ARE THERE PHASE TRANSITIONS IN THE DEVELOPMENT OF EYE-HAND COORDINATION ?

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Our hypothesis is that developmental changes in eye-hand coordination (defined in terms of reaching and grasping objects) during the first six months of life carry the characteristics of a non-equilibrium phase shift. The presence of certain transition criteria such as sudden jumps, anomalous variance, bimodality and hysteresis can, at least in theory, demonstate that the changes in question have a dynamical basis.

A longitudinal study of one infant is reported in which we tried to identify stable developmental states of prehension during the first half year of life, as well as some of the transition criteria.

In using a dynamical approach, it is hoped that more insight will be gained into these states and the substitution of one state for another in motor development.

Key words: Development, infants, phase tansitions, eye-hand coordination.

Introduction

Over the last two decades, numerous physical, chemical, and biochemical systems have been shown to exhibit spontaneous transitions between different states or patterns of activity in response to changes in external conditions that are entirely unspecific as to the emerging pattern. These so-called phase transitions between macroscopically defined states have been described mathematically in terms of low dimensional dynamics (Haken, 1977; Thom, 1975; Prigogine, 1984). If a phase transition occurs in a system which is far from equilibrium, such as a moving animal, it is termed a non-equilibrium phase transition. During phase transitions of this type, fluctuations and nonlinearities play an essential role.

Motor development in early infancy has been characterized by phases, periods of little change sometimes referred to as stages or states, and phases of rapid change (Thelen & Ulrich, 1991). The mechanisms of developmental stability and change continue to be poorly understood. An initial step in tackling this problem is to ask whether the changes in question constitute non-equilibrium phase transitions. To do so requires an unambiguous definition of what is mean by a developmental transition.

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A developmental transition takes place when a *qualitative* change occurs from one macroscopically defined developmental state to another. At some critical point, the developmental state suddenly changes, for instance, from non-reaching to reaching or from reaching without grasping to reaching with grasping. New developmental states can be viewed as stable attractors, which become available once the proper boundary conditions have been established. In that case, this new state frequently appears. Through establishing the stability of a developmental state by means of registering its frequency of occurence, changes between states can be distinguished and investigated.

The goal of this paper is to introduce certain transition criteria which, if detected, can prove that developmental changes belong to the class of non-equilibrium transitions. The meaning of these criteria in relation to developmental transitions is discussed. Some of them are then illustrated by means of a longitudinal study of reaching and grasping in one baby.

Transition Criteria

Gilmore (1981) described eight criteria by which abrupt changes can be classified as discontinuous phase transitions (or catastrophes). He called these criteria 'catastrophe flags'. Five of them, namely, *bimodality, inaccessibility, sudden jumps, hysteresis* and *divergence,* appear simultaneously when a system is in transition. The other three, namely, *anomalous variance, critical slowing down* and *divergence of linear response* can be found prior to a transition, and therefore signal an upcoming transition.

Insights into the nature of these criteria can be gained by using a cusp model. A cusp model is one of the elementary catastrophes identified by Thom (1975), in which a transition is defined as a sudden change in a behavioural variable induced by a small and continuous change in an independent variable or control parameter. Although the control parameter is entirely unspecific as to the resulting pattern, its manipulation is instrumental in creating a new order at the macroscopic level. It controls in the sense of leading the system through its respective states of equilibrium.

Figure 1 shows different potential fields that belong to a potential function which can give rise to a cusp transition. By changing the control parameters of the potential function the minimum of the function changes as illustrated by the position of the black ball. The minima correspond with stable equilibrium states of the behavioural variable. Depending on the initial position of the behavioural variable, there are two possible pathways that can be followed, namely, from 1 to 7 and from A to C. Starting from 1, there is a change in the potential function when the control parameter on the x-axis increases which results in 3, with a local maximum and a new local minimum. At 4, the two local minima are similar. If two minima are present at the same time, the potential function is said to process *bimodality*. The local maximum between the two minima gives rise to a region of *inaccessibility*. In increasing the control parameter along the x-axis, we see that at 5 the original minimum reduces, that is the system cannot dwell there, and a new single minimum is established. At 6, the old minimum disappears and a *sudden jump* occurs to the remaining minimum. Going back from 7 to 1, the black ball will stay in the minimum until it disappears at 2; again a sudden jump occurs. The difference at which point a sudden jump occurrs as the control

