

A catastrophic change in the early development of prehension?

Abstract

Two methods, catastrophe detection and catastrophe modelling, were used to examine the hypothesis that the developmental change from reaching without grasping to reaching with grasping that occurs in the neonate between 16 and 24 weeks of age, belongs to the class of discontinuous phase transitions. Catastrophe detection was applied to data from a longitudinal study and yielded evidence for the presence of some catastrophe flags (sudden jump, inaccessibility, bimodality, and anomalous variance). Catastrophe modelling was applied to data from a cross-sectional study and revealed that the cusp, an elementary catastrophe model, described the data better than a linear regression model and a logistic model. These results were discussed in the light of methodological and theoretical considerations, culminating in an agenda for future research.

Introduction

Interest in the development of action is reflected in the thirties and forties by the pioneering work of researchers such as Gesell, McGraw and Shirley. They viewed motor development primarily as a result of neural maturation, that is, behavioural changes were assumed to be caused by structural changes in the central nervous. This view on the development of action was replaced by the cognitive perspective of Piaget and the information-processing approaches. In the hands of cognitive psychologists with an extreme constructivist orientation, the development of action became almost equivalent to the development of symbolic knowledge structures encoded in dedicated mechanisms such as plans, programs, representations and schemata (Connolly, 1970; Mounoud, 1993).

In spite of the marked and non-trivial differences in emphasis between the two approaches, maturational and constructivist models share an important assumption in common: motor development is deemed to be a sequence of behavioural states that occur in a fixed order. The problem with this position is that it emphasises the *outcome* of development, whereas it downplays the importance of the *process* of development. From the maturationists we learn that the outgrowth of nerve tissues is responsible for new behaviours, but very little is said about the precise effects of such processes on the time-evolving structure of the development of behaviour as such.

Similarly, from an information processing point-of-view we learn that cognitive structures develop, and that children become faster processors with age, but little is said about exactly how these cognitive structures evolve and how they may lead to shifts in behaviour (Hopkins, Beek, & Kalverboer, 1993). As a result, the dynamic properties of development itself have not been a primary focus of attention in these theoretical perspectives, neither conceptually nor empirically.

What do we know about the process of motor development? Parents are often struck by the fact that for a relatively long time no new behaviours occur, whereas new behaviours seem to emerge within a rather narrow time span. Furthermore, it is evident that motor development does not follow a fixed sequence of behaviours. Variance in both the timing and sequencing of the occurrence of specific motor abilities is a striking feature of motor development. For instance, from the studies of Von Hofsten (1984, 1986) the development of prehension seems to be best characterised as punctuated equilibriums in which there are periods of relative stability and periods of rapid change.

By shifting the emphasis from the outcome of development to the study of the dynamics of development, it becomes possible to examine how specific behaviours actually develop in terms of their time evolution (Kugler, Kelso, & Turvey, 1982; Kugler, 1986; Thelen & Smith, 1994; Savelsbergh, 1993). Such a shift in emphasis is necessary because, for a complete account of development, a classification of the possible end states is not sufficient.

Development from a dynamical systems perspective

The dynamical systems approach is concerned with the application of the conceptual and analytical tools of non-linear dynamics to the study of movement co-ordination, learning and development (Beek & Hopkins, 1992; Beek, Hopkins, & Molenaar, 1993; Kugler, 1986; Thelen & Smith, 1994). The aim of the approach is to characterise spatial, temporal and functional patterns of motor behaviour in terms of their stability properties by describing the time-evolution of relevant variables with the help of dynamical equations of motion.

A developing organism can be seen as an open, dissipative system. An open system does not tend towards a state of thermodynamic equilibrium, but more generally towards a steady state displaced considerably from equilibrium (implying it has potential energy). This far-from-equilibrium or non-equilibrium state is maintained by a continuous flow of free energy and matter into and out of the operational components of the system. When open systems are close to thermal equilibrium, small disturbances may lead to small departures from equilibrium but the system will quickly regain maximum entropy. In this case, the relations between the system's parts can be described linearly. In contrast, when an open system is operating far from equilibrium, entirely new things can happen due to the non-linearities that dominate the relations between the components of the system. In this case, small disturbances or fluctuations can give rise to the spontaneous creation of order or structure by means of self-organisation (Haken, 1977, 1983; Prigogine & Stengers, 1985).

