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Variation and selection in the development of perception and action

Abstract

Human behavior is much more variable than traditionally assumed, and it is precisely because of this variability that many new responses are introduced into the behavioral repertoire. As individuals select and explore new behaviors, a distribution of intrinsic and/or extrinsic values drives each person to store and repeat those responses that are optimally successful. This principle of opportunistic selection is illustrated by examples from the development of interlimb coordination and postural control. It is concluded that variation serves multiple functions in organizing human behavior depending on the level of analysis and whether the variability is structured or completely random.

Introduction

One of the most remarkable characteristics of humans is the degree to which we change over time. From cradle to grave our thoughts and actions are continuously evolving and taking on new forms. Consider, for example, the relatively uncoordinated movements of the human infant and how quickly those movements are transformed into skilled actions that support reaching, standing, walking, etc.. Likewise, the mental concepts of a preschool child are fragmented and incomplete relative to those of a grade school child or someone even older. Later in life, some of our basic processing skills may begin to falter even as we continue to acquire new knowledge about the world. Developmental psychologists have been quite successful in describing many of the changes that take place across the life span. Yet, the *explanation* for these developmental changes has proven much more elusive than one might expect.

Most of the traditional theories of behavioral development emphasize stable patterns of performance that are interrupted by temporary and abrupt changes in behavior. From this perspective, it is difficult to appreciate how and why behavior changes, and we are often left with incomplete or mysterious explanations to account for the development of new forms.

Recent research is beginning to challenge this common perspective by revealing that behavior is much more variable than assumed previously, and that this variability is not merely a correlate of change but instead is often a contributor to the change itself (Bertenthal & Clifton, 1998; Newell & Corcos, 1993). In the remainder of this

paper, I will review some evidence for this proposal and show specifically how increases in the variability of human movements contribute to developmental as well as real-time changes in perceptuomotor performance.

Challenges to the Traditional View of Development

By definition, human development is a complex system, and like other complex systems it reveals global or long-term stability along with local or short-term variability. Until recently, the detailed analyses necessary to reveal short-term variability were typically unavailable, but this situation is gradually changing as developmental researchers are beginning to engage in more longitudinal studies and microgenetic analyses (e.g., Bertenthal & Clifton, 1998; Siegler, 1994; Thelen, 1995).

As a consequence, it is becoming increasingly apparent that the fine structure of behavior reveals considerable variation as a function of task, context and time. Siegler and Jenkins (1989) show, for example, that young children's addition strategies differ not only across individuals, but within individuals across testings sessions, and even from one problem to the next. This same type of local variability is also revealed at the neural level. Edelman (1992), for example, reviews evidence showing that patterns of the same nerve in genetically identical organisms or corresponding neurons in the same cortical column or on the right and left side of the same brain show considerable structural variability at a micro level of analysis. Not only does this evidence debunk the view that the brain is akin to a computer (in which all connections are fixed), but it also suggests that brain development is governed, not by a deterministic, but by a stochastic (or statistically varying) set of cellular processes, such as cell division, movement, and death.

Although developmental researchers are just beginning to examine behavioral variability, the findings are provocative and offer new insights into how and why behavior changes over time. One of the most important observations is that the level of variability in performance is far from constant and seems to increase at certain times in development (Bertenthal & Clifton, 1998; Thelen, 1995; Woolacott & Sveistrup, 1994). These intermittent increases in variability are not surprising given the many changes that occur in the organism or environment during development. For example, increases in muscle strength or the desynchronization in the movements of connected joints (e.g., hip, knee, and ankle), or the differentiation of the head and trunk afford the infant or child a greater repertoire of movement patterns for exploring the environment. Likewise, greater demands by the environment, such as maintaining balance against gravity in more challenging postures, or responding to new task demands presented by parents or self introduce more variability in performance.

Note that increases in the variability of new movements are never completely random because they are always constrained by structural and functional demands, such as limb mass and length, gravitational and centripetal forces, and the properties of objects. It is even more important to note that these variations in the behavioral reper-

toire are often adaptive, because they offer the individual an opportunity to select from a larger set of responses, and thus increase the likelihood of performing successfully. As individuals select and explore new behaviors that emerge with development, a distribution of intrinsic (e.g., minimization of energy) and/or extrinsic (e.g., intentional) values drive each person to store and repeat those actions that are optimally successful (Sporns & Edelman, 1993).

In essence, this new view of behavioral development follows the principles of variation and selection that are similar to those introduced by Darwin to explain evolution. Although the analogy is not perfect, there are some interesting parallels between the application of these principles to evolutionary change and behavioral development. According to Darwin natural selection results from two factors: (1) Heritable Variation — In each living species there is variability, some of which is inherited by the offspring; and (2) Differential Reproductive Success — In each species, some individuals leave many surviving offspring, some leave few, and some leave none at all. At a behavioral level, the transmission of this type of variability from one situation to another is exactly what allows the organism to increase the probability of successful performance if it is presumed that more successful behaviors are stored and repeated more frequently than less successful behaviors. Also, it is interesting to note that these principles of variation and selection replaced a more static view in which each species was created according to some ideal type. Variation was postulated as just so much noise superimposed on the ideal. After Darwin, the variation itself was seen as real and important, and the notion of an ideal type was recognized as much less informative (Trivers, 1985). Likewise, this new perspective on behavioral development views variation as the rule, whereas stable forms of behavior are viewed as somewhat exceptional and less informative for understanding change over time.

The relevance of these principles for explaining change are nicely illustrated by some recent findings from the development of perception and action. Two phenomena will be reviewed. The first concerns the development of crawling, and, in particular, the selection of a specific interlimb pattern for optimizing prone progression following the transition to a hands-and-knees mode of crawling. The second concerns the changes in variability of postural sway associated with the development of sitting. In both examples, developmental changes are accompanied by a proliferation of new behavioral forms that are subsequently pruned, and then followed by increasing variability in the remaining forms. This latter form of variability allows for greater flexibility or adaptability in real time.

