Motor Development in Children: Aspects of Coordination and Control

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CONSTRAINTS ON THE DEVELOPMENT OF COORDINATION

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The development of coordination is one of the most important and fascinating problems in the study of both development and action. Indeed, Weiss (1941) has characterised the ontogeny of coordination as being essentially *the* problem of the ontogenetic origin of behaviour. The significance of coordination in physical activity is most apparent in infancy because it is during this period that many of the basic patterns of posture and movement appear. These basic patterns of coordination are usually called phylogenetic activities because they are seen as fundamental to the continued survival of the human species. Ontogenetic activities, in contrast, reflect more socially driven skills and the shorter term demands of groups or individuals which vary with the culture. Traditionally, these distinct classes of activities have promoted different theoretical formulations regarding the acquisition of coordination in action.

The domain of motor development has focused primarily on the patterns of coordination that support engagement in phylogenetic activities, such as sitting, standing, walking, running and grasping. The early work of Gesell (1929), Ames (1937), McGraw (1943), Shirley (1931) and others charted the chronological milestones in the emergence of prone progression and the other fundamental activities of posture, locomotion and manipulation. These developmental studies are also important, however, because collectively they represent one of the few attempts to study the acquisition of coordination in humans. This situation has arisen because studies in motor learning with adults have focused either on tasks that require the performer to constrain only a single degree of biomechanical freedom, which by definition excludes a coordination problem at the behavioural level of analysis, or, on tasks that demand a pattern of coordination that the subject can produce on the first trial of learning (cf. Newell, 1981, 1985). Thus, the early motor development work by Gesell and other developmentalists holds potential significance from the general perspective of formulating theoretical notions about the acquisition of coordination per se.

Theoretical discussion of the development of coordination is traditionally couched in terms of the maturation vs. learning debate, or more generally, the nature-nurture issue (cf. Bower, 1974). The drawing of a sharp distinction between the impact of endogenous and exogenous factors in the development of coordination has waned in recent years (cf. Connolly, 1981), as indeed it has generally in developmental psychology. Consistent with this trend, it is primarily the similarity of the maturation and learning theories with respect to the development of coordination that is of interest here, rather than the traditional focus on their differences.

The maturation and learning theory approaches to motor development

share an important assumption regarding the development of coordination. Namely, that the coordination of activity is specified by instructions from either a genetic code or through some instance of learning theory formulations. In other words, both the maturational and learning perspectives assume that the development of coordination is due to the development of prescriptions for action, where "prescriptions" is taken as a general label for symbolic knowledge structures at some level of representation prescribing the course of action. Furthermore, recent cognitive orientations to motor development (e.g., Bruner, 1970., 1973; Connolly, 1970a; Zelazo, 1983)., essentially reflect a modern prescriptive version of a learning theory approach to the acquisition of coordination in children's physical activity (Newell & Barclay, 1982).

The traditional and contemporary prescriptive orientations to the development of coordination stand in opposition to the coordinative structure theory of action advanced by Kugler, Kelso and Turvey (1980, 1982). On this view, coordination emerges not from prescriptions for action but as a consequence of the constraints imposed on action. That is, constraints eliminate certain configurations of response dynamics, with the resulting pattern of coordination a reflection of self-organising optimality of the biological system, rather than specifications from some prescriptive symbolic knowledge structure.

In this paper, the prescriptive and coordinative structure orientations to coordination are briefly contrasted as a background to outlining the general significance of constraints to the development of coordination. It will be argued that the ubiquity of order and regularity in the developmental progressions of children's fundamental movement patterns is determined in large part by the constraints imposed on action. A general theme to emerge from the ensuing synthesis is that a research strategy that manipulates to the extremes the interaction of organismic, environmental and task constraints could prove useful in distinguishing the utility of, on the one hand, the traditional prescriptive orientations to motor development, and on the other, the coordinative structure perspective. In addition, an understanding of the significance of constraints to action opens the door to thinking about the acquisition of coordination as a general theoretical problem, independent of the class of activity and developmental stage of the individual.

The Motor Development Sequence

The development of coordination has been taken as synonomous with the development of fundamental movement and posture patterns. The ubiquity of order observed in the development of these coordination patterns has promoted the idea of a sequence of stages or steps in motor development. For example, Gesell (1946, p. 302) defined stages as a series of postural transformations. In discussing postural transformations and the development of coordination, Gesell recognised that concepts of morphology can be extended from physical phenomena to the phenomena of behaviour. In short, Gesell assumed that behaviour has shape. Specifically, Gesell (1946, p. 297) proposed "a morphological approach leads to the description and measurement of specific forms, the systematic study of topographic relations and correlations of such forms, their ontogenetic progression, and involution, their comparative features among individuals and among species". It seems that Gesell has an appreciation of the significance of the topological features of the response dynamics although he and other scholars in this early period of motor

development never pursued this approach formally with respect to the development of coordination. Some discussion of both the definition and measurement of the terms stage and coordination is essential to a theoretical consideration of the development of coordination.

Motor Stages: Progressive sequences of coordination?

The construct of 'stage' has had a checkered history in developmental psychology (cf. Brainerd, 1978; Kessen, 1962; Wohlwill, 1973). Problems have arisen from its use or misuse as both a descriptive and/or explanatory construct. In addition, the breadth of behaviours encompassed by the stage construct has made it difficult to apply a consistent definition. Although many developmentalists would agree with Flavell and Wohlwill (1969) that stage attains its maximal usefulness when it is used in reference to a set of behaviours intermediate in specificity between the case of an isolated response (e.g., crawling) and the case of a completely non-specific array of behaviours associated with a given age (e.g., infancy), this is not the interpretation generally given to discussions of the stage construct in motor development (cf. Roberton, 1978).

Typically, "stages of motor development" is the phrase used in reference to the order and regularity of the emergence of specific phylogenetic movement patterns in infancy and the early years of childhood. Shirley (1931), on the basis of observing 25 infants, identified five sequential stages in the "development" of upright locomotion: postural control of upper body; postural control of entire trunk and undirected activity; active efforts at locomotion; locomotion by creeping; and postural control and coordination of walking. Similarly, McGraw (1943) categorised seven stages of prone progression from the newborn state to the acquisition of a characteristically human gait. More recently, the development of ultrasound technology has allowed the charting of the emergence of fetal movements *in utero* (Ianniruberto & Tajani, 1981; Reinold, 1976; de Vries, Visser & Prechtl, 1984).

