A NATURAL PHYSICAL PERSPECTIVE ON THE DEVELOPMENT OF INFANT EYE-HAND COORDINATION: A SEARCH FOR THE LAWS OF CONTROL

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The goal of the article is to describe a research paradigm with respect to eye-hand coordination. Basic concepts of ecological psychology (information and affordances), of non-linear dynamics (order parameter, control parameter and stability), and of the natural physical approach (the laws of control) are discussed. The article will conclude with a description of the research program as currently conducted within the proposed research paradigm.

Key words: Information, affordances, order and control parameters, stability, laws of control.

Introduction[1]

The starting point of our research program concerning the development of infant's eye-hand coordination is the natural physical approach based on the work of Bernstein (1967), Gibson (1979) and Kugler, Kelso and Turvey (1982). According to the coordinative structure theory proposed by Kugler et al. (1982), development of coordination is brought about by changes in the constraints imposed upon action. Three categories of constraints have been proposed: organismic (e.g., nerve system), task (e.g., reaching with one hand) and environmental (e.g., large object) (Newell, 1986). These different constraints do not operate in isolation, but interact with each other, leading to a task-specific organisation of the coordination pattern. Hence, constraints have to be defined for the organism-environment complex: properties of the organism and the environment collectively determine movement possibilities.

The purpose of the paper is to show that perception and movement should be considered as inseparable (Kugler & Turvey, 1987: Savelsbergh & Van der Kamp 1993). This coupling of perception and movement is approached from a developmental perspective. To lay a basis for this, the concepts of direct perception (Gibson, 1979: information and affordances), of non-linear dynamics (Zanone, Jeka & Kelso, 1993:

[1] Portions of this article have been published in a more extensive form by Savelsbergh & Van der Kamp (1993) as Chapter 11 in G. J. P. Savelsbergh (Ed.), *The Development of coordination in infancy* (pp. 289-317) North Holland: Elsevier.

order and control parameters, stability) and of the natural physical approach (Kugler, 1986: laws of control) are discussed. The article will conclude with a description of the research program with respect to eye-hand coordination as currently conducted in our lab.

1. A new approach to perception and movement

One of James Gibson's (1979) most famous citations is 'We must perceive in order to move, but we must also move in order to perceive' (p. 223). Information guides the movement, and through movement new information is generated and becomes available to the actor. What precisely is meant by 'information'?

1. 1. Information

Gibson's (1979) ecological approach to visual perception is also known as direct perception. The word 'direct' refers to the fact that objects, places and events in the environment are unambigiously specified in the optic array. This information can be picked up by the perceiver without the need to interpret it. Hence, no cognitive mediation is needed in order to make perception meaningful. In 1988, his wife and colleague Eleanor Gibson wrote:

> The old view of perception was that "input" from stimuli fell upon the retina, creating a meaningless image composed of unrelated elements. Static and momentary, this image had to be added to, interpreted in the light of past experiences, associated with other images, etc. Such a view of perception dies hard, but die it must. There is no shutter on the retina, no such thing as a static image. Furthermore, perceiving is active, a process of obtaining information about the world....We don't simply see, we look. When we seek information in an optic array, the head turns, the eyes turn to fixate, the lens accommodates to focus, and spectacles may be applied and even adjusted by head position for far or near looking (p. 5).

In this view the information in the optic array is not static in time and space. It specifies events, place and objects. Therefore, when a child detects the information, she or he perceives events and not some kind of discrete stimulus that has to be interpreted. This concept of information is closely related to the concept of affordances.

1. 2. Affordances

In Gibson's (1979) approach the word 'affordances' is a central concept. It expresses the relation between perceiving and acting:

> The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment' (p. 127).

Affordances relate to possibilities for action of an organism in a particular environment. Therefore, they relate to the perceiver's own potential action system, which implies the use of a body-scaled and not an absolute metric (e. g., meters, kilogrammes etc.) for perceiving. 'Body-scaled' means that the coordination pattern is determined by the ratio between a metric of the action space and a metric of the actor (body dimension). For example, for an actor who wants to climb stairs, the coordination pattern is specified by the ratio between the tread height (action space) and the actor's leg length (metric of the actor) (Warren, 1984). Another example is provided during the act of grasping of an object. When the object is small, it is possible to take the object with one hand. When the object is too big for one hand, two hands are needed. When the ratio between hand size (metric of the actor) and object size (action space) reaches a critical ratio, a new coordination pattern emerges, the actors shift from one-handed to two-handed grasping. In the case of stair climbing another pattern is shown when the tread height becomes too high (e. g., normal tread height for a young child). The child crawls instead of walks. The question that now arises is: how do we detect these affordances? By picking up the information specifying and guiding the movement, affordances are detected. An affordance refers to the fit between the information and the action.