One caveat before proceeding. This new emphasis on variation and selection is not meant to imply that studying regularities in development is unimportant or even inconsistent with the current conceptual framework. In order to identify and analyze the local variability of a system associated with change, it is first necessary to identify the portions of behavior associated with global or long-term stability (Bertenthal & Clifton, 1998; Thelen & Smith, 1994). The presence of this dualism in behavior is useful for understanding why the functionally significant role of variability was often overlooked. Most actions typically appear stable and consistent at a global or macroscopic level, but they are revealed as variable at a more microscopic or

detailed level of analysis. For this reason, neither local variability nor global stability should be generalized across different levels of analysis, because both variability and stability depend on the level of magnification of the lens through which the behavior is observed. In the following discussion, it is helpful to keep in mind that the presence of variation in behavior depends intimately on the scale at which it is measured..

Transition to Hands-and-Knees Crawling

A common observation by many of the early contributors to the motor development literature was that infants begin some form of forward prone progression, such as belly crawling, around 32 weeks of age and progress to hands-and-knees crawling by around 42 weeks of age. Although a number of detailed longitudinal studies on the development of crawling were conducted (e.g., Burnside, 1927; McGraw, 1941), few studies addressed directly the interlimb patterning shown by infants following the transition to hands-and-knees. Moreover, the sparse findings that are available on this issue are inconsistent. Burnside (1927), for example, reported that infants move their limbs in diagonal couplets, such that diagonally opposite limbs (e.g., right arm and left leg) move synchronously, 180° out of phase with the other two limbs. Other researchers (e.g., Hildebrand, 1967) suggested that infants move only one limb at a time in a fixed sequential order.

From a theoretical standpoint, this particular transition is especially interesting because supporting the trunk and head above the ground places additional constraints on how the four limbs are sequenced when moving (see Figure 1). Prior to this transition, it is possible for infants to move one or more limbs in any sequence without threatening their balance. Once infants begin to support their trunks with their arms and legs, it is necessary to accommodate the dual demands of maintaining balance and moving forward simultaneously. Logically, there are many different interlimb sequences that would satisfy this goal, but they are not all equally efficient. For example, infants could move one limb at a time analogous to the walking gait of a horse or other quadruped. Alternatively, they could move two limbs at a time, such as diagonally opposite limbs (left arm and right leg followed by right arm and left leg) or homologous limbs (right arm and leg followed by left arm and leg). In fact, research on quadrepedal gait patterns suggests that there are many different possibilities (Hildebrand, 1967).

A few years ago Bob Freedland and I (Freedland and Bertenthal, 1994) set out to investigate whether this transition was consistent with the principles of variation and selection as previously outlined. In general, most animals including humans, use more energy for locomotion than for any other function (Alexander, 1992). It is thus to their advantage to select patterns of gait that keep energy costs as low as possible.

By now, it is well established that terrestrial animals select a gait pattern that minimizes energy expenditure at the speed they are locomoting (e.g., Alexander 1992).

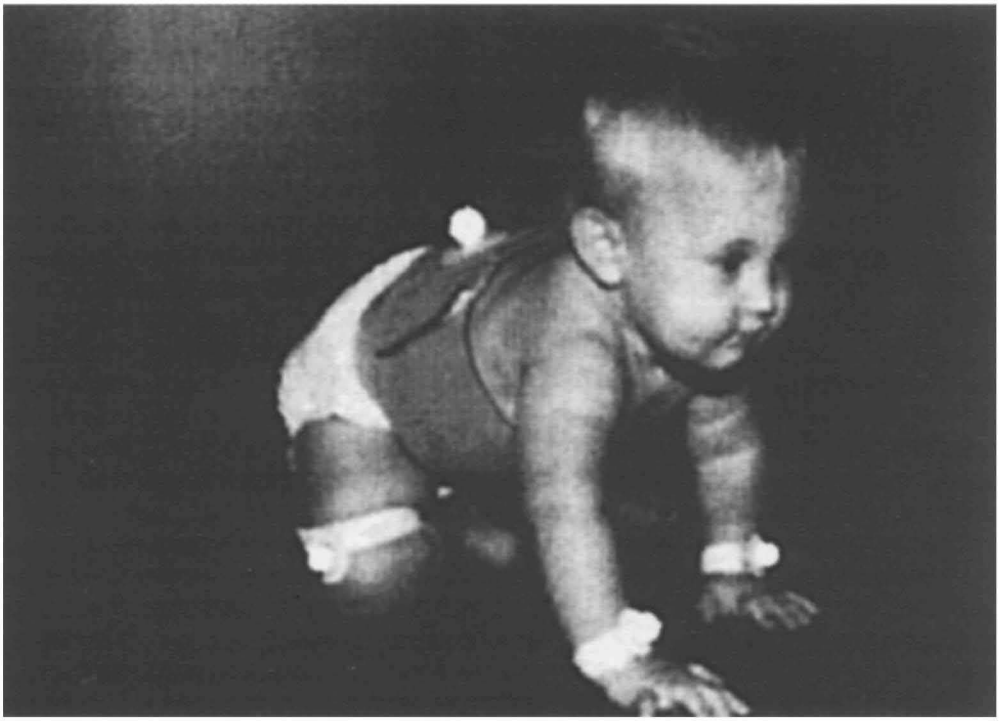

Fig. 1. Photograph of infant on hands and knees with markers affixed to left and right wrists, left and right knees, and back.