In this context, self-organisation is defined as the system's ability to acquire a new spatial, temporal or functional structure by itself (i.e., without any prescription of this structure from the outside). The ability of a system to organise itself is most salient when a qualitative change in order occurs, such as the transition from water to ice. Such transitions are called non-equilibrium phase transitions or bifurcations. Such phase transitions (in physics) or bifurcations (in mathematics) may be continuous or discontinuous, depending on whether there is a smooth, continuous trajectory from the one stable state to the other. Discontinuous phase transitions are synonymous with catastrophes (see below).

In contrast to the maturationist and constructivist points of view, the development of co-ordination is seen from this perspective as a complex, evolving dynamical process. Developmental systems are self-organising in that new behavioural forms at the macroscopic level (e.g., reaching) emerge in a non-linear fashion as a result of interactions between subsystems at more microscopic levels of organisation (e.g., neural, visceral, muscular, skeletal). Thus, co-ordinated actions such as reaching arise from complex processes of co-operation between subsystems and not from the maturation of prescriptive devices that 'tell the system what to do'.

Using tools borrowed from non-linear systems theory, it is possible to detect developmental states and qualitative changes (i.e., transitions) which are induced by quantitative (continuous) changes in one or more control parameters. Although a control parameter does not prescribe a new pattern following a change, its manipulation is instrumental in creating it. It controls in the sense of leading the system through its respective states of equilibrium, thus from one stable state to the next, from one behavioural mode to another (e.g., from water to ice, or from reaching without grasping to reaching followed by grasping).

Von Hofsten and Lindhagen (1979) found that 15 weeks old infants, who reached for moving objects, frequently contacted the object without grasping it. After that, the development of grasping accelerated rapidly. At 18 weeks the object was grasped in the majority of reaches, thus suggesting the presence of a fairly abrupt change from a developmental state of only reaching to a state of reaching followed by grasping. This suggestion gives rise to the following question: Is the developmental change from reaching without grasping to reaching with grasping during the first six months of life based on a discontinuous phase transition (catastrophe)? This question was the central topic of a series of recent studies (Wimmers et al., 1998a, b, c). The results and theoretical implications of these studies are summarised and discussed in the present chapter.

Methods for determining a discontinuous phase transitions

Conceptually and computationally straightforward methods for determining the presence of a discontinuous phase transitions in a particular data set are provided by catastrophe theory (Thom, 1975). Catastrophe theory is a mathematical theory for describing and predicting discontinuous phase transitions in gradient systems. Gradient systems with fixed parameters always move to an equilibrium state, that is, to a minimum (or maximum) of a certain quantity (entropy or energy). Catastrophe the-

ory describes the seven simplest ways for a catastrophe to occur in systems with up to two behavioural variables and four control parameters.

Catastrophe theory provides three methods to determine whether (developmental) changes constitute discontinuous phase transitions, namely, catastrophe detection, catastrophe modelling and catastrophe analysis (Van der Maas and Molenaar, 1992). Catastrophe analysis requires that a precise mathematical model of the transition process is available, which seldom, if ever, is the case in the study of development. Catastrophe modelling involves the fitting of a typically low-dimensional catastrophe model to developmental data. This requires at least some a priori insight into the nature of the observed change. Such an insight can be obtained with the help of catastrophe detection, that is, the identification of specific criteria for the presence of discontinuous phase transitions. Such criteria are also called catastrophe flags. As catastrophe detection and catastrophe modelling were the methods used in our research on the development of prehension, we summarise and discuss the main results of this research in the context of these methods.