1. 3. The detection of affordances

Crucial in the detection of affordances is the active exploration of the environment (see Van der Kamp & Savelsbergh, this volume). Exploratory activity (e. g., moving) reveals information and therefore affordances. During development, organismic constraints (depth vision, muscle power etc.) change very quickly and therefore the exploratory possibilities change dramatically. Consequently, infants start crawling, the number of action possibilities increases, leading to the discovery of new information and the detection of affordances. Furthermore, by exploratory activities infants become more sensitive to relevant information which guides their actions.

In sum, exploration is not some kind of trial and error behaviour, but controlled behaviour. As Michaeland Carello (1981) points out:

> 'Exploration (attention) is not an unconscious sifting-through and subsequent rejection of most inputs: It is directed control of what will be detected' (p. 70).

Exploration is goal-directed in the sense that it reveals the coupling between information and action or between organism and environment (Van der Kamp & Savelsbergh, this volume). Similarly, Kugler, Kelso and Turvey (1982) argue that stable modes of action (e. g., walking) emerge from the underlying dynamics of the organism-environment system and is guided by information specific to these dynamics. In this respect the concept of laws of control is relevant. However, before discussing these laws, some concepts from non-linear dynamic systems theory need to be discussed.

2. Dynamic systems

Dynamic systems theory provides tools to identify patterns of behaviour, to describe changes in these patterns and to investigate what leads to these changes (Zanone, Kelso & Jeka, 1993). In this respect, three main concepts will be discussed:

order and control parameters, and stability.

2. 1. Order and control parameters, stability

An order parameter or collective variable is the parameter that captures the behaviour (coordination pattern), while a control parameter is the parameter that leads the system through different coordination patterns. Within this approach, the behavioural pattern is regarded as a stable collective state attained by the system under certain constraints (boundary conditions) and informational settings (Zanone et al., 1993). When the control parameter passes through a critical point, a previous coordination pattern which was stable in organisation becomes unstable causing a sudden discrete transition to a qualitatively different, stable coordination pattern. Let's have a look at the same example as in section 1.2. The coordination pattern for grasping an object is dependent on the ratio of object size/hand size. When the object is larger than the hand, it will be grasped with two hands (stable mode). During development the hand will become larger (in fact a scaling-up) which implies that the ratio of object/hand size changes. At a certain ratio (critical point) the object will be grasped with one hand, and another time with two hands, that is, there is a loss of stability. If the hand grows larger, the object will be constantly grasped with one hand, that is, a new stable mode emerged. Hence, with respect to development, patterns of coordination become unstable and even disappear and new patterns of coordination suddenly emerge and become stable. We will use this way of describing developmental changes in coordination patterns and describe two general laws of control in section 3.2. In the previous section, we argued that exploratory behaviour is essential in detecting affordances. In the next section we explain the relation between exploratory behaviour and stability.

2. 2. Exploratory behaviour and stability in the workspace

According to Newell and co-workers (Newell et al., 1989), developmental changes in coordination arise from explorations of the perceptual-motor workspace. The workspace evolves from the circular relations between movement and perception (or informational processes). It is regarded as a generic concept, in which both the building blocks (equilibrium or attractor regions which are asymptotically stable solutions of the collective variable dynamics) and the exploratory behaviour to discover critical regions (border of stability and instability) in the workspace are universal. Exploration of these workspaces is guided by constraints that arise from the configurations of the field processes that characterise the space. In other words, the information organisms utilise to explore the workspace is embedded in the form and layout of the gradient and equilibrium (attractor) regions that characterise that space. By means of exploratory behaviour, the control parameter can be scaled-up or down to a critical point, and stability and instability regions can be discovered. By discovering these regions, exploitation of the stabilities and instabilities can be carried out (also by means of exploratory behaviour), which will lead to an effective solution for accomplishing a specific task.

Both from an ecological psychological approach and from a dynamic systems approach, exploratory behaviour is very important. In the former, it is important for the detection of affordances, in the latter, for the detection of critical regions. In the next section we bring these two perspectives together.