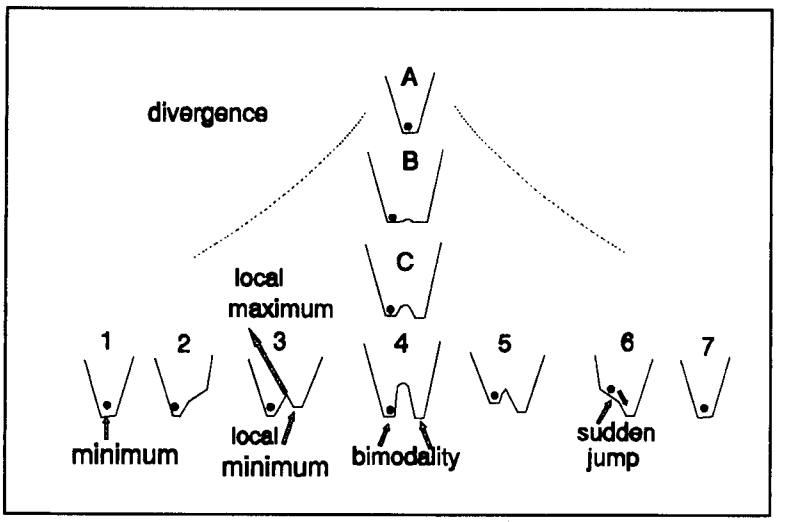

FIGURE 1 A potential landscape related to a cusp model. Different paths are possible, i. e. from A to C or from 1 to 7 or the reverse, depending on the initial starting positions and the direction of change of the relevant control variables.

parameter increases and decreases is called *hysteresis*.

Divergence takes place when two initial adjacent points diverge and result in two different states. When A constitutes the initial position and the variable on the y-axis increases, the ball can terminate in the left or right minimum, each of which correspond to a different states.

A complex system's many subsystems act to a certain degree as stochastic forces which manifest themselves as fluctuations in the macroscopical state (Haken, 1977). The size of these fluctuations can be measured by means of the variance in the occurrence of a particular behaviour. The more stable the attractor is, the smaller will be its fluctuations. Close to the transition, the fluctuations should become particularly large until a transition has occurred. These large fluctuations are called *critical fluctuations*.

An emerging equilibrium can also be a source of fluctuations. These fluctuations can be measured by means of the amount of switching between states. Critical fluctuactions and oscillations between states belong to the *anomalous variance* criteria.

Due to a flattening of the potential function as the transition point is approached, the response of the system to external forces becomes weaker, a phenomenon called *critical slowing down*. If a small perturbation is applied to the system, which drives it away from its stationary state, the time it takes for the system to return to the perturbed state, the so called relaxation time, will be larger than when a stable state is perturbed. Hence, the relaxation time is a measure of the stability of the system.

The last catastrophe flag, *divergence of linear response*, is a consequence of a perturbation near a transition; it results in a larger loss of stability and large oscillations of the behavioural variable. Thus, the magnitude of the variance increased.

Exemplifying the Criteria

How can we translate or operationalize Gilmore's transition criteria in the context of developmental transitions?

In what follows, each of the above-mentioned criteria will be further elucidated by means of specific examples.

1) *Bimodality.*

A necessary, but not sufficient requirement, for bimodality is that two qualitatively different behaviours are present. The requirement is not sufficient, because it should be possible to induce switching between the two behaviours (i. e. they should belong to the same behavioural dimension).

Bimodality within a person can be demonstrated by means of scaling the relevant control parameter(s) up and down. Two qualitatively different behaviours should be observed then.

By manipulating the control parameters, bimodal frequency distributions can be obtained.

2) *Inaccessibility.*

Inaccessibility is strongly related to the properties of bimodal score distributions. The middle part of the bimodal distribution is in principle also a particular behavioural mode, but because of its instability it is not accessible. However, by manipulating the proper control parameter(s) the inaccessible behavioral mode could stabilize again.