Catastrophe detection

Gilmore (1981) distinguished eight catastrophe flags that can be tested empirically. The first flag is the occurrence of bi (or multi) -modality, that is, the presence of two or more qualitatively different behaviours on the same (behavioural) dimension. For this flag to be confirmed, the dependent variable must exhibit at least a bimodal frequency distribution. The second flag is the sudden jump, which involves an abrupt, qualitative change in behaviour due to a small and continuous change in the control parameters. Inaccessibility, the third flag, implies that the behavioural variable cannot stably occupy a state located between the two behavioural modes. Divergence, the fourth flag, refers to the fact that, at the transition, two adjacent initial conditions may diverge rapidly and result in two different behaviours. This flag is important for revealing the stability of the behaviour for different initial conditions. The fifth flag is hysteresis, which means that the value of the control variable at which the transition occurs depends on the direction in which it was scaled (i.e., increasing or decreasing). These five flags always occur in conjunction when a system undergoes a discontinuous transition. The next three flags can be found prior to a transition, and signal an upcoming transition.

Critical slowing down, the sixth flag, is a consequence of the loss of stability of the behavioural mode prior to switching to another one. The stability of a behavioural mode is indexed by the local relaxation time, that is, the time it takes for the system to stabilise after a perturbation caused by internal or external forces. Critical slowing down refers to the increase in relaxation time as the transition is approached. The seventh flag is anomalous variance, which is associated with an increase in fluctuations of the behaviour before a transition. One way to detect such fluctuations is to examine the variance of the (relative) incidence of a particular value or behavioural category per unit of time prior to a transition. Another way is to study the degree of switching between attractor states. If, for example, two attractor states of comparable strength coexist in a particular state space, they will have competing effects on the

system's behaviour. Oscillations can then be observed between the two behaviours. The last catastrophe flag, divergence of linear response, is a consequence of a perturbation near a transition; the magnitude of the variance increases and large oscillations of the behavioural variable are seen, both as a result of loss of stability.

A longitudinal study (Wimmers et al., 1998b) was conducted to examine the presence of some of the catastrophe flags in the development from reaching without grasping to reaching with grasping. Ten infants were observed weekly from 8 to 24 weeks of age. A stick was presented at chest level at a distance of about 2/3rd of the length of the infant's arm, measured from the body's midline. The duration of each session and therefore the total number of trials depended on the interest of the infant. Video-recordings were made of movements toward an attractive looking object and were classified according to two mutually exclusive categories: reaching without grasping, in which one of the hands came within a range of 5 cm of the object or touched it without closing any of the fingers around it, and reaching with grasping, in which one of the hands touched the object, followed by a closure of one or more fingers around the object. In order to identify the transition, the scored behavioural categories were converted into a single behavioural variable: percentage of occurrence of grasping. It was derived by taking the number of occurrences of reaches followed by a grasp as a percentage of the total number of reaches. With regard to the transition criteria the following flags were found in the longitudinal data.

Over longitudinal time the group data showed an S-shaped curve spanning a period of 5 weeks. However, as the transition point was not the same for each infant the data were also graphed and studied individually with regard to the transition point of the infant in question. From this procedure it became clear that the change was not gradual, but occurred rather suddenly within a time span of one week. It also became clear that a particular region of values had a low probability of occurring, implying that it was relatively inaccessible. This finding suggested that the transition took place by means of a jump.

A binomial mixture distribution was fitted to the frequency distribution of the longitudinal data to determine the number of modalities. In terms of the Akaike Information Criteria (AIC), the amount of variance accounted for by the model (VAF), and the squared goodness of fit between model and data, the data were best fitted by a three-component model. However, the quality of the fit of the trimodal distribution was only marginally better than that of the bimodal distribution. Also the estimated frequency distribution of the three-component model had the form of a bimodal distribution, that is, it had two peaks, not three. On the basis of these findings it was concluded that the data was essentially distributed bimodally.