One of the most convincing examples of this principle is provided by a study conducted by Hoyt and Taylor (1981) in which they trained horses to walk, trot, and gallop on a motorized treadmill moving at different speeds. The results revealed that there was a speed for each gait where metabolic rate (i.e., rate of oxygen consumption divided by speed) reached a minimum value and increased at both lower and higher speeds. Additional observations revealed that freely moving horses tended to move at energetically optimal speeds. When horses were instructed to extend their gaits beyond the normal range of speeds, oxygen consumption was higher than it would have been if the animal continued to use its preferred gait pattern. Taken together, these results provide compelling evidence that horses spontaneously select the energetically optimal gait pattern; moreover, these animals switch gaits at speeds where the gait pattern no longer minimizes energy consumption. In this example, selection of the optimal gait pattern was clearly not based on any specific instruction, but instead was based on satisfying an implicit goal.

When considering human infants, we reasoned that minimization of energy coupled with optimal flexibility for moving on the ground would dictate which interlimb crawling pattern would be selected. According to Alexander (1992),

the size and speed at which the human infant moves suggests that a diagonal gait pattern (i.e., two diagonally opposite limbs move during the first half of the cycle and the other two limbs move during the second half of the cycle) would produce the most energetically efficient form of movement, because this pattern would result in the least amount of movement for the infant's center of gravity.

In addition, there is an advantage to supporting the head and trunk with only two as opposed to three limbs, because this interlimb pattern minimizes the amount of support surface that must be clear to allow any quadruped to move on that surface (Raibert, 1986).

Two specific issues were addressed by this study. The first was to test whether infants converged on a diagonal gait pattern once they began crawling on hands-and-knees.

The second objective of this study was to compare the variety and frequency of interlimb patterns displayed by infants prior to and following the transition to hands-and-knees crawling. If the emergence of hands-and-knees crawling follows the principles of variation and selection, then we would expect the presence of many different interlimb patterns prior to this transition, and the selection of the most dynamically efficient pattern following this transition.

In order to address these questions, we conducted a short-term longitudinal study with 6 infants. These infants began visiting our lab as soon as their parents reported that they could demonstrate some form of prone progression, and they continued coming every week until they had all been crawling on hands-and-knees for at least 6 weeks. At the lab, infants were given repeated trials in which they crawled toward their mother.

We videotaped their behavior, and also measured their limb movements with a motion analysis system. Figure 1 shows the anatomical locations of the light reflectant markers used for tracking limb movements. By comparing the onset and offset of the swing and stance phase of each limb, it was possible to assess the phasing of the limbs and also to normalize these movements relative to the gait cycle.

The first set of analyses compared the number of different crawling patterns displayed by infants before and after the onset of hands-and-knees crawling. At a descriptive level, our analyses revealed that infants produced many more crawling patterns preceding as opposed to following the onset of hands-and-knees crawling. Prior to this transition, infants sometimes moved all four limbs in a specific sequence, sometimes randomly, sometimes only two or three limbs were moved, and sometimes infants would pull or drag their torsos, while at other times they would try to lift their torsos and fall forward. At a quantitative level, the results revealed that a diagonal gait pattern was rarely displayed prior to the onset of hands-and-knees crawling (see Figure 2).

By contrast, this interlimb pattern became much more frequent following the transition to hands-and-knees crawling.

In order to measure the patterning of the limbs more completely, we calculated the onset of the swing phase for each limb relative to the onset of the swing phase of the

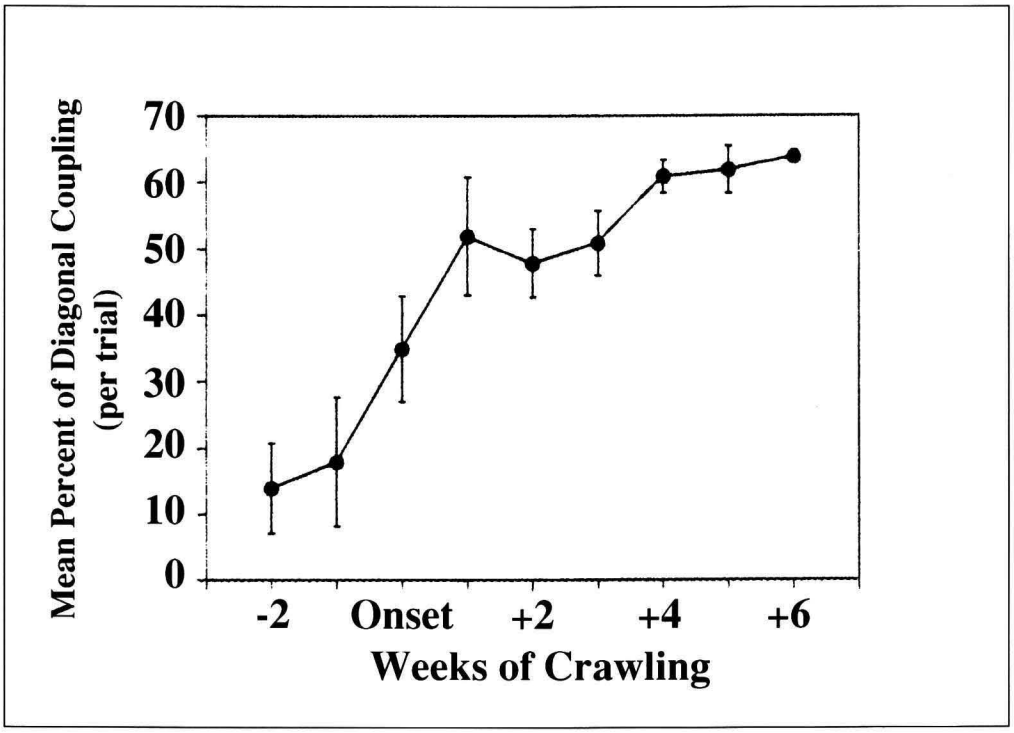

Fig. 2. Mean percent of time per trial that infants are supported by diagonally opposite limbs.

right arm (indexed by the right wrist marker). The temporal offsets between joint markers were normalized relative to the crawling cycle; thus, it was expected that the left wrist and right knee would show a 50% temporal offset relative to the right wrist, and that the left knee would show a 0% temporal offset relative to the right wrist if infants were following a diagonal gait pattern. As can be seen by the error bars in Figure 3, infants showed some variation in their gait patterns following the onset to hands-and-knees crawling, but they converged quickly to the point where they were employing a diagonal gait pattern with minimal variation.