3. Bringing ecological psychology and dynamic systems together: a natural physical approach

Kugler and Turvey (1987; Kugler 1986) proposed laws of control which express the lawful relationship between perception and action. Put another way, the laws of control involve the relationship between kinematic optic flow fields (perception) and the kinetics of force fields (movement) (see also Savelsbergh & van Emmerik, 1992; Savelsbergh & Van der Kamp, 1993).

3. 1. Laws of control

The relations between information that constrains movement and movement that generates information are consistent with, but *not reducible* to, natural laws of physics. Kugler and Turvey (1987) proposed two 'general' ecological laws of control to describe these relationships:

Law of Ecological Optics $flow = F(force)$ and
Law of Specification $force = F(flow)$

These laws identify the parameters of movement in the (kinetic) force field that are uniquely specified by the information in the (kinematic) flow field and vice versa.

Warren, Young and Lee (1986) investigated the visual control of running over an irregular surface and proposed such a law for this task. While running, the runner has to adjust step length to the (sometimes changing) demands of the support terrain. The step length of the runner is determined by the amount of vertical impulse: a large impulse causes a long step length (force). Furthermore, while running, the approaching irregularities of the surface provide an optical expansion on the retina (flow). The inverse of the relative rate of dilation of these approaching expanding optical contours generated in the optical array specifies the time of contact between the observer and the environment. This optical variable has become known as the *tau*-variable (Lee, 1980; Savelsbergh et al., 1991, 1993). The Warren et al. study (1986) demonstrated that the required duration of the step (and therefore step length) as regulated by the amount of impulse, I, between two upcoming targets is specified by the difference in time to contact between two targets (difference between the two tau's = delta T):

$$\text{Impulse} = \text{mass} \times \text{gravity} \times \text{delta T}$$
$$(\text{mass} \times \text{gravity is a constant})$$

This 'ecological' law specifies the relation between a vertical impulse (an action variable) and an optical variable tau (a perceptual variable).

3. 2. Developmental laws

By analogy with the aforementioned laws of control, two developmental laws are proposed by the authors. These general developmental laws bring together the concepts of information and affordances (section 1.1 and 1.2) and the concept of stability (section 2.1.). The two general laws are, for a given time during development and a certain set of constraints:

Law of Possibility	*affordance* = *F* (*stable mode of action*)
Law of Stability	*stable mode of action* = *F* (*affordance*)

Discovering of new affordances will lead to new stable modes of action (or order parameters). These stable modes of action (i. e., stability in a particular coordination pattern) are effective solutions for a particular task under given constraints. Changes in stable mode of action (due to the scaling-up or down of a control parameter) will lead to the discovery of new affordances. Savelsbergh and Van der Kamp (1993) mentioned the example of an infant who needs both hands to pick up a large object. If s/he is not able to sit without support (i. e., instability of this particular coordination pattern), the infant will not be able to grasp the object. However, in ontogenetic time, the postural control will improve (i. e., the control parameter will scale-up beyond a critical point) so that the infant will be able to sit without support (i. e., there will be stability of this particular coordination pattern). At this point, infants will discover that the ball is graspable with two hands (i. e., there is a new affordance).

It is important to note the way in which new affordances are discovered and new stable modes of action are acquired. This is achieved by a continuous exploration of the perception-movement cycle (Newell et al.'s perceptual-motor workspace), whereby the relevant coupling of information and movement is discovered (section 2 and Van der Kamp & Savelsbergh, this volume). This is in agreement with Warren's (1990) suggestion that dynamic stabilities and laws of control are discovered and exploited in the course of development. In other words, exploration serves to permit the laws of control to be discovered for a particular task.

4. Conclusions and the research program for eye-hand coordination

In the research paradigm outlined in this paper, development is seen as a continuous attunement of the actor to the environment accomplished by repeated exploration of the perception-movement cycle. This exploration is constrained by internal and external constraints and leads to task-specific organisations. The important issue is to investigate how this coupling between perception and movement develops and to discover their lawful relationships.

The research program concerning infant eye-hand coordination within the natural physical approach focuses on describing the development of infants reaching and grasping in terms of transitions of order parameters and the discovery of the control parameters inducing these transitions (underlying mechanism) (Wimmers, Savelsbergh, Beek & Hopkins, this volume). Further, it aims to discover the relevant informational (visual and proprioceptive; e. g., Savelsbergh et al, 1991, 1993) and movement constraints (strength; e. g., Out & Savelsbergh, this volume) controlling reaching and grasping behaviour and the way in which infants explore the perception-movement cycle in order to acquire a stable reaching and grasping pattern (Van der Kamp & Savelsbergh, this volume).

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