The transition flags discussed so far could also be explained as a rapid acceleration in a continuous developmental model instead of a discontinuous phase transition model. To eliminate this possibility, a further analysis was conducted focussing on the stochastic properties of the transition. Specifically, a switch ratio, which is part of the anomalous variance flag, was calculated to quantify the stability of the two behavioural modes during development. This ratio was defined as the number of switches divided by the possible number of switches. For instance, for a series of five

reaches without grasping and five reaches with grasping, that is, RRRRRGGGGG, the switch ratio would be 1/9. In contrast, for the series RGRGRGRGRG, the switch ratio would be 9/9. The first series would indicate that the attractor states of reaching and grasping are rather stable, the second series that both states are rather unstable (i.e., assuming that they are point attractors!).

By calculating the switch ratios around the individual transition points, it was established that the groups mean switch ratios increased while the transition point was approached, whereas the percentage of occurrence scores remained almost the same. This finding indicated that the stability of the behavioural state of reaching without grasping already decreased prior to the transition. In the period following the transition, the mean switch ratios remained high, whereas the percentage of occurrence scores remained relatively constant. These findings indicated that the system remained in the bifurcation set throughout the experiment, that is, both behavioural modes were available for the system up to week 24. It further appeared that the observed transitions were governed by the so-called Maxwell convention, implying that the system switched state before the old state actually disappeared.

In conclusion, the developmental change of a state in which reaching without grasping is predominant to a state in which reaching with grasping is predominant during early infancy might well constitute a discontinuous phase transition in that it is characterised by the presence of several catastrophe flags (sudden jump, inaccessibility, bimodality and anomalous variance).

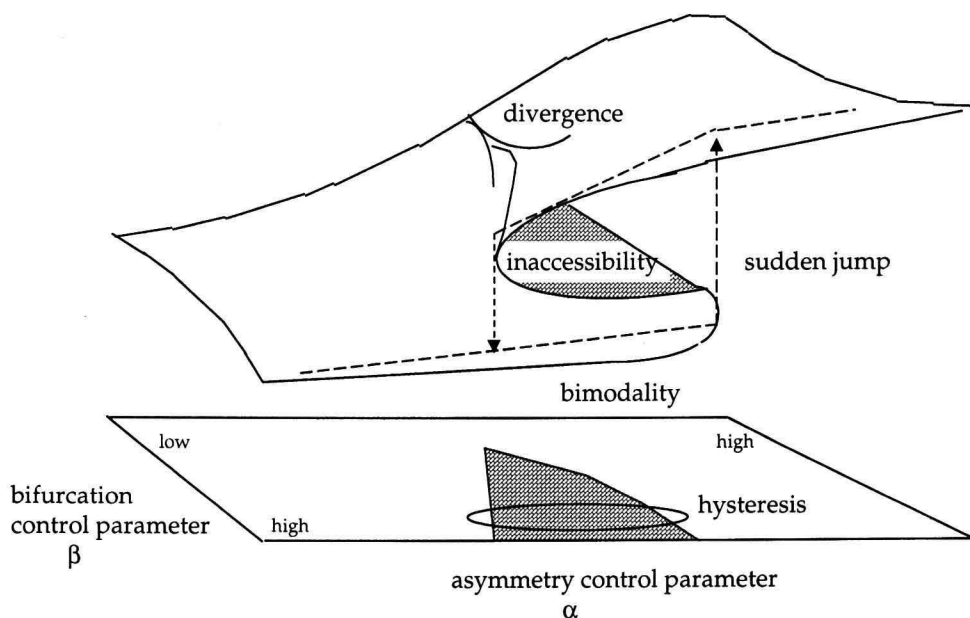


Fig. 1. The cusp model.