Early motor development researchers, therefore, defined 'stage' in terms of the specific movement patterns of children, with the implicit or explicit maturational prediction of an invariant and universal sequence of movement patterns emerging in the developing child. Although the notion of an invariant developmental movement sequence is generally accepted there have been a number of documented departures from this sequence. The primary example is that of variations in the individual rate of developmental progression that has been shown in cross-cultural (cf. Super, 1981) and training studies (e.g., Zelazo, Zelazo & Korb, 1972). However, individual differences in rate of development are not seriously damaging to the maturational perspective as long as the invariant order of the coordination sequence is preserved. Of more significance from a theoretical standpoint are examples of omissions (e.g., Robson, 1970; Touwen, 1971), and reversals (e.g., Touwen, 1971; Zingg, 1942) in the developmental movement sequence. Exceptions to the developmental movement sequence are rarely emphasised in theoretical discussions of the development of coordination, and where they are broached, they are often dismissed due to the unreliability of the data (e.g., feral children).

The discrepancy in the breadth of behaviours encompassed by current cognitive and motor interpretations of the stage construct has also been recognised (Roberton, 1978). In response to this differential use of the term

stage, Roberton proposed that the specific intra-task developmental
movement sequences be referred to as steps, allowing stage to be reserved
for the broader interpretation of a common approach to a set of motor tasks.
This caveat has not generally been heeded.

Gesell (1929, 1946, 1952) was instrumental in providing a maturational
interpretation of the developmental movement sequences exhibited in phylo-
genetic skills. Essential characteristics of the maturation process were
considered to be: 1) the appearance of new patterns of behaviour without
the benefit of practice; 2) consistency in these new patterns of behaviour
across subjects within the same species; and 3) an orderly and invariant
sequence in the development of these behaviours. Gesell (1929) did not
deny the influence of the environment but endogenous factors were viewed
as more critical than exogenous factors in the development of coordination.

The maturational perspective on motor development has been criticised
to the extent that it has now lost much of its impact as an explanatory
construct (cf. Connolly, 1970b). In spite of this trend, and the emergence
of cognitive orientations to motor skill development (e.g., Bruner, 1970;
Connolly, 1970a; Piaget, 1950, 1970), maturation is implicit, if not explicit,
in current accounts of the development of coordination. Consider, for
example, the systematic research by Roberton (1982) charting the invariant
steps in development of throwing actions in young children.

In summary, the "stage" construct in motor development has generally
referred to the specific patterns of coordination exhibited by infants and
individuals in early childhood, rather than a disposition toward a general
set of motor behaviours. The primary, although not exclusive, theoretical
account of these developing movement patterns has been the maturational
formulation, after Gesell (1929, 1946).

Behavioural Manifestation of Coordination

The development of an explanatory construct for the order and regularity
observed in the progressive sequences of children's coordination patterns
has also been hampered by the imprecise methods traditionally utilised to
describe veridically the developmental movement patterns. Furthermore, the
theoretical and operational definitions of the term coordination have usually
been formulated as verbal descriptions of movement sequences. These des-
criptions have related at various times to: anatomical units and; the
relative positions of the body and limbs with respect to the environment.
Verbal accounts of the changes in these variables in phylogenetic skills
inevitably lose the precision required to formulate theoretical constructs of
the development of coordination.

Attempts to provide a precise theoretical and operational framework for
analysis of the development of the behavioural unit in action may be enhanced
by a distinction between the terms coordination, control and skill (Kugler et
al, 1980, 1982; Newell, 1985). Briefly, Kugler et al (1980) propose that:
coordination is the function that constrains the potentially free variables
into a behavioural unit; control is the parameterisation of this function; and
skill is the optimal parameterisation of this function. The language of the
coordination function, that is, the essential variables that are being con-
strained, remains one of the fundamental unknowns in the theory of action.
Formal accounts of the behavioural unit or activity may, nevertheless, be

developed independent of the concern with the essential nature of the basic organisational principles of movement control.

Recent studies of the visual perception of biological motion (cf. Cutting & Profitt, 1982; Johansson, von Hofsten & Jansson, 1980) show that relative motion of limb segments takes priority over the observer's perception of the absolute motion of the limbs and torso in various activities. One can elaborate from this work to suggest that any activity may be defined by a unique set of topological characteristics of relative motions of the torso and limbs (Newell, 1985). In other words, it is the topological characteristics of movement, those that remain invariant in the face of transformations of scale, that distinguish patterns of coordination, and hence, the labelling of physical activities. The scaling of the set of relative motions is taken as an index of control. This operational approach provides a more rigorous basis to examine the development of coordination in general, and the traditions of stage theory approaches to motor development in particular, whereby the acquisition of fundamental skills, such as posture, locomotion and manipulation is viewed to follow a series of invariant steps with increments of chonological age.

It is proposed that the coordination patterns commonly construed as stages in the development of action are, therefore, specified by unique sets of relative motions (see Newell & Scully, in press, for an elaboration of this position). Given this perspective, it is not surprising that the concept of stage or step has been introduced in assessments of the development of action because the measurement scale used in the categorisation of relative motions is nominal. The observation of motor stages is, therefore, an instance of the general problem of categorical perception. Hence, observation of discontinuity in the development of action, as reflected by the terms stages or steps, is as much a product, if not more so, of the approach to measure-ment, as it is to changes in behaviour itself (cf. Emde & Harmon, 1984). With this proviso and, the general claim that it is the topological characteris-tics of the response dynamics that specify a pattern of coordination, I move on to contrast the constraints and prescriptions orientations to the develop-ment of coordination.

Constraints vs. Prescriptions for the Development of Action

As it was remarked earlier, the traditional (e.g. Gesell, 1929) and more recent cognitive (e.g., Bruner, 1970) approaches to the development of coordination in action each assume that coordination is specified by symbolic knowledge structures at some level of representation. In contrast, the coordinative structure theory (Kugler et al, 1980), proposes that the patterns of coordination that emerge during infancy and early childhood are due to the changing constraints imposed on action, rather than the acquisition of prescriptions for action. The issue of constraints versus prescriptions is central to any comparison of the coordinative structure theory with other formulations of the development of action (see also Kelso, 1981).

