstrated that the inverse coupling between fluctuations in body movement and visual attention was present both before and after the changes in the visual environment, which elicited transient decreases in movement and increases in inspection.

The changes in inspection and movement during orienting to the new stimuli were larger in the temp condition than in the perm condition. One likely reason for this difference is that the stimuli were in motion twice as long in the temp condition and therefore may have promoted greater orienting. Additionally, the baseline levels of inspection and movement for the infants in the perm condition were dissimilar from both the 50% midpoint and the respective Phase 1 means from the other conditions so that ceiling and floor effects might have contributed to the smaller magnitude changes observed.

The stable coupling between fluctuations in movement and visual inspection reveals a clear linkage between action and attention early in development that may have important consequences for the infant. First, the sustained, inverse pattern of the coupling may ensure an efficient (Rapp, 1987), balanced integration of looking and movement, both of which benefit the developing infant. In addition, that the coupled fluctuations can be interrupted, as demonstrated by the orienting response, permits

infants a great deal of flexibility in responding to environmental demands and acting on the environment.

Another possible consequence of coupling between movement and attention is that it may provide a foundation for the infant to begin to exercise greater motor control. Because infants' goal-directed actions emerge from spontaneous movements (Thelen et al., 1993), the early coupling of visual attention and spontaneous movement could facilitate motor learning as the infant explores the linkages between his or her looking patterns and body movements. For example, infants may learn to modulate their movements by selectively attending to objects or people. Infants' ability to modulate fluctuations in overall body movement may be a precursor to selective, goal-directed movement of the limbs.

Lead-Lag Relation Between Movement and Inspection

In Experiment 2, increases in movement systematically preceded the first decrease in sustained inspection following the change in visual stimuli despite a wide range of initial inspection times. It is not known whether the pattern of increasing movement preceding decreasing inspection is characteristic of the coupling or whether it is unique to the context of orienting. However, if the fluctuations in body movement consistently lead changes in inspection, then increases in movement may play a causal role in decreasing inspection. If fluctuations in movement do play a role in attentional disengagement, then the inverse coupling may promote visual exploration of the environment early in development (Robertson, 1993).

Further investigation of the function, development, and mechanisms of the temporal linkage between visual attention and body movements in early infancy is likely to reveal that the coupling of action and attention is pervasive and affects other behavioral systems. The presence of the coupling in both static and changing environments suggests that the inverse coupling also will be observed in rapidly changing contexts more common to infants, such as social interaction. Evidence already exists that the tempo of social interactions with infants is related to the fluctuations in infants' body movement (Lalley, 1993). Therefore, future studies of the dynamic relationship between body movement and visual inspection in young infants are likely to deepen our understanding of the fundamental interactions between action and attention and the roles they play in behavior and development.

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