Short Communication

NO SINGLE FACTOR HAS PRIORITY IN ACTION DEVELOPMENT
A TRIBUTE TO ESTHER THELEN’S LEGACY

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Among Esther Thelen’s most important contributions to developmental theory is that there is no single factor that has priority in driving development. In this paper, we discuss how this notion influenced our research on perceptual-motor development. We show that multiple factors constrain perceptual-motor development, but that a relatively minor change in one of them may lead to significant changes in the observed perceptual-motor behavior.

Keywords: Development; psychology; biology; maturation; constraints; perceptual-motor; rate-limiting.

1. Introduction

Scientific views on how infants learn to move adaptively has been changed dramatically during the last two or three decades. The seminal work of Esther Thelen and her colleagues instigated this shift in thinking (although it was not the single factor). Traditionally, the development of action was seen as a rather rigid and gradual unfolding of posture and movement milestones. Developmental change was mainly attributed to a general process of maturation of the central nervous system. It followed that variations in the appearance of the milestones signaled error or deviant development [45]. Thelen [41, 45] claimed that ascribing functional
behavioral repertoires to something as vague and all encompassing as neural maturation fails to capture the complexities of the developmental processes involved. Many observations have now revealed that development is not often a process of gradual change; it is much better characterized by high levels of movement variability, discontinuities, jumps, instabilities and regressions [37]. These ideas have rejuvenated research on the development of action to the extent that it is (again) a field of study in its own right and has become an important testing ground for new concepts in developmental theory.

Since the topic of this paper is a tribute to Esther Thelen's legacy and contributions to the field of developmental science, we aim to show how she inspired our research. We do this by providing an overview of the studies that we conducted at the Infant Perception-Action Laboratory in Amsterdam. Esther Thelen aimed for a general theory of development that includes action, perception and cognition. In her publications, at least three major topics can be distinguished. Namely, no single factor has priority in shaping development, developmental processes are nonlinear and, variability in development has to be considered as functional. In this paper, we focus on the notion that there is no single causal factor for development, but that at different times different factors may influence developmental change. Our research on the development of action was and still is tributary to Esther Thelen's work, but it is also heavily influenced by the early neurophysiological work of Bernstein [5], the Gibsons' ecological approach to perception and action [16, 17], Newell's constraint-led approach [31], and the dynamic systems theory as formulated by Kelso and Turvey [25, 26, 27, 46]. These perspectives are based on disciplines like biology, psychology and physics and thus have a strong foundation in the natural sciences. In this tribute to Thelen's legacy, we start with her seminal work on the disappearance of stepping movements in early development, and illustrate how these experiments laid the foundation for our research in the last fifteen years.


The basic premise for our research is the idea that the development of action is brought about by changes in the constraints that are imposed upon the organism-environment system [31]. Particular constraints may act, at certain developmental times, as rate-limiting factors in the emergence and mastering of new motor actions. We consider constraints as those factors that somehow set boundaries for the control and coordination of an action and changes therein. Constraints do not prescribe the pattern or form of an action, but they guide the direction of development by making the occurrence of certain patterns more or less probable. Newell [31] proposed a categorization in the available constraints with respect to their origin; organismic, task and environmental. Organismic constraints range from simply the size of the hand, interocular distance, and muscular strength, to more complex abilities such as the degree of mastery of movement control. The second category of constraints that are imposed upon action, are those that originate from the task, such as the size
or the speed of the object to-be-grasped. The third category is the environmental constraint, which includes the laws of nature such as gravity and so forth (for e.g., the difference of carrying out of a task in water or on land). Newell argued that an organism’s action emerges from the interaction between the three categories of constraints. A change in the confluence of constraints, therefore, can eventuate in a change in action, without one constraint being considered as the prime determinant. It is the interaction between environmental, task and organismic constraints that makes some but not other actions possible at a particular time and place [36]. Moreover, a change in action does not occur in isolation. It can, analogous to a scaffolding process, lead to the emergence of other actions or perceptions as well. A change in the action repertoire, for instance, result in a change in the way the infant perceives the world, as perception is closely linked with the infant’s action capabilities. This is illustrated in a study of Gibson and others [18]. Crawling and walking infants were confronted with rigid and deformable surfaces and were encouraged to traverse it. Crawling infants showed no preference for the rigid surface or the more pliable waterbed. Infants that were able to walk, however, preferred the rigid surface, and the few walkers who chose the waterbed surface crawled over it. Crawlers and walkers also showed different exploratory activity before they traversed the surface. These observations indicate that the infants’ current action repertoire influenced the perception of what the surroundings offer or afford for action.