Gesell (1929) postulated that maturation refers to those phases and products of growth that are wholly or chiefly due to innate and endogenous factors. In short, maturation is mediated by genes (Gesell, 1952, p. 48). The traditional maturation theory of development offers a form of genetic predeterminism for the control of development in general, and in regard to the focus of this paper, the development of coordination patterns in particular

The central consequences of this position are that the sequence of development is predictable and is approximately the same for all children, although the rate at which developmental changes take place may vary from child to child.

The maturation viewpoint of development rests on the idea of genetically coded instructions prescribing progressive sequence of coordination patterns such as those observed in phylogenetic skills. However, Gesell's maturation theory also emphasised the notion of biological constraints on development. In discussing the developing child Gesell remarked that "his biological equipment sets the primary limits, directions, and modalities in which he reacts to his personal environments" (1952, p. 60). In spite of the above viewpoint, Gesell, and subsequent proponents of the maturational view of development, have largely failed to distinguish the contribution of pre-scriptions and constraints to be observed progressions in children's motor behaviour. While it can be argued that prescriptions are a special class of constraint, it seems more useful to reserve the term prescriptions for symbolic rule based knowledge structures. Thus, it is not clear from Gesell's writings to what extent the order and regularity observed in children's progressions of coordination are due to the "read-out" of prescriptions from the genetic code or the changing status of organismic constraints, although the pre-scriptive perspective is always emphasised in maturation theory.

Interpretations of the role of maturation theory in motor development (e.g., Gesell, 1946; McGraw, 1943) have emphasised the genetic code basis to maturation and, as a consequence, a programming notion to the patterns of behavioural development. Indeed, as Prechtl and Connolly (1981) have remarked, we have been left with the legacy of maturation as a substitute notion for the genetical control of development in general. This legacy also includes to some lingering degree a predetermined formulation of genetics and its prescribed framework for motor development rather than a probabilis-tic view of the pathways travelled in development on the epigenetic landscape (Waddington, 1957).

There have been attempts to characterise the genetic information coded in DNA as a constraining rather than prescribing process (e.g., Goodwin, 1970). Indeed, Kugler et al (1980) have elaborated these arguments from the micro level of analysis in proposing scale-independent physical principles to account for the development of coordination. Their general claim is that "order in biological and physiological processes is primarily owing to dynamics and that the constraints that arise, both anatomical and functional, serve only to channel and guide dynamics; it is not that actions are caused by constraints, it is rather that some actions are excluded by them" (1980, p. 9). This position allows a different interpretation of the strong preformationist maturation hypothesis because genetic information can be viewed as permissive, rather than deterministic, in relation to the development of movement patterns.

Although the traditional maturational perspective has failed to dis-tinguish between prescriptions and constraints there is no doubt that the idea of biological constraints (broadly conceived) is central to the maturation view. In contrast, traditional learning theory and its modern cognitive counterparts, have typically ignored or played down the significance of biological constraints to the development of coordination. In particular, cognitive notions of the development of action have been largely neutral with respect to the role of biological constraints to action. Further-more, as Kugler et al (1980, 1982) have emphasised, modern cognitive notions

place a heavy reliance on computatinal solutions to the degrees of freedom problem in action (Bernstein, 1967), and in effect, claim to accommodate every posisble action circumstance by means of intelligent executive action.

This divergence of emphasis on biological constraints by the maturational and cognitive approaches may be due in part to the respective focus of these research programs on phylogenetic and ontogenetic skills. However, Zelazo (1983), has argued that even the onset of voluntary locomotion is reflective of a general cognitive shift that occurs at around the chronological age of one year. This cognitive change is viewed as a necessary although not sufficient condition for the onset of locomotion. It is of interest to note that the reverse causal sequence of mental and motor activity has been proposed with the onset of self-produced locomotion being viewed as the organiser of many psychological processes (Berthenthal, Campos & Barrett, 1985). There is no convincing evidence that the problems of coordination in the development of so-called phylogenetic and ontogenetic skills reflect fundamentally different processes, although the constraints on action clearly change with growth of the child. The differing emphasis on the significance of biological constraints reflects an apriori theoretical bias rather than an emphasis resulting from the experimental focus on a certain set of activities.

In summary, the significance of the constraints perspective to action advanced by the coordinative structure theory (Kugler et al, 1980, 1982) has not been fully explored with respect to the order and regularity observed in the development of young children's fundamental posture and movement patterns. The emphasis on constraints by the maturational perspective has largely been implicit whereas the cognitive orientation has been neutral on this issue. The explicit role of constraints in the coordinative structure theory stands, therefore, in marked contrast to traditional and contemporary accounts of motor development that emphasise the role of prescriptions in the development of coordination.

Constraints on Action

Constraints may be viewed as boundaries or features that limit motion of the entity under consideration. In engineering parlance, constraints reduce the number of possible configurations of a system. Constraints exist at various levels of analysis of the organism and its interaction with the environment (e.g., biochemical, biomechanical, morphological, neurological). Furthermore, constraints may be relatively time dependent or time independent. That is, the rate with which constraints may change over time varies considerably with the level of analysis and parameter under consideration. Kugler et al (1980) have argued that descriptions of constraints are essentially no more than alternative accounts of the degrees of freedom, although constraints may or may not reduce the number of degrees of freedom. Formal kinematic descriptions can be applied to the space-time properties of the constraints on coordination (see McGinnis & Newell, 1982).

The significance of the coordinative structure theory is not simply its recognition of the role of constraints on degrees of freedom in the development of action, but rather, the emphasis it gives to constraints in determining the development of coordination. In emphasising the dynamical processes of action, it proposes that constraints eliminate certain configurations of response dynamics. The resulting patterns of coordination reflect the propensity towards self-organising optimality in biological systems.

Constraints are not accommodated by reparameterising a knowledge structure that symbolises these constraints, as would be reflected, for example, by the schema theory of motor learning (Schmidt, 1975). Rather, the optimality principles reflect the search for a stable pattern of coordination and control that accommodates the prevailing constraints.

It is proposed that there are three categories of constraints that interact to determine for a given organism the optimal pattern of coordination and control for any activity (Newell, 1984a). These are organismic constraints, environmental constraints and task constraints (see Figure 1). The first two categories are based on familiar principles but the latter category of task constraints requires justification and elaboration. The impact of organismic, environmental and task constraints to the development of coordination is now considered in some detail.
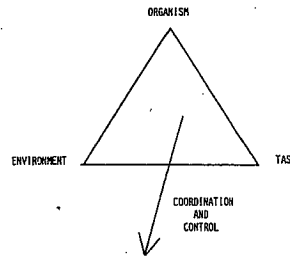
ORGANISM

ENVIRONMENT

TASK

COORDINATION
AND
CONTROL

Fig. 1. A schematic diagram of the categories of constraints
that specify the optimal pattern of coordination and control.

