Intraindividual Variability in the Development of Motor Skills in Childhood

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Since the inception of the field, researchers have considered intraindividual variability to be a signature component of motor development. In this chapter, we describe three types of developmental changes in intraindividual variability in infancy and childhood and speculate about the potential functions of each pattern of developmental change. Intraindividual variability decreases for repeated performance of the same movements; the apparent function is improvement in consistency and control. Variability continues or increases when selecting and modifying actions in response to variations in local conditions; the presumed function is greater behavioral flexibility and adaptability. Developmental changes in the structure of intraindividual variability reflect changes in the temporal organization and coordination of movements; the putative function is to ensure sufficient consistency for successful performance and sufficient flexibility to cope with changing circumstances. We use case studies to illustrate each type of developmental change in intraindividual variability and to highlight the time scales of motor actions typically associated with each pattern of developmental change. We conclude the chapter by identifying important shortcomings of current developmental research, including lack of integration across recognized patterns of developmental change, overreliance on artificial laboratory tasks, and lack of experimental evidence for how different types of variability promote or hinder development. We offer suggestions for future research that promises to facilitate a deeper understanding of the role of intraindividual variability in motor development.

Keywords: variability, motor development, infants, children, consistency, flexibility, time scales

Introduction And Chapter Overview

However you look at it, children’s movements are variable. Intraindividual variability is a signature component of motor development. A toddler’s foot traces a variable trajectory through the air, each shaky step is a different wobbly variant of the previous one, and the shape of the walking path varies from trial to trial. For some aspects of motor skill, intraindividual variability decreases over development: An infant’s foot trajectory becomes smoother in the course of a step, each step in a sequence becomes more similar to the last, and the walking path becomes more consistent across trials (Cheron et al., 2001; Looper, Wu, Barroso, Ulrich, & Ulrich, 2006). For other aspects of skill, variability continues or increases over development: Foot trajectory varies to clear obstacles in the path, steps vary to accommodate variations in the terrain, and the shape of the walking path varies to navigate a cluttered room (Adolph et al., 2012; Dominici, Iavenko, Cappellini, Zampagni, & Lacquaniti, 2010). For still other aspects of motor skill, the structure of variability changes over development: In a novice walker, speed and step length vary willy-nilly from step to step causing a random pattern of variability, but in an experienced infant walker, step length and speed increase in tandem over the sequence and step-to-step variability has a coherent structure (Badaly & Adolph, 2008).

As these examples of infant walking make clear, the term “intraindividual variability” can refer to very different aspects of motor behavior occurring at very different temporal and spatial scales. Researchers can observe intraindividual variability in the milliseconds of a single step, the seconds that comprise a sequence of steps, and the months and years of developmental changes in walking. Variability is apparent in repetitive, cyclical movements such as walking or riding a bicycle, discrete movements such as executing a reach or doing a cartwheel, and in continuous movements such as maintaining a sitting or standing posture. We see variability in the real-time strategies children select for grasping the handle of a spoon (e.g., palm up or palm down) and in the developmental strategies infants select for posture and locomotion (e.g., crawling on their bellies or on hands and knees).

Research on motor development encompasses all of it, but not all at once by a single research team within a single study. Instead, researchers who are interested in the development of motor control tend to focus on decrease in intraindividual variability and to rely on standardized laboratory tasks in which consistency is paramount. Studies on developmental improvements in adaptability tend to focus on continuance or increase in intraindividual variability and to test infants in novel and variable conditions in which behavioral flexibility is critical. Studies on developmental changes in the organization of move-
ment tend to focus on the structure of variability and to record long time series of movements in which optimal levels of predictability and complexity are important.

Descriptions of variability and how it changes are common in research on motor development. So, rather than present a comprehensive review of the field, we have selected illustrative case studies to highlight our points. Given that intraindividual variability is endemic in motor development, the overall aim of the chapter is to examine the potential functions of developmental changes in intraindividual variability—how developmental changes in intraindividual variability might serve to promote motor skill acquisition.

We begin the next section by asserting that variability—both intra- and interindividual variability—is integral to motor development and that researchers have always treated it as such. We describe the work of the early pioneers and how their legacy of studying variability has influenced modern investigators. The subsequent three sections reflect our focus on the potential functions of developmental changes in intraindividual variability. We describe how motor development can entail decrease in variability, continuance or increase in variability, and changes in the structure of variability. Our case studies illustrate the types and time scales of intraindividual variability that are typically associated with the particular pattern of developmental change. Each section ends with speculations about the potential functions of that developmental pattern. We conclude the chapter with suggestions for future research, which promise to facilitate a deeper understanding of the role of intraindividual variability in motor development.