From a constraints-led perspective, a particular constraint may act as a rate-limiting factor in the emergence of new action. In that case, a change in or the emergence of an action is directly contingent upon, but not solely determined by a (small) change within that constraint. The classic example of this idea stems from Thelen’s experiments on the development of leg movements.

3. The Disappearance of Stepping Movements

The experiments that put Esther Thelen on the science map in the early eighties are her studies on the development of leg movements [42–44]. It was long known at that time that around eight weeks after birth, the stepping-like movements that infants make from birth, when they are held upright, disappear. The disappearance of these stepping movements had traditionally been explained by an increasing maturation of the cortex that inhibited the so-called lower and more primitive “stepping reflex” centers. In an elegant series of experiments, Thelen and co-workers made two important observations. Firstly, when eight-week-old infants were lying supine, they made leg movements that were kinematically similar to the stepping movements. These kicking movements did not disappear from the infants’ action repertoire. Secondly, when the eight-week-old infants were held upright with their legs submerged in water, the stepping movements reappeared. It is very unlikely that cortical inhibition would suddenly fail when an infant is lying supine or has its legs submerged in water. The idea of cortical inhibition as a single factor in the disappearance of the stepping movements was clearly wrong. Instead, Thelen
demonstrated that it was contingent upon a disproportionate growth of leg muscles and fat tissues. Specifically, during the second month after birth, infants gain fat at a far greater rate than muscle mass, which leads to relatively less muscle force. Thus, the occurrence (and disappearance) of stepping movements is a consequence of the interaction between organismic constraints (body proportions) and environmental constraints (the direction of the leg movements in relation to the gravity vector), and not uniquely determined by neuro-maturational constraints. Moreover, a relative minor change in one of these constraints (e.g., an increase in body fat) may suddenly result in a change in the action repertoire of an infant.

4. Constraints in the Development of Reaching and Grasping

Inspired by Thelen’s studies, we hypothesized that something akin may occur in the development of grasping, and examined the effect of body orientation on infants’ reaching, and grasping [39] and spontaneous infant arm movements [23]. In the Savelsbergh and Van der Kamp experiment [39], 12–27-week-old infants were sitting in an infant chair that could be adjusted to three positions: vertical (90° from horizontal), recline (60°), and supine (0°). The infants were presented with a black card board on which nine balls were attached with Velcro. The three positions differed with respect to the direction of the arm movement in relation to the gravity vector. The direction of the arm movement is perpendicular to the gravity vector for the vertical orientation and opposite to the gravity vector in the supine orientation. Reaching and grasping was affected by age and body orientation. Specifically, in the vertical orientation, but not in the other orientation, the 12–19-week-old infants showed patterns of reaching and grasping behavior that was comparable to that of 20–27-week-old infants in regardless of body orientation positions. However, when the younger infants were lying supine they not only reached and grasped less often, but seem to do so with poorer control and coordination. The observation that only the young infants’ reaching and grasping was affected by body orientation suggests that biomechanical constraints may act as a rate-limiting factor during the development of reaching and grasping. In a follow-up study, Wimmers, Savelsbergh, van der Kamp, and Hartelman [60] provided further evidence for this suggestion. The change from reaching to reaching with grasping during the first six months of life was shown not to be linear but carried the characteristics of a discontinuous phase transition that was best described best with a Cusp catastrophe model, in which arm weight, arm circumference (as organismic constraints), and body orientation (environmental constraints) significantly contributed to the control parameters that led the system through the transition from reaching to grasping.