Organismic Constraints

Constraints reside at each level of analysis of the organism. Relatively time independent organismic constraints are typically interpreted as structural constraints whereas the relatively time dependent constraints are viewed as functional constraints. For example, at the macro level of analysis, body weight, height and shape are assumed to be structural constraints to the development of coordination because of their very slow (although systematic) rate of change with development. In contrast, the development of synaptic connections is often taken as a functional constraint. The structural-functional distinction is not as qualitative as it first appears, due to the qualifier that constraints are *relatively* time dependent or independent.

It is clear that a variety of organismic constraints converge to specify the appropriate pattern of coordination for the developing child. In spite of this realisation, certain classes of biological constraints have been over and underplayed in accounts of the development of coordination and control. For example, the status of the child's central nervous system has long been *the* basis for the increasing behavioural organisation exhibited by the developing child. The evidence for a direct link between neural development and the onset of new patterns of coordination is considerably less than might be assumed from most developmental text books, although it should be evident that methodological problems dictate that neurological evidence is invariably gleaned from species or from preparations other than normal healthy infants.

Prechtl (1984) in summarising evidence for a link between neural

development and motor development offers two important observations. First, growth and differentiation of the nervous system do not consist of an autonomous 'read-out' of genetic instructions, but involve an intimate inter-action with extrinsic factors in an extremely complex epigenetic process. Second, neural development is not a simple linearly progressive increase in the number of elements and their interconnections, and hence in complexity, but also includes retrogressive processes for matching and removing transient age-specific adaptations. These observations capture the difficulty of mapping a causal relationship between neural constraints and the development of coordination.

At the whole body level, a key problem to be resolved is how the motor system accommodates to the changes in growth that occur throughout the life span. Changes in growth and form (Thompson, 1917) are particularly evident in infancy and the early years of childhood. These changes have a strong impact on, among other parameters, the biomechanical constraints to action. Cognitive notions to the development of coordination implicitly accommodate growth changes through a rescaling of the designated knowledge structure and its attendant burden on computational function. The coordinative structure theory handles the change in growth and form through the concept of constraints on the emergent dynamics of coordination.

A major consequence of children's growth is the change in the absolute and relative size of respective bodyparts. These changes in body size lead to changes in the biomechanical constraints on the system. An important biomechanical parameter in posture and movement is the moment of inertia of each body segment, but there have been very few studies of the rate with which moments of inertia of body segments vary as a consequence of growth. An exception is the study of Jensen (1981) who examined the effect of 1 year's growth on the moment of inertia of children's body parts. 12 caucasion boys were studied with one endomorph, one mesomorph and one ectomorph at each age of 4, 6, 9 and 12 years. The children were somato-typed and the principal whole body moments of inertia calculated at the beginning and end of a 12 month period.

The results of Jensen's (1981) study showed that as a consequence of growth, the moment of inertia of the centroidal transverse axis reflected individual increases from 12% to 57% (mean 30.8%), while the increments for the longitudinal centroidal axis ranged from 8% to 92% (mean 33.5%). These percentage changes in the moments of inertia far exceeded the percentage changes in age, height (mean 4.7%) and mass (mean 15.8%). The best predictor of the constraints on rotational movements imposed by growth was the product of mass multipled by the square of the standing height. This index showed an average subject increase of 27.7% over the 12-month time span. Interestingly, Jenson found no relationship between body type and amount of change in the moment of inertia. The changes observed in the moments of inertia need to be accommodated by systematic (although non-proportional) changes in strength of the individual if the same function for coordination and control is to be appropriate for a given individual.

A more direct example of the influence of macro bodyparameters on the development of coordination can be found in Shirley (1931) and Bayley and Davis (1935). They showed that children with proportionately longer legs who were not overweight tended to walk earlier than did children with proportionately shorter legs. Norval (1947) also found that an increase in body length of 1 in led on average to a 22 day advantage in the onset of

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voluntary walking. Changes in body form could also be strong contributors
to the differences in gait pattern produced by children between 1-7 years
(Bernstein, 1967; Grieve & Gear, 1966). The establishment of an adult-like
gait pattern at about 7 years tends to correlate with the emergence of
adult-like proportions to body segments. A similar relationship exists for
the development of stance (Sinclair, 1978).

Although it is clear that many organismic constraints influence the
development of coordination, it is difficult to provide a direct operational
test of the prescriptions versus constraints view of coordination. Indeed, a
recent pair of papers on the development of upright voluntary walking in
infants reflects both the theoretical contrast and the methodological problem.
Zelazo (1983) argues that the onset of upright walking can largely be
accommodated by understanding the biomechanical constraints on walking.

A compelling and challenging line of evidence implicating the significance
of self-organisation principles in coordination is the shift of gait pattern
observed in the centipede *(lithobius)* when various combinations of its legs
are amputated (von Holst, 1973). That is, the normal wavelike leg motion of
the centipede is instantaneously replaced by the asymmetric gaits of
quadrupeds when all but two pairs of legs are amputated and the gaits of
six-legged insects emerge when all but three pairs of legs are amputated.
As Kugler et al (1980) indicated, the cognitive programming perspective has
considerable difficulty handling the instantaneous onset of these new patterns
of coordination. Of course, this kind of direct manipulation is not possible
with humans although accidents and illnesses can create similar human
circumstances for study.

The coordinative structure theory would also find support in Thelen's
(1983) empirical demonstrations of shifts in locomotor coordination patterns
of the infant. It would be inferred that the onset of walking in human
infants reflects the self-organising optimality in biological systems. This
position is difficult to uphold empirically, but as prescriptive formulations of
the development of coordination do not address biological constraints in a
predictive manner, it would seem that the demonstration of a relationship of
patterns of coordination to biophysical principles would provide evidence
consistent with the coordinative structure viewpoint. It should be noted,
however, that without a direct link to biophysical principles, interpretations
of the development of coordination in terms of optimality theory in biological
systems are likely to be as hollow as many of the cognitive claims to mental
processes and the like.

Environmental Constraints

Environmental constraints are generally recognised as those constraints
that are external to the organism. Any constraint on the organism-environ-
ment interaction that is not internal to the organism can be viewed as an
environmental constraint. It is useful, however, to distinguish between
environmental constraints that are general and those that are task specific.
Environmental constraints and task constraints are not mutually exclusive as
their definition depends on the nature of the task.

