EXPLORING EXPLORATION IN THE DEVELOPMENT OF ACTION

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In this paper the role of exploration in the development of action is discussed from the perspective of the natural physical approach. It is argued that by means of repeated exploration of the perceptual-motor work space, infants discover new couplings between information and movement; that is, new stable modes of action are acquired for a particular task. Furthermore, it is assumed that exploration is the behavioral equivalent of the fluctations that are indicators of transitions in movement actions. Exploration is assumed to be constrained by, and specific to, the transition at hand. Three exploratory search strategies (blind, local and non-local) are discussed and illustrated with the example of infant reaching.

Keywords: Exploration, development of action, natural physical approach.

Introduction

In this paper the role of exploration with respect to the development of action is discussed. This discussion partly reflects the growing awareness of the importance of exploration in the development of movement action (see, for example, the special issue of *Child Development,* 64, 1993). To assess the concept of exploration in the development of action, a short overview of the concept of exploration from the point of view of traditional drive and information processing approaches is presented first. Then, by combining the tools from non-linear dynamics with the ecological approach to perception and action, a natural physical approach (see Savelsbergh & Van der Kamp, this volume) of exploration is offered. In this approach exploration is regarded as a search of the perceptual-motor work space as result of which new couplings of perception and action are discovered. Furthermore, following Newell, Kugler, Van Emmerik & McDonald (1989), different search strategies are mentioned and illustrated by reaching in 3 to 6 month old infants.

The traditional view

The classic perspective asserts that exploration is instigated by organismic drives

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(e. g. Nissen, 1954). To reduce primary drives like hunger, thirst, sex etc., the organism starts exploring until a consummatory response reduces the specific need. This terminates the exploratory activity. Through repetition of this sequence, the response is learned. It became clear, however, that various exploratory activities occurred in the absence of primary needs. In the famous study of Butler for example, monkeys learned to make discriminations in order to peek through a window, solely for the purpose of peeking. To accomodate these findings, alterations to the traditional scheme were suggested. Among others, a kind of independent exploratory drive was postulated which could be evoked by novel, complex or unfamiliar external objects or events (e. g. Montgommery, 1954).

Two decades later, cognitive approaches were predominant in psychology and exploration was considered to have a motivation inherent in information processing and action. Exploration was said to be instigated by an incongruence between a stimulus and a standard. An information conflict led to the modification or construction of the cognitive schemas and representations (e. g. Hunt, 1963; Nunnally & Lemond, 1973). Difficulties often arose, however, if one tried to differentiate between acquiring new skills and adapting a skill to slightly altered situations. Hence, it was unclear whether exploration should be confined to skill acquisition or if it should also involve adaptation to local circumstances. In short, within an information processing approach, exploration in relation to action was a poorly defined concept with no formal status. This paper seeks to find a more formal description of the role of exploration in the development of action.

A new view of exploration: A natural physical approach

Today, in the age of non-linear dynamics, the tools of catastrophe theory (and most recently complexity theory, see Levin, 1993) have become available to detect and describe qualitative changes or transitions. As a consequence, many studies concerned with the development of movement action are focusing on transitions (e. g. Goldfield, Kay & Warren, 1993; Thelen & Ulrich, 1991; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke 1993; Wimmers, Savelsbergh, Beek & Hopkins, this volume). Several indicators of the presence of transitional behaviour can be discriminated; Namely, hysteresis, enhanced fluctuations, critical slowing down (for a enumerative description of these criteria, see Wimmers et al., this volume). We would like to argue that, in relation to exploration, enhanced fluctuations are particularly interesting (see also Robertson, 1993; Turvey & Fitzpatrick, 1993). Enhanced fluctuations are reflected by larger variability or unpredictability in behaviour. These fluctuations enable the actor to discover or acquire new movement possibilities. In this sense, the concept of exploration is confined to the emergence of new skills (or stable modes) and does not involve adaptation or tuning to local circumstances. If fluctuations during transitions are the equivalent of exploratory activities, what picture emerges of the development of movement actions?

Although the nativist theories of researchers such as Gesell, McGraw and Shirley are not widely held anymore, the value of their descriptive studies is unquestioned. They described the development of action as a sequence of different motor milestones

such as reaching, grasping, crawling, creeping, sitting, walking etc. From the point of view of the natural physical approach (Savelsbergh & Van der Kamp, this volume), the emergence of these motor milestones is not just a consequence of the maturation of the nervous system, but a consequence of changing interaction between organismic *and* environmental constraints (Out & Savelsbergh, this volume). Important in this respect is the notion of the perceptual-motor workspace (Kugler & Turvey, 1987: Newell, Kugler, Van Emmerik & McDonald, 1989; Newell, McDonald & Kugler, 1991). The perceptual- motor workspace is regarded as;

> the dynamic interface between informational flows arising from perception and the kinetic flows arising from action. These fields are viewed as complementary in that not only can forces (kinetics) give rise to changes in flows (kinematics) but, in addition, flows can give rise to changes in the forces (Newell et al., 1991, p. 96).