An examination of newborns’ spontaneous arm movements provides a second example of Thelen’s influence on our research. We found a higher incidence of a variety of spontaneous arm movements when the newborn is in a vertical position compared to a supine position [23]. Furthermore, like Thelen et al. [42] we found data for newborn stepping movements, chubbiness (as indicated by the ponderal index) correlated with the frequency of arm movements in the supine position. Thus, similar
to Thelen’s observations on leg movements, this experiment demonstrated that the development of reaching is not uniquely determined by the maturation of the central nervous system, but reflects a change in the interaction between organismic (e.g., arm mass), task (e.g., body position) and environmental (e.g., gravity) constraints. This has also important clinical implications for using either the quantity or quality of spontaneous movements as a diagnostic instrument of the status of the central nervous system [e.g., 33]. Specifically, it should be taken into account when assessing spontaneous movements the infants’ body position and anthropometrics.

In a more recent experiment, van Hof, van der Kamp and Savelsbergh [48] examined how the development of crossing the midline is interwoven with the development of bimanual reaching. Traditionally, it was thought that the development of midline crossing is uniquely determined by the maturation of the hemispheric specialization [e.g., 34] or the maturation of spinal tracts [30]. Van Hof et al. [48] observed infants longitudinally at 12, 18 and 26 weeks of age while reaching for a small and large ball (3 and 8 cm in diameter) that were presented at three positions (i.e., at the body midline, or in front of the right and left shoulder). With age, the infants increasingly adapted the number of hands they used to the size of the object. Also, the number of reaches that crossed the body midline increased with age. Most interestingly, however, was the finding that, the majority of the midline crossings were made during two-handed reaches for the large ball; they first occurred at or after the onset of bimanual reaching. The development of crossing the body midline seems to emerge in the context of bimanual reaching. It indicates that the need to grasp a large ball that is positioned in front of the shoulder induces midline crossing. The development of midline crossing is not exclusively dependent on organismic constraints (e.g., the maturation of hemispheric connections), but on their interaction with environmental constraints (e.g., object size and position).

In sum, we have repeatedly shown a point first made by Esther Thelen. There is no privileged status for the maturation of the central nervous system in the development of action. The empirical evidence indicates that it is the presence of the confluence of constraints from which actions emerge. Individual constraints may sometimes act as a rate-limiting factor for the emergence of new actions. These rate-limiting constraints do not cause the emergence of new actions. However, new actions may be directly contingent on relatively small changes in such rate-limiting factor (e.g., change in fat/muscle ratio; or object/hand size ratio). Obviously, also maturation in the central nervous system may act as a rate limiter, but it is not likely to be the only one. By identifying organismic, task and environmental constraints and their relative contribution, we can come to understand the emergence of patterns of action in real time as well as in developmental time, [28] including variation therein (as shown above).

5. Visual Information as a Constraint in the Development of Action

What behavior will be successful depends on the situation, and hence the ensemble of various constraints imposed on the organism-environment system. Constraints
imply restrictions, and restrictions are usually thought of as negatively. A highly constrained task, however, reduces the “problem” to solve, as illustrated by the infant’s visual immaturity. In the reduced search space, exploration can then occur efficiently such that behaviorally relevant information will be noticed [see also Ref. 32]. Being not capable of detecting every piece of information in a wealth of information allows one to focus on crucial information. For a particular action, therefore, constraints enable behavior to change (i.e., provide the conditions for learning), and in that light, less can be more [36].

A constraint that has usually been overlooked is the degree to which infants are able to control their movements. That is, if the environment informs the infant what action can be realized, then their perception must (logically speaking) be constrained by what movements an infant can execute. The better the movement execution, the more accurate action possibilities, [17] should be perceived. To examine whether the development of the perception of affordances is constrained by the development of infants’ abilities to control their movements, a characterization is required of how movement control itself changes and how different types of constraints influence the information-based control of movement.