Generally, environmental constraints are those that are not manipulated
by the experimenter and are relatively time independent. Environmental
constraints may include gravity, natural ambient temperature, natural light
and other environmental features that are not usually adaptations of the task.
However, these environmental features can be manipulated for a given

individual by changing the environment in which the activity takes place. Shifts in geographical location on earth change the impact of gravity on the performer, in addition to the natural ambient temperature and light. Extreme changes in the influence of gravity on performance occur when moving an individual to a space vehicle or submerging him in water.

There have been very few tests of the influence of environmental constraints on the development of coordination. One important environmental contrast is the prenatal versus post-natal development period (e.g., Hooker, 1969; Ounsted & Ounsted, 1973), but few direct prenatal examinations of the development of coordination have been undertaken until the recent use of ultrasound technology (e.g., de Vries et al, 1984). As indicated earlier, this technology has allowed a mapping of the movements of the developing fetus *in utero*. There appears to be a systematic order to the development of voluntary action in the fetus. However, it is interesting to note that this order does not follow the cephalo-caudal trend established for post-natal phylogenetic activities. This may be due to the fact that the constraints of gravity in the womb are only about one third of those facing the neonate. The shift from the womb to the outside environment presents additional qualitative shifts in environmental constraints, rather than mere scaling changes of a given environmental parameter (such as gravity).

Qualitative shifts in environmental constraints influence the patterns of coordination exhibited by infants. In the buoyant medium of water infants display coordinated movement patterns long before they can support themselves posturally on land (McGraw, 1939). Similarly, rats can swim as soon as they are born whereas it takes one week or so for them to locomote on terra firma (Bekoff, 1978). Interestingly, the movement patterns exhibited in water by infants and rats are similar to those that they produce respectively on land. This suggests that the initial failure of infants and rats to locomote on land after birth is largely due to the severe biomechanical constraints on the onset of voluntary locomotion.

Thelen (1983) has demonstrated the interaction of organism and environmental constraints in the development of upright walking in infants. The stepping reflex typically disappears in infants between the age of 4 to 16 weeks and this change is often attributed to maturation and neurological development. However, Thelen (1983) showed that the stepping reflex 'reappears' when the infant is supported in water. This suggests that the disappearance of the stepping reflex is influenced by the environmental constraints of the medium in which the action takes place. In this case, supporting the child's limb in water served to counteract gravitational force.

A more extreme test of environmental constraints on the development of coordination are reflected in the traditional studies on the effect of specific rearing patterns (Gesell & Thompson, 1929; McGraw, 1940). Another broader example is the impact of different cultural backgrounds on the development of fundamental motor skills (cf. Super, 1981). These training and cross-cultural studies are often interpreted as tests of the maturation and learning perspectives of motor development, although the manipulation is not as clear cut as is generally assumed (cf. Bower, 1974). More importantly, from the perspective of this paper, is the proposal that these studies are primarily manipulating task constraints rather than environmental constraints, as the key feature of the rearing and cross-cultural studies is the specific task interactions that the child experiences rather than the effect of the relative time independent constraints of the environment per se. The cross-cultural

studies primarily reveal variations in the timing of the onsets of the steps of the developmental movement sequence rather than systematic shifts in the order of the developing movement sequences (cf. Super, 1981). This finding suggests that the general experience of interacting with the environment may not be as influential as the various physical constraints (organismic, environmental and task) in determining the optimal patterns of coordination.

Task Constraints

There have been a variety of definitions and classifications of tasks (cf. Fleishman & Quaintance, 1984). These attempts at definition vary on many dimensions, particularly with respect to their narrowness/breadth and their inclusion or exclusion of performer perceptions. The performer's perception of the task constraints and the optimal patterns of coordination for the task will be discussed subsequently. Environmental constraints reflect the ambient conditions for the task, whereas the focus of task constraints is the goal of the activity and the specific constraints imposed. Three categories of task constraints are proposed. These relate to: 1) goal of the task; 2) rules specifying or constraining response dynamics; and 3) implements or machines specifying or constraining response dynamics.

All tasks have goals that relate to the product or outcome of the action. In the majority of tasks the way in which the performer may satisfy the outcome of the act is not specified. That is, most tasks do not specify the pattern of coordination to be utilised by the performer. In some ontogenetic skills, however, task constraints specify or limit the kinematic or dynamic nature of the response that a performer is able to produce.

In a number of closed sporting skills, for example, the rules of the event specify that a specific pattern of coordination must be produced. Indeed, as indicated earlier, some tasks are defined solely by a given pattern of coordination. A Yamashita vault in gymnastics has a unique set of topological characteristics dependent upon a set of relative motions. As a consequence, the performer either executes a Yamashita or does not.

In other tasks the rules merely constrain the range of response dynamics that can be produced in pursuit of the task goal *without* dictating a specific pattern of response dynamics. For example, the sporting events of shot put, breaststroke swimming, and tennis, provide boundaries to the action patterns that can be generated by the performer without specifying an appropriate or optimal pattern of coordination. The performer's task is to optimise performance within the imposed task constraints (Newell, 1985).

When the task constraints merely limit the range of coordination patterns that can be produced, the issue of what the optimal pattern of coordination is for a given individual becomes paramount. Skilled performance, as reflected in the optimal pattern of coordination and control, will be determined in the interaction of the organismic, environmental and task constraints. As a consequence, the optimal pattern of coordination and control for a given task will be individual specific. Sometimes, however, individuals interpret the imposed constraints differently, leading to the production of different patterns of coordination for the same set of task constraints. By the same token, individual differences in organismic constraints can lead to different optimal patterns of coordination for the same set of environmental and task constraints.

An interesting example of the significance of the interpretation of task constraints occurred many years ago in the swimming event of breaststroke. One of the rules (task constraints) indicated that the legs and arms should be moved simultaneously and symmetrically. The rule, however, did not mention whether the arms and legs could be brought out of the water. A swimmer in the 1930's recognised that increased power could be gained from an out of the water arm and leg recovery and the butterfly stroke was born (see Wallechinsky, 1984). Indeed, in the breaststroke final at the 1952 Helsinki Olympic Games 7 out of 8 finalists in the men's event swam the butterfly stroke. World records for the breaststroke event were broken frequently as a consequence of this technique change. After the Helsinki games, the administrators of the swimming associations separated the breaststroke and butterfly events. In doing so, they effectively specified different task constraints for the two events.