Catastrophe modelling

One of the main challenges for the application of dynamical systems theory to (motor) development is to derive and build quantitative models that capture the identified dynamics in a meaningful and compact way. For instance, based on a cusp model (Figure 1), which is one of the elementary catastrophes identified by Thom (1975), 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. In a cusp model, the transition between two behavioural states of a unidimensional behavioural variable is governed by two control parameters. Cobb (1980, 1981; Cobb & Zacks, 1985) developed a method for fitting a cusp catastrophe model to observed data. By using stochastic differential equations, he derived the following probability density function for the cusp:

$$f_s(z; \alpha, \beta) = \xi \varepsilon^{-\alpha+1/2^2-1/4z^4} \quad (1)$$

where

$$z = (x - \lambda) / \sigma. \quad (2)$$

In Equation (1), ξ is a normalisation constant dependent on the control parameters α and β , z is the standardised behavioural variable involving the location parameter λ and the scale parameter σ . These parameters can be estimated by means of the maximum likelihood method.

The control parameters are represented by a linear combination of a number of independent variables in the following way:

$$\begin{aligned} \alpha &= (\alpha_0 + \alpha_1 I_1 + \dots + \alpha_n I_n), \\ \beta &= (\beta_0 + \beta_1 I_1 + \dots + \beta_n I_n) \end{aligned} \quad (3)$$

The α 's 1 to n and β 's 1 to n are weights given to each independent variable I . Together, they represent the control parameters α and β .

A cross-sectional study (Wimmers et al., 1998c) was conducted to model the transition from reaching without grasping to reaching with grasping as a cusp catastrophe, and to identify potential control parameters for this transition. The subjects were 58 normal, full-term infants (33 boys and 25 girls) ranging in age from 60 to 407 days. A black curved board with nine balls was presented for 1 minute within reaching distance at shoulder height. From the literature, the following variables were considered as possible constituents of the control parameters for the transition under study:

- a. Ponderal index (weight / length³) * 100;
- b. Crown-heel length (cm);
- c. Total body weight (g);
- d. Arm volume ('average of circumference of upper- and forearm²/4 π ' * arm length);
- e. Arm length (cm);
- f. Arm circumference (cm):

- g. Estimated arm weight (Schneider & Zernicke, 1992).
- h. Position of the body relative to the horizontal plane. Three different angles to the horizontal plane were used: supine (0°), recline (60°), and vertical (90°).

The best-fitting cusp plane, which was determined with an analysis programme (Hartelman, 1996, 1997) based on the maximum likelihood algorithm of Cobb, applied in combination with a forward selection procedure, revealed that arm circumference (f) and arm weight (g) made significant contributions to the control parameters. The pseudo- R^2 for this model was .81, the log likelihood -83.48, and the AIC 182.95.

The cusp model was compared with a linear model and a logistic model (i.e., an acceleration mode). A stepwise multiple regression analysis revealed three significant variables, namely, arm weight (g), arm volume (d) and arm length (e). The R^2 for the linear model was .57, the log likelihood 235.61 and the AIC 481.23. Comparing the relevant log likelihood's yielded a statistical better fit for the cusp model ($\chi^2(3) = 304.26, p < .001$).

The R^2 for the logistic model, with arm circumference (f) and arm weight (g) as variables, was .60, the log likelihood -123.75 and the AIC 261.50. Given that it cannot be statistically compared with the cusp model, the AIC was used in order to select the best fitting model. Based on the AIC, the best fitting model was again the cusp model.

The overall conclusion was that the findings demonstrated that the cusp model fitted the behavioural data better than a linear model or a logistic model. Again, this finding supports the hypothesis that the developmental change of a state in which reaching without grasping is predominant to a state in which reaching with grasping is predominant during early infancy might well constitute a catastrophe or discontinuous phase transition.

Discussion

The main question addressed in this contribution was whether the rapid changes in the organisation of prehension that occur in early development (16-24 weeks after birth) constitute a discontinuous phase transition. Collectively, the results of our longitudinal and cross-sectional studies point in the direction of an affirmative answer to this question.