Proponents of the ecological psychology approach argue that movement control requires an appropriate relationship between informational and movement variables. From this perspective, we investigate how infants’ grasping and catching movements are constrained by optical information. Informational variables, selected to regulate movement control, differ in the degree of usefulness for a task. The informational variable that is most useful in a situation is the variable correlating highly to or even specifying the to-be-perceived or the to-be-acted-upon property [22]. One of the factors that may induce developmental change in the control of movements is a change towards regulating movements with a more useful informational variable [24], that is, a convergence towards more useful non-specifying or even specifying optical variables [16, 17, 22, 54]. This is what Eleanore Gibson called differentiation or selection. However, a term that better captures the idea of coming to rely on better informational variables is education of attention [15] or attunement [22]. Thus, learning to act involves a change in the informational variables used to control movements [40, 56, 57]. In view of this perspective, a prerequisite is to describe the changes in the informational basis of infants’ interceptive movements, and then to deduce regularities to understand developmental processes of how infants acquire and improve their skills. Although

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*For example, in the case of catching a frontally approaching ball, the to-be-acted-upon property is assumed to be the time remaining before contact. Optic angle, for instance, can inform about the time-to-contact, but only if the ball is always of the same size and traveling with the same speed from the same direction. Under more global constraints (e.g., in the case of varying diameter, speed and direction of motion) only a few (or perhaps one, e.g., the inverse of the relative rate of expansion) variables specify ball approach.

bHere, we follow Jacobs and Michaels (2002) who in the context of perception refer to a variable as specifying only if it specifies the property that the perceiver intends to perceive, and to a non-specifying variable when it does not specify that property.
Esther Thelen never directly examined visual constraints, as shown earlier, our work is not only based on her ideas, but in fact extends these ideas into the visual domain.

In this spirit, Van Hof, Van der Kamp and Savelsbergh [49] sought to uncover what types of visual constraints use to guide their catching movements, and how this changes during development. In this respect, several researchers have noticed that the dramatic improvement in reaching and catching skill around 3 to 5 months of age appears to coincide with the onset of binocularity [4, 10, 51]. This co-occurrence in time suggests that attunement to binocular information is one of the processes that underlies infants’ development to adaptively control goal-directed arm movements. For instance, at birth, the visual system is not fully functional, and this immaturity restrains the detection of information [see for a review 4]. One example is binocularity. The horizontal offset of the two eyes results in slightly different images of the objects and surfaces on each retina. These differences, known as retinal disparities, provide information about the distance, orientation and shape of objects [13, 59]. However, the anatomical substrates involved in detecting this binocular information develop postnatally [7, 8, 11]. That is, although fibers carrying signals from both eyes have established terminations on the striate cortex well before birth [35], their separation into ocular dominance columns is not complete until several weeks postnatally [21]. It has been demonstrate that infants lack stereopsis until a layer IV of the primary visual cortex shows this organization in ocular dominance columns. Hence, it is only between the age of 12 to 16 weeks that the perception of depth-based-upon binocular information emerges [3, 14, 20]. More recent studies have provided estimations of the onset of binocularity between 8 [9] and 24 weeks of age [12]. Moreover, after the onset of binocularity, the range of disparities to which infants are sensitive expands gradually [58], whereas stereoacuity (i.e., the minimum disparity which can be detected) shows a very rapid increase [4, 8, 10]. We thus have a rather detailed picture of the developmental changes of binocularity. The development of infants’ sensitivity to binocular sources of information, however, is mainly tested in habituation, preferential looking, and VEP (visual evoked potential) studies. And although these perceptual studies may be indicative, it is rather hazardous to automatically generalize their findings to infants’ development of utilizing binocular information in movement control; that warrants experimental consideration in itself [4, 29, 52, 53]. From a pure maturation point of view, one could argue that with development (thus age) the visual system improves and therefore the reaching becomes under visual control. However, from an Esther Thelen’s point of view, maturation is just one of the components and has no priority. The attunement to the visual information (or optical variable in ecological psychology terms) needs still to be happen. For that reason, we investigated in three- to eight-month olds the developmental changes in the relative contribution of monocular and binocular variables in the guidance of interceptive arm movements. We were particularly interested in the changes underlying the control of the timing of goal-directed
arm movements. A cross-sectional and a longitudinal experiment were conducted that examined developmental changes in the relative contribution of monocular and binocular variables in the guidance of interceptive arm movements [49]. In these experiments three- to eight-month-old infants were observed while presented with different sized balls that approached frontally with a constant velocity under both monocular and binocular viewing conditions. The movement onset indicated that with age, infants increasingly come to rely on binocular variables to control the timing of the interceptive arm movements. That is, from seven-eight months of age, movement onset was independent from object size under binocular but not under monocular viewing. By contrast, binocular viewing enhanced the spatial accuracy of the interceptive arm movements at all ages. This study is the first to show with a longitudinal design that attunement is one of the processes that underlie the development of movement control. More specifically, it shows that infants increasingly come to rely on binocular variables when learning to intercept moving objects. Yet, catching involves the formation of multiple on-line couplings (e.g., coupling between monocular information and reaching next to binocular information and reaching) between optic and movement variables that are dependent on task constraints. The findings suggest that these multiple couplings develop asynchronously. Attunement not only facilitates adjustment to the requirements of the environment, but it also results in the formation of a repertoire of effective couplings between optic and movement variables that allows for an ever increasing interaction between the infant and his or her environment. In other words, maturation of visual system is one of the players but has no priority above others.