Variability Is Integral To Motor Development

The most familiar and iconic representation of motor development is the so-called “milestone chart.” As illustrated in Figure 4.1, the common features of such charts are the ordering of skills by age of attainment and the associated age norms for each skill. Typically, the salient aspect of the chart is the average age at which children display each skill (here, shown by the black vertical lines along each bar). However, most milestone charts also depict an important measure of interindividual variability: the normative range in age of attainment (total length of each bar). For postural and locomotor skills, age bands span several months and show considerable overlap. Moreover, the depicted age ranges would be considerably wider if onset ages were normed across different cultural groups and reflected the true diversity of human development (Adolph & Robinson, in press).

Although the great pioneers in motor development—Gesell, McGraw, and Shirley—are responsible for our legacy of milestone charts, age norms, and the related fictions of “the average child” and prescribed developmental “stages”, these same researchers viewed intra- and interindividual variability as fundamental to development (Newell, Liu, & Mayer-Kress, 2003; Thelen & Adolph, 1992). Gesell, for example, is most famous for popularizing normative summaries of development, as in the 9-month-old who “sits alone” and “opposes thumb in seizing a cube” and the 10-month-old who “pulls self up to stand” and “plucks pellet with precise pincer prehension” (Gesell & Thompson, 1929, p. 132). But Gesell (1925) also recognized that infants frequently express behaviors belonging to other age norms and wrote extensively about “developmental peers of incongruent age”.

Interindividual Variability

Since the inception of the field, interindividual variability—differences between children—has been a central focus of research. The early pioneers acknowledged that individual infants need not progress lockstep through each stage in the same order. Stages can be skipped, revisited, and expressed in variable orders (Ames, 1937; Gesell & Ames, 1940; McGraw, 1945). Gesell and McGraw liberally sprinkled their work with data tables and figures illustrating individual differences in onset age and duration of expression (Gesell & Thompson, 1938; McGraw, 1941). Many early works list the onset age of every infant studied (Ames, 1937; Shirley, 1931, 1933) and contain graphs of individual infants’ developmental trajectories (Ames, 1937; McGraw & Breeze, 1941). Indeed, McGraw (1935) dedicated an entire book to a description of twins Johnny and Jimmy, replete with fold-out graphs of their individual trajectories. Detailed qualitative descriptions of individual infants also were common (Burnside, 1927). Such case studies, including descriptions of illnesses that prevented movement, periods of rapid weight gain, and changes in body dimensions, led researchers to speculate that individual differences in onset ages stem from differences in infants’ experience, physique, and temperament (Gesell & Thompson, 1938; Shirley, 1931).
The pioneering researchers also reported individual differences in infants’ abilities within particular stages of motor development. Average step length and walking speed, for example, vary widely among infants at the same stage of walking development (McGraw & Breeze, 1941). Shirley (1931), who painstakingly recorded walking skill based on footprints created by dipping infants’ feet in oil and sprinkling graphite over the oily marks, reported that each infant’s footprint paths were so distinctive that researchers could deduce which baby had produced them.

Although modern researchers no longer focus on skill onset ages, the practice of depicting individual differences among infants is widely adopted and descriptions of individual trajectories are commonplace. Toddlers, for example, discover different strategies to accomplish walking. Some initiate movement by lifting their legs in short, tiny steps; some do it by twisting their torso and swinging their legs from side to side; and some initiate movement by leaning forward and falling into each step (McCollum, Holroyd, & Castelfranco, 1995; Snapp-Childs & Corbetta, 2009). Similarly, weekly observations of infants over the transition to reaching reveal that each infant has a different movement problem to solve (Thelen et al., 1993). More active infants must dampen inertial forces from spontaneous arm flaps to guide their hands to the target, and more sedentary infants must generate muscle force to lift their arms to the target. All infants learn to adjust the force and compliance of their arms, but each finds an individual solution to the problem. Each begins at a different starting point and forges a unique developmental path.

Intraindividual Variability

The great pioneers also recognized the importance of intraindividual variability—variability expressed by individual children. Infants frequently straddle adjacent stages and occasionally express behaviors from distant stages (Gesell & Ames, 1940; McGraw, 1941). Gesell (1946) viewed overlapping stages as integral to development. Infants straddle multiple stages because they display the behaviors characteristic of their current level of maturity, they revert to less mature forms as part of a cyclical process of reciprocal interweaving, and they display behaviors from the next stage as part of the mastery process (Gesell & Ames, 1940).

Recent research reveals a similar story. Motor skills do not turn on and off like a faucet. Rather, skills sputter in and out of infants’ repertoires, with variable, oscillating trajectories spanning days, weeks, or months (Adolph & Robinson, 2011; Adolph, Robinson, Young, & Gill-Alvarez, 2008). Infants typically express a new skill to criterion on one day, but not on the next; likewise, they reject an old skill on one day, but not on the next. The developmental transition from crawling to walking, for example, takes most infants several months. During the transition period, both skills are alternately expressed within and across days, and long after crawlers become walkers, they revert to crawling when needed.