3) *Sudden jumps.*

Within a small range of time (as measured against the time scale of the behaviour), a qualitative change in the behaviour occurs while there is only a small change in the control parameter. In longitudinal data it is important to distinguish between a jump and an acceleration (Van der Maas & Molenaar, 1992). A jump occurs between two attractors, which correspond to two qualitatively different forms of behaviour. That is why this criterion is directly coupled to bimodality and inaccessibility. An acceleration implies a quantitative amplification of a particular type of behaviour. This might be due to an increase in strength of the underlying attractor.

4) *Hysteresis.*

To demonstrate hysteresis requires knowledge of changes in the values of the control parameter(s). Hysteresis only appears when the so-called Delay convention is satisfied. This is the case when the system changes only as the old state becomes unstable. When, in contrast the system always seeks out the lowest potential minimum it is said to be governed by the a Maxwell convention. The system switches state before the old state actually becomes unstable. In these systems hysteresis does not occur.

In studying the development of reaching, the muscle/fat ratio of the arm can be viewed as a control parameter. When this ratio increases and decreases over time, one can expect to see a jump to a qualitatively new behaviour and a regression to the old one respectively. If the jump and the regression appear at different muscle/fat ratios, hysteresis has occured, but not if they appear at the same ratio. It should be clear then that regression itself is not synonymous with hysteresis. To firmly establish hysteresis, the changes in the control parameter(s) need to be known precisely.

5) *Divergence.*

This criterion is important for revealing the stability of the behaviour at different initial situations. If small changes in an experimental setup result in different behaviours, divergence has occurred. An important implication of this criterion is that it directs one to the role of different test conditions in inducing behavioural change.

6) *Critical fluctuations.*

Frequency distributions of the occurrence of the behavioural categories provide information about the relative stablility of the underlying attractive states. The frequency of occurrence is proportional to its local stability. Thus, changes in frequency of occurrence indicate changes in the stability of the behaviour, therefore can be used to detect the presence of this criterion. Changes between states can also inform us about the stability of the system. If, for instance, two attractor states exist and neither of them is strong enough to win, competition between them is to be expected. Fluctuations between the two behaviours can then be observed.

7) *Critical slowing down.*

An increase in relaxation time before a transition is only expected in systems obeying the Delay convention. Perturbing, for example, a reaching movement has normally little effect on the total movement time, but prior to a transition large effects may be observed.

8) *Divergence of linear response.*

Perturbation of the system close to a transition will enlarge the fluctuations within the present behaviour or the amount of switching between those behaviours present.

Applying the Criteria to Developmental Transitions: Some Preliminary Results

In the remainder of this paper, we discuss data obtained in a longitudinal study of one infant. The purpose of the study is twofold: to identify stable developmental states of prehension during the first six months of life, and to find evidence for one or more of the above mentioned criteria. One boy was observed weekly from 8 to 24 weeks. No observations were made at week 17 because the subject was ill.

The infant was seated in a purpose-built chair, placed on a table at an angle of 70° to the horizontal plane. The seat and head supports could be adjusted in accordance with the size of the child. The baby was secured in the chair by belts.

A wooden dowel (14cm long and 5mm in diameter), with different colours, was presented to the baby. This object was attached to the tip of a black wooden rod 2.7 meters in length. A little bell was attached to the dowel to draw the infant's attention when necessary.

The sessions were videotaped with four cameras, two for each arm. Two cameras were placed above the infant's head, the other two being positioned obliquely left and right in front of the infant.

The dowel was presented at chest level along the midline section of the infant at a distance of about ¾ of his arm length. Four dowel orientations were presented randomly, namely, horizontal, vertical and 45° to the left and to the right. The total number of trials was dependent on the interest of the infant.

For the present purposes, video recordings were decoded into readily observable behavioural categories:

1) **non-reaching**, in which the hand did not come within a range of 5cm of the object;
2) **reaching without grasping**, in which the hand came within a range of 5cm of the object or contacted it:
   a) the hand is *closed* during the reaching attempt;
   b) the hand is *open* during the reaching attempt;
3) **reaching with grasping**, in which the hand contact the object, and then grasped it.

Using these categories, we sought for exitence of transitions between them. As already mentioned, frequency distributions of occurrence of the behavioural categories provide information about the relative stability of the underlying attractor states.