This example of task constraints in swimming reflects how the performer's interpretation of the task constraints can influence the pattern of coordination produced. Of course, in many sporting events the search for the optimal pattern of coordination continues and formal approaches to optimisation in human motion are being developed. Progress in the area of biomechanical optimisation has largely superceded the traditional 'champion's model' approach (Hatze, 1983).

The goal of the task, together with the constraints that specify or limit the response dynamics for a given task, reflect rules that are implicit to the task. Task rules are not physical barriers or limitations that physically eliminate certain responses, nevertheless, they influence the pattern of coordination produces by an individual in a given task. The champion's model alluded to above is an instance where an innovative individual has produced a widely accepted solution to the problem of optimising performance within the task constraints.

The third category of task constraints listed is a physical constraint in that it represents implements or machines that are indigenous to the task and that specify or constrain the response dynamics. These might be construed as a narrow interpretation of environmental constraints but it seems useful to preserve the distinction between task and environmental constraints. As mentioned earlier the distinction is task specific. An object could be a task constraint in one activity and an environmental constraint in another. In the main, however, objects used for grasping, implements used in task interactions, and machines such as lawn mowers, cars, bicycles, etc., will be viewed as imposing task constraints. These physical objects specify or constrain the response dynamics in a manner similar to the rule based constraints discussed above.

The size and weight of task objects or machines relative to the body size of the individual, reflect physical constraints on the optimal pattern of coordination in relation to the task goal. There have been very few tests of task by organismic constraint interactions on the pattern of coordination. For example, while object size is often implicated as a significant factor in prehension, the classical normative data on the development of prehension is severely restricted with respect to the range of object size manipulated. Indeed, the continued reliance on the Halverson (1931, 1932) project as reflective of the normative data on the development of prehension seems unwarranted. In the main, the impact of body scale on the development of coordination has been underemphasised, in spite of the early writings of

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Thompson (1917) and the recent analysis by Kugler et al (1982).

Other task constraint limitations to investigations of the development of prehension have been exposed by von Hofsten (1979, 1982, 1983; von Hofsten & Lindhagen, 1979). When 2 week-old infants have appropriate postural support they reach and make contact with a brightly colored moving object in a manner consistent with anticipatory behaviour. This kind of infant catching skill (von Hofsten, 1983) is counterintuitive to traditional notions about the development of coincident timing behaviour and prehension.

In practice, the impact of task constraints on the development of coordination is slowly being acknowledged. An increasing number of toy manufacturers and sporting associations are body scaling the task constraints, which generally means reducing the size of implements and activity boundaries for younger children. The establishment of physical principles of body size to implement size ratios specifying a given pattern of coordination remains an interesting possibility and one that would be consonant with the co- ordinative structure theory. Dimensionless body scaled ratios that correspond to shifts in gait pattern (cf. Alexander, 1984) and the perception of affordances (Warren, 1984) have been reported.

Summary

The optimal pattern of coordination and control for a given individual is specified by the interaction of organismic, environmental and task constraints. The relative impact of these three categories of constraint on the pattern of coordination varies according to the specific situation. Interestingly, in terms of whole-body mechanical constraints, appropriate changes in two or three of the constraint categories, can preserve the relative effect of forces on a given pattern of coordination.

The extant theories relating to the development of coordination recognise to some greater or less degree the significance of constraints on action although the theoretical interpretation given to constraints varies. Traditionally, it is the organismic immaturity of the neurological system that is taken as the limiting factor in the development of coordination. It is proposed that a research strategy that manipulates to the extreme the interaction of organismic, environmental and task constraints could prove useful in tests of the prescriptions versus constraints perspectives to the development of coordination. Theoretical orientation aside, it would appear that the impact of task constraints in relation to the body scale of the subject is an overlooked factor in descriptive accounts of coordination in general, and the progressions of the developmental movement sequence in particular.

Concluding Remarks

The current synthesis suggests that a more extreme manipulation of the constraints on action than heretofore undertaken might provide a strong test of current notions of the development of coordination. A key point is the recognition that the optimal pattern of coordination is specified by the *interaction* of the three sources of constraints, namely; organismic, envir- onmental and task. The impact of task constraints may primarily reside in the development of ontogenetic skills, although prehension is clearly influenced

by task factors.

In a general sense, the manipulation of constraints holds some similarities to the early tests of the maturation and learning theory accounts of development. However, the theoretical significance given to constraints in the coordinative structure theory (Kugler et al, 1980, 1982) is very different. Even on a descriptive level, the elaboration of the constraints perspective offered here is much broader than traditional tests of maturation and learning theory and seems a more viable approach to determine the degree to which departures from the traditionally accepted norms of motor development can occur. A major problem is that the bandwidth of the stability of the co-ordination patterns for the phylogenetic skills is so robust that it is difficult to engender shifts in the pattern of coordination.

The manipulation of constraints in studying the development of co-ordination should not proceed in isolation with respect to children. Indeed, manipulation of constraints with adults will offer a basis to understand the generality of the principles advanced. One problem is that adults are typically seen as the "norm" or "bench mark" for comparison with children. If organismic constraints influence coordination patterns along the lines suggested here, children will not necessarily exhibit adult-like patterns of coordination and control for the same set of environmental and task constraints. Indeed, if they did, concerns might be expressed about the integrity of the central nervous system. This philosophy for comparing child and adult patterns of coordination is counter to traditional prescriptive views of development which have been driven by the maturational perspective. One can probably change or reverse the developmental progression of coordination by the manipulation of mechanical constraints and induce adults to generate coordination patterns that are typically dubbed as immature or child-like.

In summary, the emphasis of constraints in the coordinative structure perspective (Kugler et al, 1980, 1982) offers a firm theoretical base to re-examine the traditional notions of motor development. In particular, the constraints perspective forces a different interpretation of both the developmental movement sequence and the traditional distinction between phylogenetic and ontogenetic activities. Arising from such a reexamination is the notion that principles of the acquisition of coordination may cut across class of activity and developmental maturity of the individual.

The constraints perspective suggests that the ubiquity of order and regularity in the development of coordination is due to the similarity of constraints imposed on the infant and young children rather than a conse-quence of a common set of genetic prescriptions for the human species. The range of constraints manipulated in the infant to date has not been sufficient generally to engender significant shifts in the developmental movement sequence. It is not surprising, therefore, that the universality of an invariant developmental movement sequences gives prima-facie evidence for the maturational theory of motor development.