In the longitudinal study, a number of catastrophe flags were detected. Although none of these flags by themselves was sufficient to conclude that a discontinuous phase transition was present, the specific combination of detected catastrophe flags rendered this hypothesis probable. Whereas sudden jump, inaccessibility and bimodality were sufficient to reject a continuous linear change model, they did not rule out other (non-catastrophic) non-linear models such as the logistic growth model, involving a continuous acceleration, and the discrete step model, involving a discontinuity without loss of stability. Even when the observed changes look discontinuous, as in the longitudinal data, it could always be argued that the measurement

density was not sufficient to discriminate between the two classes of models. Fortunately, in addition to sudden jump, inaccessibility and bimodality, anomalous variance was detected, which is a catastrophe flag that indicates that the changes in question were accompanied by loss of stability. Further evidence for this was found using measures directly related to anomalous variance, such as the switch ratio. The loss of stability that was observed prior to and during the transition is a strong index for a discontinuous phase transition, as it is absent in both the logistic growth model and the discrete step model.

In conclusion, the data from the longitudinal and cross-sectional study lend support for (but do not rigorously prove) the hypothesis that motor development constitutes a non-equilibrium phase transition. Theoretically, this would imply that the system in question is an open system that can suddenly exhibit qualitatively new forms when aspecific control parameters are changed continuously, which is the signature of self-organisation. The identification of such non-equilibrium phase transitions is important in that it suggests that development is a continuous process involving gradual modification of underlying structures (i.e., internal control parameters) resulting in discontinuous transitions from one behavioural mode to another. Thus, the identification of non-equilibrium phase transitions sheds new light on the old continuity-discontinuity theme in developmental theory as they incorporate both aspects.

Given the results obtained thus far, there are several interesting directions for future research. Here, we restrict ourselves to a discussion of four.

Firstly, further work is needed to determine whether the transition is accompanied with loss of stability of the initial state or not. The switch ratio data indicated that the transition from reaching without to with grasping abides by the Maxwell convention, implying that the system switches state without the old state disappearing altogether. This would run counter to a long-established claim about the nature of motor development stating that the neonatal repertoire of reflexes has to disappear via a process of cortical inhibition before voluntary-controlled movements can become established (McGraw, 1943). This particular claim is more in keeping with the delay convention, as it implies that the system changes only as the old states becomes unstable and finally disappears. In a longitudinal study of 51 infants, no correlation was found between the disappearance of the palmar grasp and the onset of voluntary radial grasping (Touwen, 1976). Instead, the two patterns co-existed for some time with the infant switching from one to the other when presented with a standard-sized object. Thus, this study is consistent with our finding that qualitative changes in the development of prehension abide by the Maxwell rather than the delay convention. Following Gilmore (1981), it should be emphasised that the two conventions represent the extremes of a range of possibilities. In between these extremes, the nature of the transition becomes fuzzy such that it is often not possible to define the requisite bifurcation set (i.e., the set of points in the space of the control parameters at which a transition occurs from one local minimum to another). To resolve this issue, experiments have to be conducted to probe for the presence of both conventions by means of incorporating conditions that employ different time scales for the control parameters (see Wimmers et al., 1998a, for an overview of the time scales involved).

Secondly, and in conjunction with the previous point, detection of two catastrophe flags, not yet found in the data, is of paramount importance, namely divergence of linear response and hysteresis. Divergence of linear response helps to index which behavioural variable is undergoing change, whereas hysteresis helps to identify the responsible control parameter(s). Both flags obey the delay convention and are difficult to detect in that the control parameter(s) has to be known *a priori* and manipulated experimentally to induce the behaviour corresponding to the two. If the Maxwell convention applies, then both flags will disappear under the inherently stochastic conditions that characterise developmental systems (Van der Maas, 1993). Also in this regard, there are compelling reasons for devising experiments in and around transitional ages geared towards distinguishing between the two conventions. Firm evidence that the transition under study involves divergence of linear response as well as hysteresis would considerably strengthen the claim that it complies with the dynamical properties of a second-order non-equilibrium phase transition (to which the delay convention applies).