The transition from non-reaching to just reaching is shown in Figure 2. Not present at 8 weeks (session 1), reaching activity increases rapidly up to 12 weeks (session 5). In dynamical terms, this probably means that reaching has become a stable attractor. However at 16 weeks (session 9) a regression in the amount of occurrence of reaching occurred. It is probably due to the establishment of a new state, namely, grasping (see Figure 3).

The transition from reaching to that involving grasping is shown in Figure 3. At week 13 (session 6) grasping suddenly emerges. After that, a jump to a high grasping activity level occurs. A jump can be illustrated by means of a multiple regression analyses. We define two independent variables, one continuous and the other discontinuous, with a real jump between week 15 and 16 (session 8 and 9). We found that two variable together explains 84% of the data ($R^2 = .8433$). However, only the discontinuous variable has a significant (Beta continuous .0643, $p > .79$: Beta discontinuous .8640, $p < .05$) linear relation with the observed grasping data. The conclusion is that the

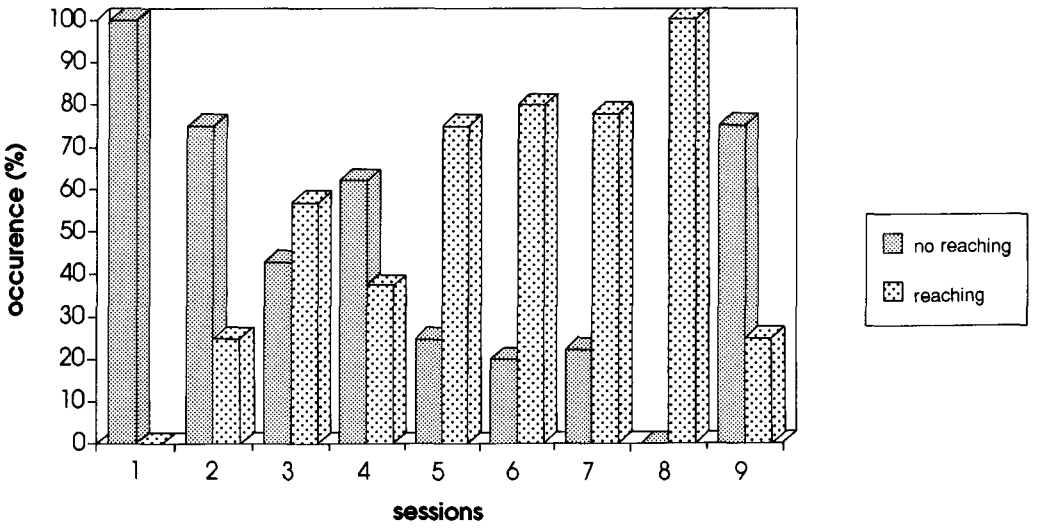

FIGURE 2 The emergence of reaching. The percentage of occurrences of non-reaching and reaching from 8-16 weeks of life.