It would appear that only strong manipulations of the physical con-straints to action are likely to give rise to patterns of coordination different to those of the traditional developmental movement sequence. In the main, the manipulations required will not be the norm for societies of any culture, and, therefore, it is unlikely that many naturally emerging examples of new patterns of coordination will be generated that depart from the traditional developmental sequence. However, as it was documented earlier, exceptions

to the developmental movement sequence already exist. The constraints perspective suggests that these departures need to be considered more seriously than they typically are. Furthermore, stronger manipulation of the constraints to action would provide additional evidence of departures from the developmental sequence and the emergence of new patterns of co-ordination. Broadening the range of constraints to action would help promote and test the idea that it is the influence of constraints that is important rather than an emphasis on either endogenous or exogenous factors. These intrinsic and extrinsic factors to the development of coordination cannot be separated via an analysis of variance model to motor development.

The constraints perspective also leads to the postulation that the traditional distinction between activity classes does not carry with it any significance for theoretical principles regarding the acquisition of co-ordination per se. From the constraints perspective, phylogenetic activities are common to the species because of the ubiquity of the constraints imposed to the development of coordination.

The distinction between phylogenetic and ontogenetic activities has been at the heart of the division between the fields of motor development and motor learning. Eliminating the basis of the distinction between these classes of activity opens the door to the establishment of principles for the acquisition of coordination per se, independent of activity class and stage of individual development.

Author Notes

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References

Alexander, R. Mc. (1984). Walking and running. *American Scientist, 72,* 348-354.

Ames, L. (1937). The sequential patterning of prone progression in the human infant. *Genetic Psychology Monographs, 19,* 409-460.

Bayley, N. & Davis, F.C. (1935). Growth changes in bodily size and proportions during the first three years: A developmental study of sixty-one children by repeated measurements. *Biometrika, 27,* 26-87.

Bekoff, A.A. (1976). A neuroethological approach to the study of the ontogeny of coordinated behavior. In G.M. Burghardt and M. Bekoff (Eds.), *Comparative and evolutionary aspects.* New York: Garland.

Bernstein, N. (1967). *The coordination and regulation of movement.* New York: Pergamon.

Berthenthal, B.I., Camps, J.J. & Barrett, K.C. (1984). Self-produced locomotion: An organizer of emotional, cognitive, and social development in infancy. In R.N. Emde and R.J. Harmon (Eds.), *Continuities and discontinuities in development.* New York: Plenum.

Bower, T.G.R. (1974). *Development in infancy.* San Francisco: Freeman.

Brainerd, C.J. (1978). The stage question in cognitive-developmental theory. *The Behavioral and Brain Sciences, 1,* 173-214.

Bruner, J.S. (1970). The growth and structure of skill. In K.J. Connolly (Ed.), *Mechanisms of motor skill development.* London: Academic Press.

Bruner, J.S. (1973). Organization of skilled action. *Child Development, 44,* 1-11.

Connolly, K.J. (1970a). Response speed, temporal sequencing and information processing in children. In K.J. Connolly (Ed.), *Mechanisms of motor skill development.* London: Academic Press.

Connolly, K.J. (1970b). Skill development: Problems and plans. In K.J. Connolly (Ed.), *Mechanisms of motor skill development.* London: Academic Press.

Connolly, K.J. (1981). Maturation and the ontogeny of motor skills. In K.J. Connolly and H.F.R. Prechtl (Eds.), *Maturation and development: Biological and psychological perspectives.* Philadelphia: Lippincott.

Cutting, J.E. & Profitt, D.R. (1982). The minimum principle and the perception of absolute, common and relative motions. *Cognitive Psychology, 14,* 211-246.

Emde, R.N. & Harmon, R.J. (Eds.) (1984). *Continuities and discontinuities to development.* New York: Plenum.

Flavell, J.H. & Wohlwill, J.F. (1969). Formal and functional aspects of cognitive development. In D. Elkind and J.H. Flavell (Eds.), *Studies in cognitive development.* New York: Oxford University Press.

Fleishman, E.A. & Quaintance, M.K. (1984). *Taxonomies of human performance: The description of human tasks.* New York: Academic Press.

Gesell, A. (1929). Maturation and infant behavior pattern. *Psychological Review, 36,* 307-319.

Gesell, A. (1946). The ontogenesis infant behavior. In L. Carmichael (Ed.), *Manual of child psychology.* New York: Wiley.

Gesell, A. (1952). *Infant development.* New York: Harper and Brothers.

Gesell, A. & Thompson, H. (1929). Learning and growth in identical twins: An experimental study of the method of co-twin control. *Genetic Psychology Monographs, 6,* 1-124.

Goodwin, B. (1970). Biological stability. In C.H. Waddington (Ed.), *Towards a theoretical biology (Vol. 3).* Chicago: Aldine.

Grieve, D.W. & Gear, R.J. (1966). The relationship between length of stride, step frequency, time of swing and speed of walking for children and adults. *Ergonomics, 5,* 379-399.

Halverson, H.M. (1931). An experimental study of prehension in infants by means of systematic cinema records. *Genetic Psychology Monographs, 10,* 107-283.

Halverson, H.M. (1932). A further study of grasping. *Journal of Genetic Psychology, 7,* 34-63.

Hatze, H. (1983). Computerized optimization of sports motions: An overview of possibilities, methods and recent developments. *Journal of Sport Sciences, 1,* 3-12.

von Hofsten, C. (1979). Development of visually directed reaching: The approach phase. *Journal of Human Movement Studies, 5,* 160-178.

von Hofsten, C. (1982). Eye-hand coordination in the new born. *Developmental Psychology, 18,* 450-461.

von Hofsten, C. (1983). Catching skills in infancy. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 75-85.

von Hofsten, C. & Lindhagan, K. (1979). Observations on the development of reaching for moving objects. *Journal of Experimental Child Psychology, 28,* 158-173.

von Holst, E. (1973). *The behavioral physiology of animals and man.* Coral Gables, FL: Univesity of Miami Press.

Hooker, D. (1969). *The prenatal origin of behavior.* New York: Hafner.

Ianniruberto, A. & Tajani, E. (1981). Ultrasonographic study of fetal movements. *Seminars in perinatalogy, 5,* 175-181.