Thirdly, a more detailed description of the distinguished behavioural states is required. So far, developmental change was studied in terms of a transition between two globally defined states (reaching without and with grasping). The next step could be to attempt to describe these states in terms of specific kinematic measures with the aim of identifying appropriate order parameters. Candidates for the reaching movement could include the number of movement units, the straightness of the reach and the speed-curvature relationship. The first two measures have been shown to change with age (Von Hofsten, 1991) while the latter appears to be developmentally invariant (Fetters & Todd, 1987; Von Hofsten & Rönqvist, 1993). An appropriate measure to capture the developing relationship between reaching and grasping could be the temporal co-ordination between maximum grip aperture and the point of deceleration in the reaching movement (Jeannerod, 1981; see Von Hofsten & Rönqvist, 1988). The advantage of such measures is that they are continuous rather than discrete, and therefore optimally suited for the detection of catastrophes.

Fourthly, and finally, catastrophe detection and modelling should be applied to other putative transitions during infancy. Previous work has identified the age range of 7-9 months as a period in which major developmental transitions (Emde et al., 1976). Recent studies have indicated that towards the end of this period vision of the hand relative to the object begins to play a crucial role in successful prehension (Ashmead et al., 1993; Clifton et al., 1993). It could therefore be the case that behavioural transitions during this particular stage of infancy have markedly different characteristics than those observed during the early development of prehension.

References

- Ashmead, D.H., M.E. McCarty, L.S. Lucas and M.C. Belvedere (1993). Visual guidance in infants' reaching toward suddenly displaced targets. *Child Development*, **64**, 1111-1127.
- Beek, P.J. and B. Hopkins (1992). Four requirements for a dynamical systems approach to the development of social coordination. *Human Movement Science*, **11**, 425-442.
- Beek, P.J., B. Hopkins and P.C.M. Molenaar (1993). Complex systems approach to the development of action. In G.J.P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 497-515). Amsterdam: North-Holland.