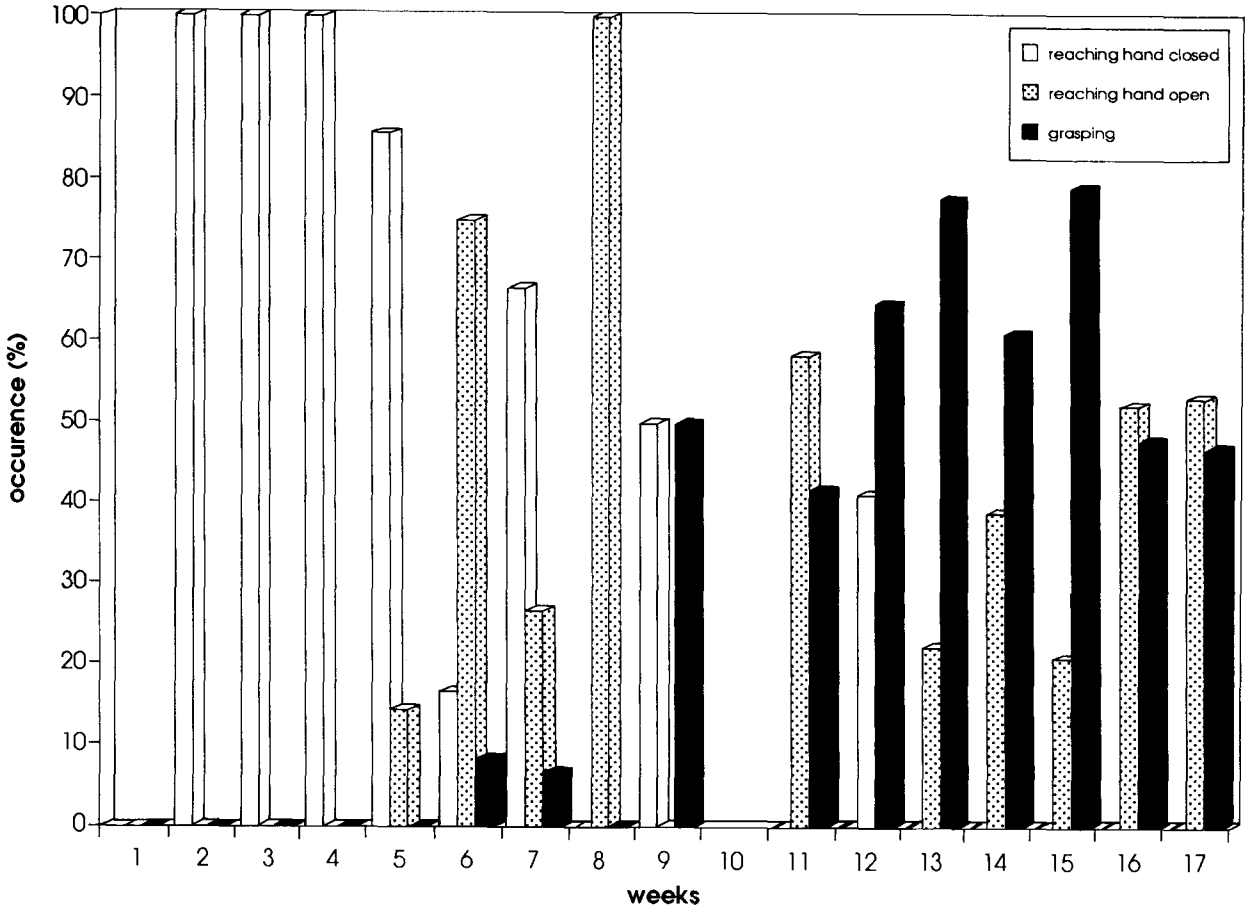

FIGURE 3 The emergence of grasping. The percentage of occurrence of reaching and grasping from 8-24 weeks. Competition between different states of prehension can be seen. Reaching with hand closed disappears and reaching with hand open and grasping emerges and then the states co-exist with each other.

emergence of grasping appears as a jump. Although reaching activity without grasping does not disappear, a qualitative change in reaching is evident, namely, reaching with the hand closed changes to reaching with the hand open (Figure 3). The existence of two states, reaching with and without grasping, can be seen as exemplifying the presence of bimodal.

Oscillations between states during a period of bimodality can be regarded as fluctuations. This probably means that both behaviours are competitive attractors, but neither of them is as yet strong enough to win. Another way of demonstrating fluctuations is to look at the variance of the occurrence of one particular category. Evidence for this sort of fluctuation can be seen in Figure 3 where the variance in the occurrence of reaching with the hand open is large from week 12 to week 16 (session 5 to 9), and established in week 18 to week 24 (session 11 to 17) with significant ($F(4)=7.56$; $p<.05$) smaller fluctuations.

Discussion

Sudden jumps, bimodality and fluctuations are some of the criteria indicative of nonequilibrium phase shifts. Finding such 'fingerprints' of change provides preliminary confirmation of the hypothesis that the development of prehension during early infancy is based on non-equilibrium transition between stable states of action. If replicated with more infants such finding may offer a substantial contribution to a general theory of developmental transitions based on dynamical principles.

Of course, the detection of such criteria in longitudinal data has to be confirmed by means of appropriate statistical analyses.

For the time being, the most pressing task is to discover the relevant control parameters which when scaled-up beyond some critical value result in a discontinuous change of the behavioural state. As such, experimental manipulation of perception or action or both are required in and around the transitional ages identified by our longitudinal research.

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