The perceptual-motor workspace of the organism-environment interaction can be modelled as a 'layout' of gradient and equilibrium regions, i. e. as a field of interacting attractors. These attractors are defined over both physical and informational factors i. e. as a specific coupling between perception and action (Gibson, 1979). On a behavioural level, the attractors specify different stable modes of action (motor milestones). From this perspective, development is regarded as the transition from one stable mode of action to another (e. g. from reaching to grasping; see Wimmers et al., this volume). Stated differently, development is the emergence of new dynamical attractors (Kugler, Kelso & Turvey, 1982). The question that arises is how these new attractors or perception-action couplings are discovered. In other words, how are new stable modes of action acquired?

Discovering new perception-action couplings and acquiring new stable modes of action involve exploring and locating the gradient and equilibrium regions of the perceptual-motor workspace at hand. Exploration of the perceptual-motor workspace guides the organism to the discovery of new couplings between the informational and kinetic flows, thereby providing new stable modes of action (Goldfield et al., 1993; Kugler & Turvey, 1987; Newell et al., 1989, 1991: Savelsbergh & Van der Kamp, 1993, this volume; Thelen, 1990, Warren, 1990). Hence, development of action is achieved through exploration, i. e. by repeatedly producing (slightly) different movements or experimenting with different musculoskeletal organisations (cf. Goldfield et al., 1993) whereby the infant learns how to co ordinate and control his action system. The infant perceives information (proprioceptive, visual) produced by his/her movements and discovers how this information can be used to guide his/her movements. As argued above, this exploratory behaviour is especially prominent during transitions. This is nicely shown by Thelen in her earlier ethologically oriented studies (1979). She studied the occurrence of rhythmical behaviours like kicking, rocking, arm waving and banging in natural settings and showed that these behaviours occurred most frequently around transitions in movement actions. Rocking on hands and feet, for example, emerged in development just before the onset of crawling. This rocking presumably represents the

infant's exploration of his action capabilities and the (proprioceptive) information it produces. This eventually leads to a new stable mode of action (crawling). Through exploration of the perceptual-motor workspace the infant discovers how perception and action are coupled.

Exploration of the perceptual-motor workspace (i. e. moving in it) both creates and annihilates equilibrium or gradient regions (Kugler & Turvey, 1987). Hence, the dynamical structure of the perceptual-motor workspace changes during exploration. This provides information which can be used to guide exploration (Newell et al. 1989, Gibson, 1988). In other words, exploration is not completely random but is constrained by, and specific to, the transition at hand. It is constrained because the exploration is dependent on the already acquired stable mode. Thelen et al. (1993) showed that the onset of reaching and grasping involves an increase or decrease of the initial muscle stiffness depending on the state of spontaneous movements before the onset of reaching. It is specific because exploration is directed toward one particular new stable mode of action, such as the rocking of hands and feet occurring only before the onset of crawling (Thelen, 1979).

Thus, exploration is constrained and specific. What about the instigation of exploratory behaviour? Bak & Chen (1991) argued that large interactive dynamical systems

> 'perpetually organise themselves to a critical state in which a minor event starts a chain reaction that can lead to a catastrophe (p. 26)'.

They termed this the theory of self-organised criticality. The action systems of humans with its many components (joints, muscles and nerves) might be such a large interactive system. If so, action systems evolve to fields where transitions from one stable mode of action to another stable mode of action are to be expected, i. e. to transitional regions. By this reasoning exploration can be considered as an inherent dynamical property of developing action systems, guiding the system to new stable modes of action. Intuitively and tentatively, this might also open new perspectives on intentionality in development.

If, as argued, exploration of the evolving perceptual-motor workspace is important in motor development and skill acquisition, a characterisation of such exploratory behaviour might help us to understand development. Following Gelfand & Tsetlin (1962), Newell et al. (1989) proposed three exploratory strategies: blind search, local search and non-local search. Blind search represents a strategy in which single equilibrium regions (attractors) are explored or located in a random or well-defined order without the use of memory characteristics. Local search, on the other hand, represents a continuous search of one equilibrium region or attractor space using knowledge from a previous search. A non-local search can be described as a non-continuous or intermittent search that is not confined to one equilibrium region or attractor. It enables a greater part of the workspace to be explored, often in conjunction with local search strategies.