These findings are important for two reasons. First, they show convincingly that the development of crawling is not simply replacing one stable behavioral pattern with another. Infants displayed many different crawling patterns prior to the onset of hands-and-knees crawling. There were significant inter-individual and also intra-individual differences. Different infants tended to select different crawling patterns with different frequencies, and the same infants tended to show considerable variability in their selection of crawling patterns from one trial to the next. This variability thus offered infants an opportunity to sample a range of different crawling patterns so that they were prepared to select reasonable candidates once the task became more demanding. (Adolph, Vereijken, & Denny, in press, report similar findings with a much larger sample.)

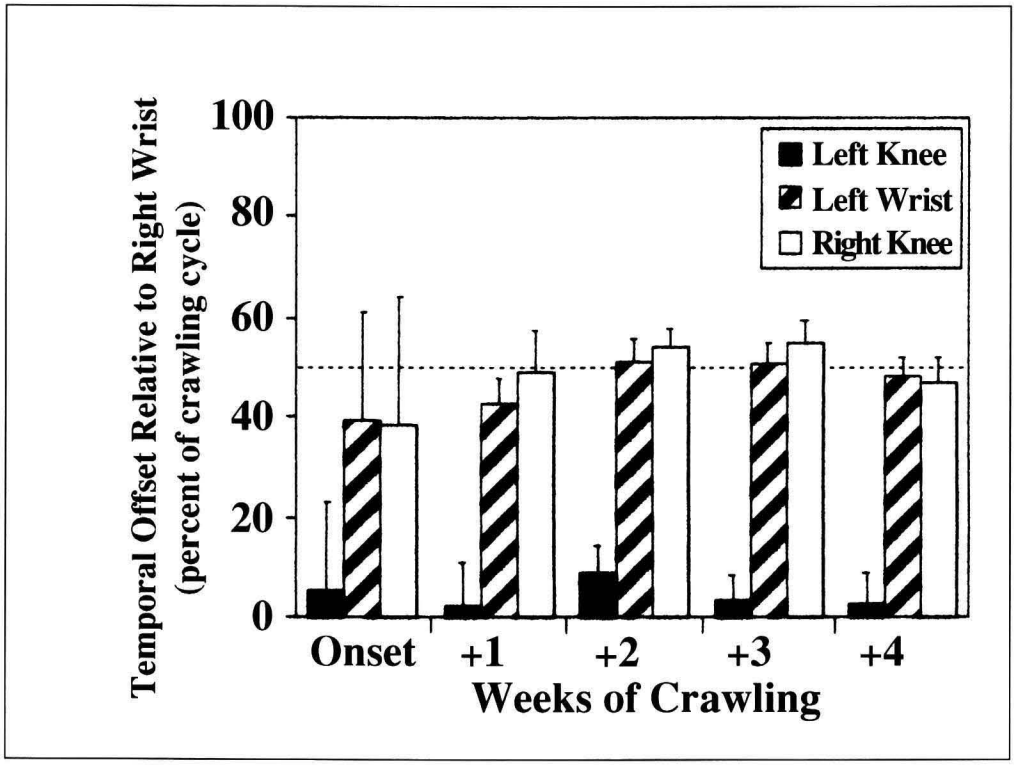

Fig. 3. Temporal offsets for the beginning of the swing phase of the 3 limbs (indexed by joint markers on the left knee, right knee, and left wrist.) Error bars = +1*SD*.

Second, a number of different crawling patterns could have satisfied the multiple demands of hands-and-knees crawling; nevertheless, infants quickly converged on the interlimb pattern that was the most dynamically efficient and flexible. This finding thus suggests that infants are biased to select behaviors that optimize intrinsic goals, such as minimization of energy.

Finally, the consistent selection of a diagonal gait pattern followed, rather than preceded, the development of hands-and-knees crawling. Thus, it appears that a diagonal gait pattern is induced by the specific requirements of hands-and-knees crawling rather than prescribed ahead of time by some genetic code or cognitive program

A second experiment by Freedland and Bertenthal (1992) suggests that the interlimb patterning that emerges with hands-and-knees crawling shows some flexibility in response to local conditions. In this study, 10-month-old infants were studied while ascending ramps that reached heights of 0, 6, 12, or 18 inches. Unlike the results from the preceding study, these infants did not consistently select the same interlimb pattern across trials. In fact, they showed considerable variability, especially with the highest ramp (see Figure 4). This finding is important, because it suggests that all measures of movement variability cannot be

interpreted in the same way. The variability revealed at the onset of hands-and-knees crawling (as presented in the previous study) is most likely attributable to lack of experience with selecting and producing a diagonal gait pattern. By contrast, the variability displayed in the ramp task by more experienced infants is most likely attributable to their selecting more conservative gait strategies in response to the additional demands placed on both strength and balance when ascending a ramp. In this latter situation, the more variable performance shown by infants is not an index of poor coordination or control, but rather it represents the adaptability available to infants to select different gait patterns depending on local conditions.