Jensen, R.K. (1981). The effect of a 12-month growth period on the body moments of inertia of children. *Medicine and Science in Sports and Exercise, 13,* 238-242.

Johansson, G., Von Hofsten, C. & Jansson, G. (1980). Event perception. *Annual Review of Psychology, 31,* 27-63.

Johnston, F.E., Roche, A.F. & Sussane, C. (Eds.). (1980). *Human physical growth and maturation: Methdologies and factors.* New York: Plenum.

Kelso, J.A.S. (1981). Contrasting perspectives on order and regulation in movement. In J. Long and A. Baddley (Eds.), *Attention and performance IX.* Hillsdale, NJ: Erlbaum.

Kessen, W. (1962). "Stage" and "structure" in the study of children. *Monographs of the Society for Research in Child Development, 28,* 2, (Whole No. 83).

Kugler, P.J., Kelso, J.A.S. & Turvey, M.T. (1980). On the concept of coordinative structures as dissipative structures: 1. Theoretical lines of convergence. In G.E. Stelmach and J. Requin (Eds.), *Tutorials in motor behavior.* Amsterdam: North-Holland.

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 and J.E. Clark (Eds.), *The development of movement control and coordination.* New York: Wiley.

McGinnis, P.M. & Newell, K.M. (1982). Topological dynamics: A framework for describing movement and its constraints. *Human Movement Science, 1,* 289-305.

McGraw, M.B. (1939). Swimming behavior of the human infant. *Journal of Pediatrics, 15,* 485-490.

McGraw, M.B. (1940). Neural maturation as exemplified in achievement of bladder control. *Journal of Pediatrics, 16,* 580-590.

McGraw, M.B. (1943). *The neuromuscular maturation of the human infant.* New York: Columbia University Press.

Newell, K.M. (1981). Skill learning. In D.H. Holding (Ed.), *Human Skills.* New York: Wiley.

Newell, K.M. (1984a, May). *The development of coordination: Significance of task constraints.* Paper presented at the meeting of the American Association for the Advancement of Science, New York, NY.

Newell, K.M. (1984b). Physical constraints to development of motor skills. In J.L. Thomas (Ed.), *Motor development during childhood and adolescence.* Minneapolis: Burgess.

Newell, K.M. (1985). Coordination, control and skill. In D. Goodman, I. Franks and R.B. Wilberg (Eds.), *Differing perspectives in motor learning, memory, and control.* Amsterdam: North-Holland.

Newell, K.M. & Barclay, C.R. (1982). Developing knowledge about action. In J.A.S. Kelso and J.E. Clark (Eds.), *The development of movement control and coordination.* New York: Wiley.

Newell, K.M. & Scully, D.M. (in press). Steps in the development of coordination: Perception of relative motion? In J.E. Clark and J.H. Humphrey (Eds.), *Motor development: Current selected research* (Vol. II). Princeton: Princeton Book Co.

Norval, M.S. (1947). Relationship of weight and length of infants at birth to the age at which they begin to walk alone. *Journal of Pediatrics, 30,* 676-678.

Ounsted, M. & Ounsted, C. (1973). *On fixed growth rate.* Philadelphia: Lippincott.

Piaget, J. (1950). *The psychology of intelligence.* New York: International Universities Press.

Piaget, J. (1970). Piaget's theory. In P.H. Mussen (Ed.), *Carmichaels manual of child psychology.* New York: Wiley.

Prechtl, H.F.R. (Ed.). (1984). *Continuity of neural functions from prenatal to postnatal life.* Oxford: Blackwell.

Prechtl, H.F.R. & Connolly, K.J. (1981). *Maturation and development: Biological and psychological perspectives.* Philadelphia: Lippincott.

Reinold, E. (1976). *Ultrasonics in early pregnancy.* Karger: Basel.

Roberton, M.A. (1978). Stages in motor development. In M.V. Ridenour (Eds.), *Motor development: Issues and applications.* Princeton, NJ: Princeton.

Roberton, M.A. (1982). Describing "stages" within and across motor tasks. In J.A.S. Kelso and J. Clark (Eds.), *The development of movement control and coordination.* New York: Wiley.

Robson, P. (1970). Shuffling, hitching, scooting or sliding: Some observations in 30 otherwise normal children. *Developmental Medicine and Child Neurology, 12,* 608-617.

Schmidt, R.A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225-260.

Shirley, M.M. (1931). *The first two years: A study of twenty-five babies. Vol. 1. Postural and locomotor development.* Minneapolis: University of Minnesota Press.

Sinclair, D. (1978). *Human growth after birth.* London: Oxford University Press.

Super, C.M. (1981). Cross-cultural research on infancy. In H.C. Triandis and A. Heron (Eds.), *Handbook of cross-cultural psychology: Developmental Psychology (Vol. 4).* Boston: Allyn and Bacon.

Thelen, E. (1983). Learning to walk is still an "old" problem. A reply to Zelazo (1983). *Journal of Motor Behavior, 15,* 139-161.

Thompson, D.W. (1917). *On growth and form.* Cambridge: Cambridge Univesity Press.

Touwen, B.C.L. (1971). A study of the development of some motor phenomena in infancy. *Developmental Medicine and Child Neurology, 13,* 435-446.

de Vries, J.I.P., Visser, G.H.A. & Prechtl, H.F.R. (1983). Fetal mobility in the first half of pregnancy. In H.F.R. Prechtl (Ed.), *Continuity of neural functions from prenatal to postnatal life.* Oxford: Blackwell.

Waddington, C.H. (1957). *The strategy of the genes*. London: George, Allen & Unwin.

Wallechinsky, D. (1984). *The complete book of the Olympics*. New York: Viking Press.

Warren, W.H., Jr. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 683-703.

Weiss, P. (1941). Self-differentiation of the basic patterns of coordination. *Comparative Psychology Monographs, 17,* 1-96.

Wohlwill, J.F. (1973). *The study of behavioral development*. New York: Academic Press.

Wyke, B. (1975). The neurological basis of movement – A developmental review. In K.S. Holt (Ed.), *Movement and child development*. Philadelphia: Lippincott.

Zelazo, P.R. (1983). The development of walking: New findings and old assumptions. *Journal of Motor Behavior, 15,* 99-138.

Zelazo, P.R., Zelazo, N.A. & Kolb, S. (1972). Newborn walking. *Science, 177,* 1058-1059.

Zingg, R.M. (1942). Feral man and cases of extreme isolation. *American Journal of Psychology, 53,* 487-517.