To illustrate the above search strategies we will discuss some data from a recent

experiment (Savelsbergh & Van der Kamp, 1993, submitted). In this experiment, 3 to 6 month old infants seated in an infant chair were presented with a cardboard of nine red foam plastic balls (diameter 2.5cm). These balls were equally distributed in three rows and three columns. The balls were presented to the infants in three times for one minute each time. The number and duration of the reaches were scored. It was found that, in addition to one-handed and two-handed attempts an third type of coordination occurred. The younger infants (3 and 4 month olds) did not, but the older infants (5 and 6 month olds) did grasp the edge of the board with one hand, while reaching for the ball with the other hand. This strategy occurred only in the 5 and 6 months olds, that is, near the time of onset of a more stable form of reaching, grasping and catching (Von Hofsten, 1984). What is the significance of this particular behaviour in the older infants? One hypothesis is that, by grasping the board, infants become able to change the reaching distance. This enables the infants to explore the perceptual-motor work-space for this reaching task in new ways. In other words, by varying the reaching distance, an optimal fit between infant and environment is actively being sought.

If this true, a different search strategy would be expected when the cardboard is grasped. To test this assumption, the nine balls in the reaching task were considered as attractors, and the balls which were successively grasped or contacted (Figure 1) was plotted.

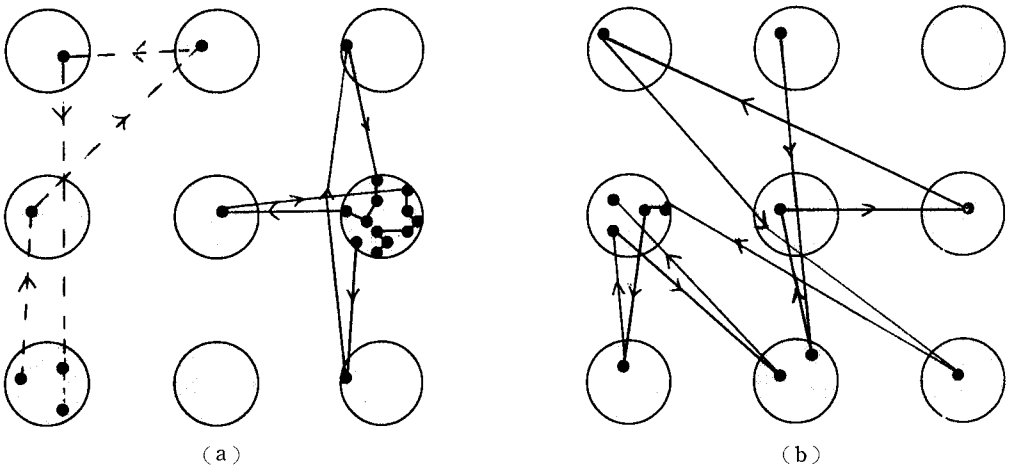

FIGURE 1 The distribution of the contacted and grasped balls. The left pannel shows a 24-weeks-old infant not grasping the board, the right pannel shows the same infant grasping the board with the left hand (– – –left hand; —— right hand).

Differences in the distribution of contacted balls may indicate different search strategies. If contacts and grasps are concentrated around one ball, a local search strategy is assumed to be represented. If, on the other hand, contacts and grasps are distributed equally between several balls, a non-local or blind search strategy is assumed to be represented (it is difficult to distinguish blind and non-local search strat-

egies on basis of spatial distribution only*). Figure 1 (a) shows the distribution of contacted and grasped balls for a 24 week old infant for one minute when the board was grasped only once. In this situation, the right hand seems to represent a local search strategy; that is, the hand is predominantly directed to one ball. Figure 1 (b) shows the same infant for another minute. Now all contacts were made while the contra-lateral hand was grasping the edge of the cardboard. Here, the right hand is not directed to one particular ball, and shows a non local or blind search strategy. A tentative conclusion is that the emergence of grasping the board with one hand while reaching with the contra-lateral hand is accompanied by a change in search strategy, indicating that this behaviour may be regarded as a form of exploraton. In other words, when the cardboard comes within reach —as a consequence of growth of arm length— the dynamical layout of the perceptual-motor workspace changes, giving rise to a change in search strategy, which is specific for this task and the transition to reaching and grasping.

Conclusion

The natural physical approach, i. e. the ecological approach to perception and action using the tools of non-linear dynamics, offers a new point of view on exploration in the development of movement action. By means of repeated exploration of the perceptual-motor workspace, infants discover new couplings between information and movement. Hence, new stable modes of action are acquired for a particular task. It is assumed that exploration is inherent in the dynamics of large interactive dynamic systems and that exploration is reflected by the larger variability in behaviour in particular during transitions. Furthermore, exploration is thought to be constrained by, and specific to, a particular transition of one stable mode of action to the other.