In sum, it appears that the results from this research on the transition to hands-and-knees crawling are consistent with a selectionist view of development. The production of many different interlimb crawling patterns prior to the transition increases the likelihood that the most adaptive response would be included in the infants' response repertoire for different conditions. Once this learning phase is completed, most of the variation in selecting an interlimb pattern occurs in response to variations in task and environment. An intriguing question prompted by this latter finding is whether movement variability is sometimes equivalent to the flexibility associated with skilled performance. In order to address this question we turn to the development of the visual control of sitting.

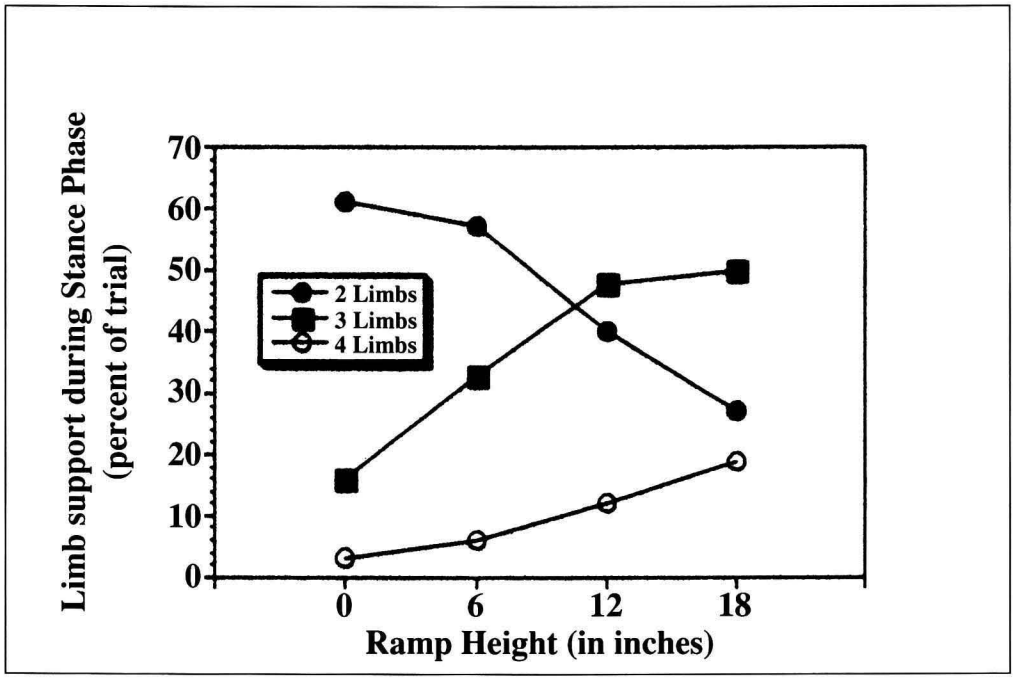

Fig. 4. Mean percent of time per trial that infants are supported by 2, 3, or 4 limbs.

Visual Control of Sitting

Infants begin sitting without support around 6.6 months of age (Bayley, 1969). The emergence of this new posture shares some important similarities with the development of hands-and-knees crawling. In both cases, it is necessary for infants to learn to dynamically control their own balance. While sitting, the center of mass is suspended above the surface of support and must remain balanced within its stability limits.

Moreover, the maintenance of equilibrium is a dynamic process in which the trunk and head are continually readjusting their relation to each other and to the rest of the body in response to movements of the body and other changes in the environment. For this reason, it is necessary that all body forces involved in maintaining postural equilibrium are perceptually modulated. It is well-established that proprioceptive stimulation contributes to postural control (Howard, 1986). In addition, more recent research suggests that visual information specifies self motion and contributes to the control of posture. The coordination between visual information and posture shows marked improvements following the development of independent sitting (see Bertenthal & Clifton, 1998, for a review).

We recently investigated the development of the visual control of sitting by placing infants in a moving room and measuring their postural responses (Bertenthal,

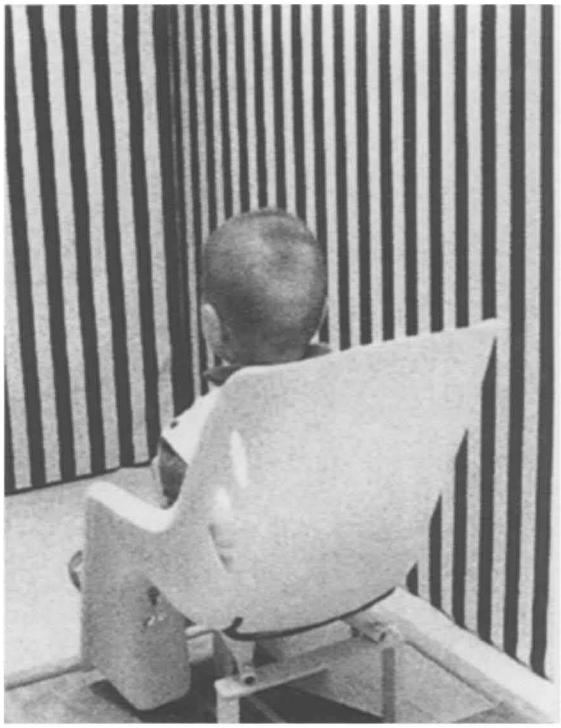

Fig. 5. Photograph of infant sitting inside of moving room facing the front wall.

Rose, & Bai, 1997). In essence, a moving room is a large boxlike enclosure with three walls, a ceiling, and a floor (see Figure 5). While the infant sits in the room facing the front wall, the walls and ceiling are rhythmically moved back and forth for a period of 10 sec. This movement induces a perception of postural sway (Bertenthal et al., 1997). Infants were presented with a series of trials in which the room was moved at different frequencies and amplitudes. If infants were capable of controlling their posture in response to the changing optical information, then their responses should covary with the movements of the room.