- Clifton, R.K., D.W. Muir, D.H. Ashmead and M.G. Clarkson (1993). Is visually guided reaching in early infancy a myth? *Child Development*, **64**, 1099-1110.
- Cobb, L. (1980). Estimation theory for the cusp catastrophe model. *Proceedings of the Section on Survey Research Methods*, 772-776.
- Cobb, L. (1981). Parameter estimation for the cusp catastrophe model. *Behavioral Science*, **26**, 75-78.
- Cobb, L. and S. Zacks (1985). Applications of catastrophe theory for statistical modelling in the biosciences. *Journal of the American Statistical Association*, **80** (392), 793-802.
- Connolly, K.J. (1970). Skill development: problems and plans. In K.J. Connolly (Ed.), *Mechanisms of motor skill development* (pp. 3-21). London: Academic Press.
- Emde, R.N., T.J. Gaensbauer and R.J. Harmon (1976). Emotional expression in infants: A biobehavioral study. *Psychological Issues*, **10**, no. 37.
- Fetters, L. and J. Todd (1987). Quantitative assessment of infant reaching movements. *Journal of Motor Behavior*, **19**, 147-166.
- Gesell, A. and C.S. Amatruda (1945). *The embryology of behavior*. New York: Harper.
- Gilmore, R. (1981). Catastrophe theory for scientists and engineers. New York: Wiley.
- Haken, H. (1977). *Synergetics: An introduction*. Heidelberg: Springer.
- Hartelman, P. (1996). *Cusp analysis program*. Internal manuscript. Department of Psychology, Universiteit van Amsterdam.
- Hartelman, P. (1997). *Stochastic catastrophe theory*. Academic thesis, Universiteit van Amsterdam.
- Hopkins, B., P.J. Beek and A.F. Kalverboer (1993). Theoretical issues in the longitudinal study of motor development. In A.F. Kalverboer, B. Hopkins and R.H. Geuze (Eds.), *Motor development in early and later childhood: Longitudinal approaches* (pp. 343-371). Cambridge: Cambridge University Press.
- Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. In J. Long and A. Baddeley (Eds.), *Attention and performance IX* (pp. 153-168). Hillsdale, NJ: Erlbaum.
- Kugler, P.N. (1986). A morphological perspective on the origin and evolution of movement patterns. In M.G. Wade and H.T.A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 459-525). Dordrecht: Martinus Nijhoff.
- Kugler, P.N., J.A.S. Kelso and M.T. Turvey (1982). On the control and coordination of naturally developing systems. In J.A.S. Kelso and J.E. Clark (Eds.), *The development of movement control and coordination* (pp. 5-78). New York: Wiley.
- McGraw, M. (1943). *The neuromuscular maturation of the human infant*. New York: Hafner.
- Mounoud, P. (1993). The emergence of new skills: Dialectic relations between knowledge systems. In G.J.P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 13-46). Amsterdam: North-Holland.
- Prigogine, I. and I. Stengers (1985). *Orde uit chaos* [Order out of chaos]. Amsterdam: Bert Bakker.
- Savelsbergh, G.J.P. (1993). *The development of coordination in infancy*. Amsterdam: North-Holland.
- Schneider, K. and R.F. Zernicke (1992). Mass, center of mass, and moment of inertia estimates for infant limb segment. *Journal of Biomechanics*, **25**, 145-148.
- Thelen, E. and L.B. Smith (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.
- Thom, R. (1975). *Structural stability and morphogenesis*. Reading, MA: Benjamin.
- Thomas, H. (1989). A binomial mixture model for classification performance: A commentary on Waxman, Chambers, Ynteman, and Gelman (1989). *Journal of Experimental Child Psychology*, **48**, 423-430.
- Touwen, B.C.L. (1976). *Neurological development in infancy*. London: Heinemann.
- Van der Maas, H.L.J. (1993). *Catastrophe analysis of stepwise cognitive development*. Academic thesis, University of Amsterdam.
- Van der Maas, H.L.J. and B. Hopkins (1998). Developmental transitions: So what's new? *British Journal of Developmental Psychology*, **16**, 1-13.
- Van der Maas, H.L.J. and P.C.M. Molenaar (1992). Stepwise cognitive development: An application of catastrophe theory. *Psychological Review*, **99**, 395-417.
- Von Hofsten, C. (1984). Developmental changes in the organization of prereaching movements. *Developmental Psychology*, **20**, 378-388.
- Von Hofsten, C. (1986). The emergence of manual skills. In M.G. Wade and H.T.A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 167-185). Dordrecht: Nijhoff.
- Von Hofsten, C. (1991). Structuring of early reaching movements: A longitudinal study. *Journal of Motor Behavior*, **20**, 280-292.
- Von Hofsten, C. and K. Lindhagen (1979). Observation on the development of reaching for moving objects. *Journal of Experimental Child Psychology*, **28**, 158-173.

- Von Hofsten, C. and L. Rönnqvist (1988). Preparation for grasping an object: A developmental study. *Journal of Experimental Psychology: Human Perception and Performance*, **14**, 610-621.
- Von Hofsten, C. and L. Rönnqvist, (1993). The structuring of neonatal arm movements. *Child Development*, **64**, 1046-1057.
- Wimmers, R.H., P.J. Beek, G.J.P. Savelsbergh and B. Hopkins (1998a). Developmental changes in action: Theoretical and methodological issues. *British Journal of Developmental Psychology*, **16**, 45-63.
- Wimmers, R.H., G.J.P. Savelsbergh, P.J. Beek and B. Hopkins (1998b). Evidence for a phase transition in the early developmental of prehension. *Developmental Psychobiology*, **32**, 235-248.
- Wimmers, R.H., G.J.P. Savelsbergh, J. Van der Kamp and P. Hartelman (1998c). A developmental transition in prehension modeled as a cusp catastrophe. *Developmental Psychobiology*, **32**, 23-35.

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