REFERENCES

Bak, P., & Chen, K. (1991). Self-organized criticality. *Scientific American, January,* 26-33.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology,* **39**, 1-41.

Gibson, J. J. (1979/1986). *The ecological approach to visual perception.* Hillsdale: Lawrence Erlbaum.

Goldfield, E. C., Kay, B. A., & Warren, W. H. (1993). Infant bouncing: The assembly and tuning of action systems. *Child Development,* **64**, 1128-1142.

Hofsten, C. von (1984). Developmental changes in the organization of prereaching movements. *Developmental Psychology,* **20**, 378-388.

Hunt, J., McV. (1963). Motivation inherent in information processing and action. In O. J. Harvey (Ed.), *Motivation and social interactions: Cognitive determinants.* (pp. 35-94) New York: The Ronald Press Company.

Kugler, P. N., Kelso, J. A. S, & Turvey, M. T. (1982). On the control and coordination of naturally developing systems. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement*

* Of course there are some problems in this strategy of analysing the data. Newell et al. (1991) for example, suggest that "it is the form of the search strategy through space (which could be guided by a general informational decision criterion) that is general, rather than the specific, output of the motor system" (p. 107). Moreover, in the experiment the number of 'attractors' change when a ball is removed from the board.

control and coordination (pp. 5-78). New York : Wiley.

Kugler, P. N., & Turvey, M. T. (1987). *Information, natural law, and the self-assembly of rhythmic movement : Theoretical and experimental investigations.* Hillsdale : Lawrence Erlbaum.

Levin, R. (1993). *Complexity : Life on the edge chaos.* London : Phoenix.

Montgommery, K. C. (1954). The role of the exploratory drive in learning. *Journal of Comparative Physiological Psychology,* **47**, 60-64.

Newell, K. M., Kugler, P. N., Van Emmerik, R. E. A., & McDonald, P. V. (1989). Search strategies and the acquisition of coordination. In S. A. Wallace (Ed.), *Perspectives on the coordination of movement* (pp. 85-122). Amsterdam : North-Holland.

Newell, K. M., McDonald, P. V., & Kugler, P. N. (1991). The perceptual-motor workspace and the acquisition of skill. In J. Requin & G. E. Stelmach (Eds.), *Tutorials in motor neuroscience* (pp. 95-108). Dordrecht : Kluwer Academic Publishers.

Nissen, H. W. (1954). The nature of the drive as innate determinant of behavioral organization. In M. R. Jones (Ed.), *Nebraska Symposium on Motivation* (pp. 281-321). Lincoln : University of Nebraska Press.

Nunnally, J. C., & Lemond, L. C. (1973). Exploratory behavior and human development. In H. W. Reese (Ed.), *Advances in Child Development & Behavior,* **8**, (pp. 59-101). New York : Academic Press.

Out, L., & Savelsbergh, G. J. P. (this volume). The role of strength in the development of reaching.

Robertson, S. S. (1993). Oscillation and complexity in early infant behavior. *Child Development,* **64**, 1022-1035.

Savelsbergh, G. J. P., & Kamp, J. Van der (1993). The coordination of infant reaching, grasping, catching and posture : A natural physical approach. In G. J. P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 289-317). Amsterdam : Elsevier Publishers.

Savelsbergh, G. J. P., & Kamp, J. Van der (this volume). A natural physical perspective on the development of infants eye-hand coordination : A search for the laws of control.

Savelsbergh, G. J. P., & Kamp, J. Van der (submitted). *The effects of gravity on infant reaching.*

Thelen, E. (1979). Rhythmical stereotypies in normal human infants. *Animal Behaviour,* **27**, 699-715.

Thelen, E. (1990). Coupling perception and action in the development of skill : A dynamic approach. In H. Bloch & B. I. Berthenthal (Eds.), *Sensory-motor organizations and development in infancy and early childhood* (pp. 39-55). Dordrecht : Kluwer Academic Publishers.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching : Mapping intention and intrinsic dynamics. *Child Development,* **64**, 1058-1098.

Thelen, E, & Ulrich, B. (1991). Hidden skills : A dynamic analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development,* **56**.

Turvey, M. T., & Fitzpatrick, P. (1993). Commentary : Development of perception-action systems and general principles of pattern formation. *Child Development,* **64**, 1175-1190.

Warren, W. H. (1990). The perception-action coupling. In H. Bloch & B. I. Berthenthal (Eds.), *Sensory-motor organizations and development in infancy and early childhood* (pp. 23-38). Derdrecht : Kluwer Academic Publishers.

Wimmers, R. H., Savelsbergh, G. J. P., Beek, P. J., & Hoplins, B. (this volume). Are there phase transitions in the development of eye-hand coordination ?