Infants at 5, 7, 9, and 13 months of age were tested in the moving room while sitting on a force plate so that we could measure their changing center of pressure (COP) during the trial (sampling rate = 50 Hz). Postural sway was operationalized as the change in COP from one sample to the next.

The first analysis was designed to assess whether postural sway covaried with the driving frequency of the walls, and whether this covariation changed with age. In order to address this question, it was necessary to transform the time series for wall movements as well as the time series for postural sway to the frequency spectrum with a fast Fourier transform. It was then possible to assess the percent variance of

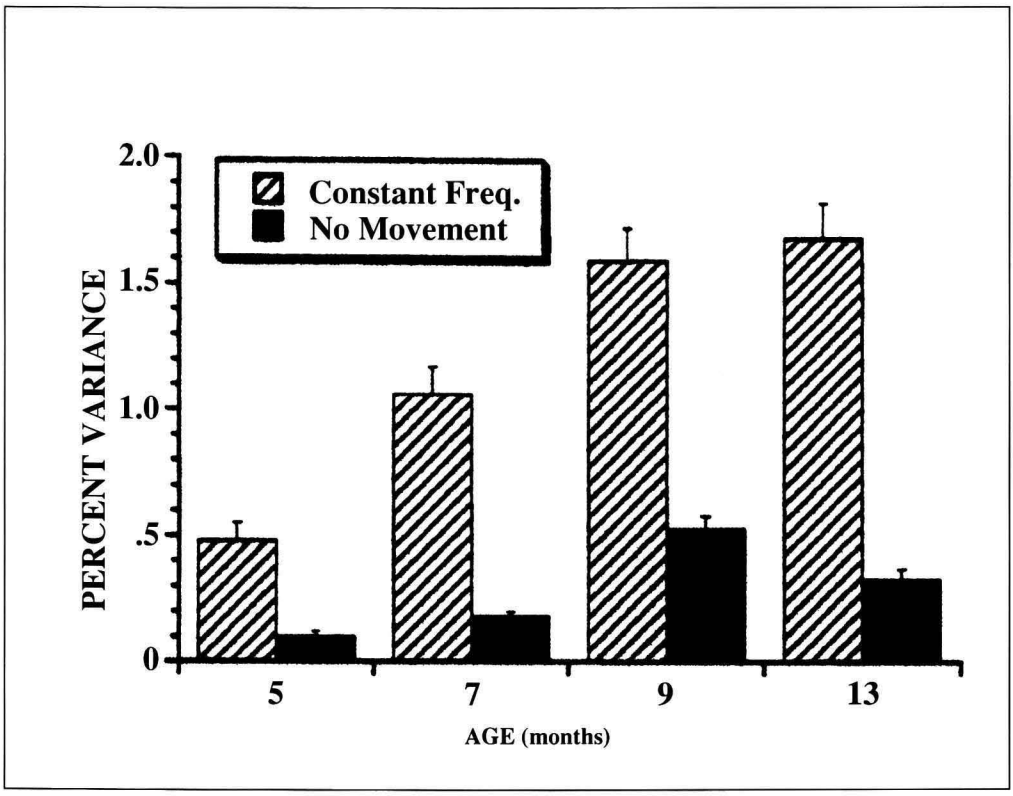

Fig. 6. Mean magnitude of spectral density function (+*SE*) calculated at the wall movement frequency as a function of condition and age.

postural sway that matched the driving frequencies of the wall movements. We also assessed the percent variance of postural sway at the driving frequencies in a baseline condition (i.e., no wall movement) to insure that infants' responses were indeed coupled to the visual information. As can be seen in Figure 6, postural sway at the driving frequencies showed a substantial increase as a function of age, whereas postural sway measured at those same frequencies in the no movement condition was significantly less at every age. This finding thus suggests that infants learn to structure their responses to the visual information, and that this coupling shows a significant improvement between 5 and 9 months of age.

Based on the preceding analysis, it is not entirely clear whether developmental changes in the visual control of sitting are systematically related to changes in movement variability. One possibility is that this variability is initially due to poor stability, and it is precisely because of this greater variability that younger infants show poorer coupling between the wall movements and their postural sway. In order to test this interpretation, we assessed the total variability of infants' postural responses by calculating the root-mean-square (RMS) of their changing center of pressure on each trial. (Recall that the preceding analyses were restricted to the variability associated only with the driving frequencies of the walls. By contrast, the RMS assesses the total variance of the changing COP and is very similar to a measure of the total power (or variance) of the entire frequency spectrum.) Interestingly, the results from this analysis did not completely support the preceding interpretation. As can be seen in Figure 7, movement variability does not show a linear decrease with age. Instead, this measure conforms to a U-shaped function where 7-month-old infants show the least amount of sway variability and both younger and older infants show greater amounts of sway variability. Of course, this type of developmental function is quite familiar in the motor learning literature.

During the development of new motor skills, it is not uncommon for individuals to begin learning a new skill by temporarily increasing muscle stiffness to reduce chances of producing highly variable movements that threaten balance or the outcome of the action (Bernstein, 1967).

It thus appears that total sway variability is not always a measure of poor stability; otherwise it would be necessary to conclude that 9- and 13-month-old infants show less postural control than do 7-month-old infants. This is simply not true! A more likely interpretation of this result is that postural stability is not always consistent with minimization of movement. In most traditional tasks designed to assess postural control, the goal is specifically to minimize movement. Yet, the goal in the moving room task is not to minimize movement, but rather to respond as quickly and accurately as possible to the perceived postural perturbation. This type of dynamic task benefits from a greater dispersion of movement as long as the movement is structured by the driving frequencies. As such, this increased movement variability translates into greater flexibility and accuracy (Bertenthal et al., 1997). It is unlikely that this same explanation applies to the performance of the 5-month-old infants because they were truly unstable (i.e., they could not yet sit without support). Thus, the interpretation for the magnitude of the RMS differs as a function of whether infants are capable of controlling their own sitting posture.