This picture is confirmed by a follow-up experiment which was concerned with the question how perception and action mutually influence each other [50]. That is, how does the visual guidance of action develop? And, vice versa, how does action constrain the development of perception? To this end, the accuracy of three- to nine-month-old infants’ perception of the affordance of the ball’s catchability was determined by assessing whether the infants attempted to catch the ball at a given speed. In the case of the infant trying to catch the ball, the visual information that was involved in the control of the catching movement was established. The researchers determined the outcome of each infant’s catching attempts, that is, whether these attempts were successful (resulting in ball-hand contact) or not. The lower the proportion of failing the catching attempts, the more accurate the infant perceived the ball’s catchability. This accuracy is also reflected in the difference between the ball speed that was still perceived as catchable (e.g., affordance) and the highest ball speed that was actually successfully managed. The study showed that three- to five-month-old infants faced with a slowly approaching object discovered that it can be contacted through reaching. Albeit unrefined, these young infants perceive that an object moving slowly towards them affords catching or making contact. However, the large proportion of failures to actually contact the object suggest that it is not until the age of approximately six- to seven-months that the infants accurately
perceive their own capability to intercept the approaching object. Around six- to seven-months after birth, the accuracy by which infants perceived the catchability of the object in relation to their own capabilities improved dramatically. But they are not fully accurate in their perception of the ball’s catchability. In contrast, the eight- to nine-month-old infants did show less failing catching attempts, indicating that the oldest infants in the present study did take into account their action capabilities in order to decide whether or not to intercept a moving object. A similar developmental pattern of first discovering the affordance and then improving the accuracy of its perception has been reported for locomotion in somewhat older infants [1, 2, 18, 47].

Furthermore, we assessed each infant for the optical information on the basis of which the onset of the catching movement is timed. At the same age, infants perceptually differentiate between balls that were catchable from those that move too fast to be caught. They selected more useful optical information that guided the temporal properties of the catching action. It is concluded, therefore, that developmental changes in the perception of whether objects that move at different speeds can be caught and the visual control of the catch are mutually constraining, again illustrating our point with respect to priority.

6. Epilogue

The aim of this paper was to illustrate the influence of Esther Thelen’s approach to issues in perceptual-motor development, her train of thought and how she catalyzed research into new directions about these issues based on biology, psychology and physics. Four issues can be distinguished. That is, no single factor has priority, action and perception to form an inseparable loop. Developmental processes are non-linear and, variability in development has to be considered as functional. From the constraint-led perspective, we show evidence for the first issue. The core of our contributions lies with the interaction between the task (e.g., reaching), environmental (e.g., visual information, postural position with respect to the gravity vector; water) and organismic (e.g., muscle/fat ratio, cortical inhibition, maturation of hemispheric connection; binocular vision) constraints and indicate the relative contribution of these different constraints at different moments in time with respect to the development of goal-directed behavior. A rather small change in one of the constraints can lead to changes in the observed co-ordination pattern. However, none of these has priority in action development.

References


No Single Factor has Priority in Action Development