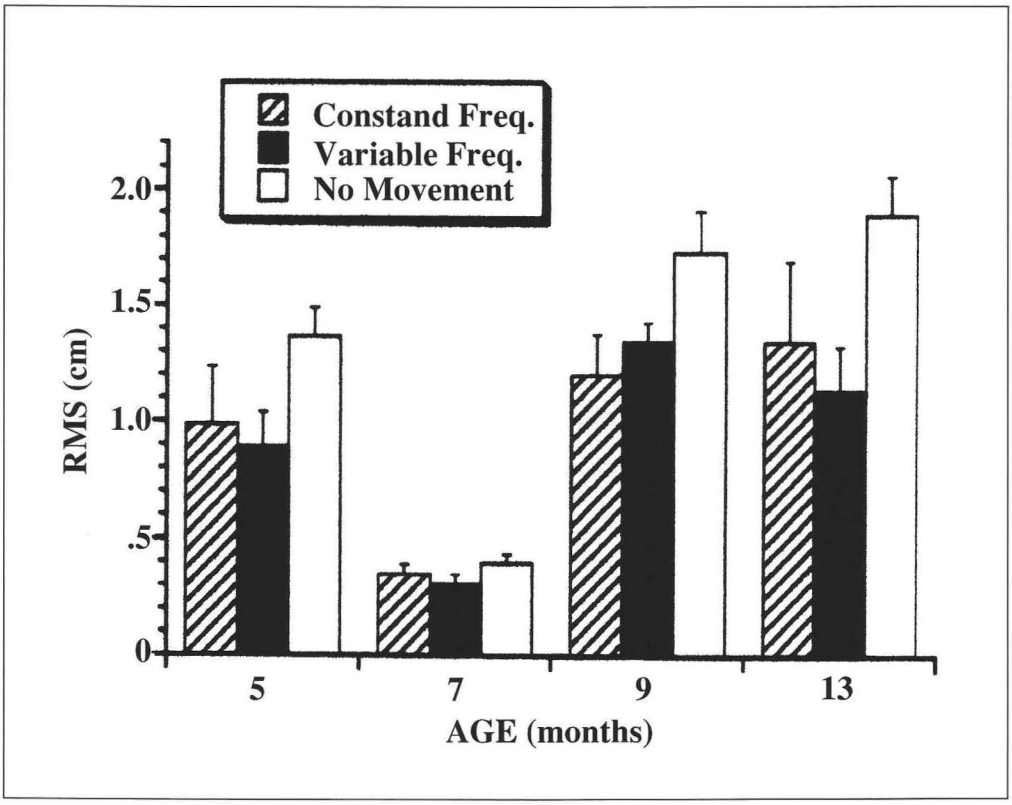

Fig. 7. Mean root-mean-square (RMS) of postural sway (+*SE*) as a function of condition and age.

Nonlinear Analyses of Movement Variability

In view of the preceding results, it appears that measures of variable performance are ambiguous without additional clarifying information, It is not necessarily the case that movement variability predicts either better or poorer performance. There are many situations, such as postural responses to a moving scene, that demand sufficient movement to enable detection of a perturbation when it occurs (Riccio, 1993).

In such cases, the variable movements that are structured by the situation offer greater flexibility to respond to local conditions than do more constrained movements (Bertenthal et al., 1997). If, however, these responses are not structured by the situation, then the likelihood of a successful performance decreases. The implication from this research is that variation in performance can be structured or unstructured, and the consequences of this difference are quite substantial.

This distinction between structured and unstructured movement variability is similar to that seen in the perception of movement.

An excellent example involves the presentation of points of light on a computer screen that are programmed to move as if attached to the major joints and head of a

person walking. When observers are presented with these displays they perceive them instantaneously as depicting the structure of the human form (Bertenthal & Pinto, 1994). By contrast, these same moving point-lights are perceived as merely noise if the spatial relations between the point-lights are scrambled. In this latter display, the absolute motions of the point-lights are identical to the absolute motions in the former display. Yet, the point-light motions recognized as the human form are spatially structured to conform to a coherent figure, whereas the point-light motions in the scrambled display do not conform to a familiar structure. It is precisely because of this additional structure in the biological motion display that the moving point-lights are perceived as depicting the human form.

The lesson from this example is that simply measuring the absolute amount of variation in a spatial array or a time series is not sufficient to ascertain whether that variation is structured.

For this reason, my colleagues and I are beginning to explore different methods for analyzing the structure of variable postural responses. It is especially important to assess whether the structure embedded in the time series is modeled adequately by linear pairwise correlations or whether nonlinear dependencies are also present in the data. If the only dependencies in the series are linear, then it is sufficient to test the data with linear stochastic models similar to those described in the previous section. If, however, there is a significant proportion of nonlinear structure in the data, then it is also necessary to test the data with nonlinear dynamical models; otherwise, this structure remains indistinguishable from the error variance calculated with a linear model.

In order to test whether a linear stochastic model was sufficient to describe the postural sway data, my colleagues and I (Boker, Schreiber, Pompe, & Bertenthal, 1998) followed the method of surrogate data testing (Kennel & Isabelle, 1992). For each selected time series, twenty surrogate data sets were generated which matched the source time series in mean, variance, distribution of scores and amplitude spectrum; but the phase spectrum was shuffled so that these surrogate data sets were limited exclusively to linear dependencies. The results revealed a significant difference between the measures calculated with the source time series and those calculated with the surrogate data on between 55% and 90% of the trials.

Accordingly, it was concluded that the time series of responses consisted of nonlinear as well as linear structure.

We then conducted a series of additional nonlinear dynamical analyses to test whether the previously reported developmental differences were still present when the nonlinear structure in the data was included in the analyses. One of the most practical and informative approaches for testing the nonlinear dynamical structure of relatively small time series is the method of false nearest neighbors (Kennel, Brown, & Abarbanel, 1992). In essence, this method determines the embedding dimension necessary for geometrically reconstructing an attractor. The time series is embedded in state spaces of increasing dimension and points that are artifactually close to each other are defined as false nearest neighbors. The resulting percentage of false nearest neighbors for each embedding dimension is then plotted against the corresponding embedding dimension, and the first minimum of the function specifies the best fitting embedding dimension (see Figure 8).

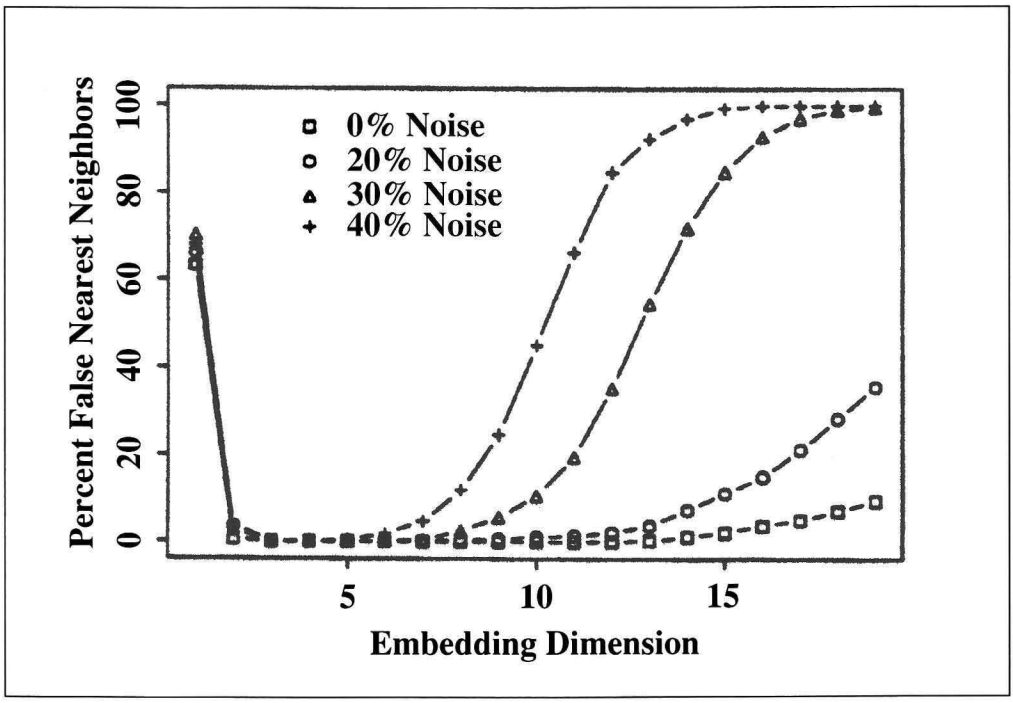

Fig. 8. False nearest leighbors curves for Gaussian noise adcded to a 1024 point time series of the Lorenz Equation.

This method is useful for estimating the dimensionality of the control system used for generating the time series.

It is also possible to use these false nearest neighbor plots to determine the relative amount of random variance or noise in the time series. The relation between Gaussian noise and the false nearest neighbor plot is illustrated in Figure 8. As can be seen, the effect of additive noise on the plot of a nonlinear signal (i.e., a time series of the Lorenz Equation) is systematically related to the slope of the curve on the right hand side of the plot. This slope increases as the amount of additive noise is increased. Thus, it is possible to compare plots of different time series to assess the relative amounts of random noise in the data.

This false nearest neighbors analysis was applied to the postural sway data discussed in the preceding section, and the results revealed that the best fitting embedding dimension was equal to 3 at every age (5, 7, 9, and 13 months). Thus, there was no evidence of a developmental change in the overall structure or general organization of the control system at any of the ages tested. By contrast, the slope of a regression line fit to the right side of the false nearest neighbors curve revealed that the amount of noise in the time series decreased significantly between 5 and 9 months of age. The value of this slope was calculated as 2.09, 0.57, 0.33, and 0.34 for 5-, 7-, 9-, and 13-month-old infants, respectively. It thus appears that the significant improvements in

postural control revealed by the previous linear analyses are mirrored by these nonlinear analyses. This finding is important because it is not necessarily the case that the results from the linear and nonlinear analyses will lead to the same conclusion about developmental changes.

Concluding Comments

One of the principal contributions of recent research on the development of perception and action is to focus attention on the variability of behavior. In contrast to conventional views of behavioral development which emphasize the structure of stable patterns of behavior, this new research is focusing on the structure of variable patterns of behavior. It is clearly no longer sufficient to think about variability in behavior as simply equivalent to stochastic noise or the error variance in a statistical analysis. There are multiple sources of variation in behavior, and these different sources contribute to our understanding of inter- and intra-individual variability.

From a developmental perspective, these patterns of variation change over time, and offer important insights into how children change with age. As we develop finer measures of variation and learn more about the ways these measures are structured, our understanding of both abrupt and more continuous changes will improve. If we are truly successful in this pursuit, it is possible that the explanation for developmental change will not seem as elusive in the future as it does in the present.

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