Development Entails Decrease In Intraindividual Variability

As researchers and parents can attest, motor development often entails decrease in intraindividual variability. When infants first achieve new motor skills, movements are noisy and unstable. Newly reaching infants often miss the target. Novice sitters wobble and fall. As infants gain strength, control, and experience, movements become smoother and more economical and performance becomes more successful and consistent. After months or years, children eventually achieve adult-like stability in execution and performance outcome.

From this perspective, intraindividual variability in early skill acquisition reflects poor motor control (Deutsch & Newell, 2005; Vereijken, 2010). A key component of motor development therefore is acquiring the necessary control to reduce variability. Increase in control arises from several factors: less noise in the sensory-motor system (Schmidt & Lee, 2011), better and faster use of perceptual feedback, and greater reliance on feedforward mechanisms (Deutsch & Newell, 2005). The current section illustrates the classic developmental trend of decreasing intraindividual variability accompanying increasing control in basic manual, postural, and locomotor skills.

Variability Within A Single Movement

Long before infants can reach successfully for objects, they spontaneously flap their arms in bouts of flailing, variable movements. Arm flapping increases in the presence of a toy and brings the hand closer to the toy—as though infants carve goal-directed reaching out of the noisy, variable arm movements already in their repertoire (Bhat & Galloway, 2006; Lee, Bhat, Scholz, & Galloway, 2008).

Between 11 and 24 weeks of age, infants finally make consistent contact with objects (Berthier & Keen, 2006; Clifton, Muir, Ashmead, & Clarkson, 1993; Konczak, Borutta, Topka, & Dichgans, 1995). Flapping the arms as a prelude to reaching eventually disappears (Thelen, Corbetta, & Spencer, 1996), but the arm movements for reaching are still highly variable. Perhaps the most salient developmental change in infant reaching is a straighter, more direct hand path to the goal (Berthier & Keen, 2006; Konczak et al., 1995; von Hofsten, 1991). In adults, the length of the reaching path is roughly equivalent to the initial distance between hand and target (Konczak et al., 1995). The hand rapidly accelerates toward the target and then slows and adjusts for grasping. In newly reaching infants, however, the hand lurches and swerves through the air in an indirect zigzag path that can be 2.2 to 3.8 times longer than the straight-line distance to the object (Konczak et al., 1995; von Hofsten, 1991). Each zigzag change in direction results in acceleration and deceleration of the hand. Over development, infants’ reaches become straighter (Figure 4.2A-C). As the
reaching path becomes more direct, the number of speed peaks and jerk (change in the rate of acceleration) decrease (Berthier & Keen, 2006; von Hofsten, 1991). Straightness continues to improve and by two to three years of age, the length of the hand path is only 1.2 to 1.4 times the direct path to the object (Berthier & Keen, 2006; Konczak & Dichgans, 1997). Variability in infant reaching also illustrates a general developmental trend: Improvements in proximal body segments occur before distal ones. Here, shoulder movements become smooth and consistent before infants tackle the challenge of controlling the elbow (Berthier & Keen, 2006).

After infants successfully reach for an object, they face the problem of how to grasp it. Development progresses from immature whole-hand power grips where the object is pressed between fingers and palm to more mature pincer grips where the object is held between thumb and forefinger (Halverson, 1931). However, from 6 to 20 months of age, infants employ multiple configurations of both power and pincer grips. Even 6-month-olds can perform pincer grips—but they do not do so consistently (Butterworth, Verweij, & Hopkins, 1997). In fact, on repeated presentations of objects, 6- to 11-month-olds switch grip types as frequently as they repeat a single grip. From 12 to 24 months of age, infants still employ different grip types from trial to trial, but the mature pincer grip becomes increasingly dominant (Butterworth et al., 1997).

Tool use provides another example of decreasing variability. When the handle of a tool points away from their dominant hand, adults consistently adjust their initial grip to ensure “end-state comfort” (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). In contrast, between 9 months and 4 years of age, children use a variety of strategies to grasp a spoon oriented away from their dominant hand, many of which reflect “start-state,” not end-state, comfort and some of which fail to bring food to mouth without spilling (Keen, 2011; Keen, Lee, & Adolph, 2014). Eight-year-olds use mature grasps more frequently, but still revert to awkward, immature strategies on some trials. Development entails gradually winnowing out ineffective grip strategies and retaining more effective ones.

### Variability In Repetitive Movements

When adults walk on a treadmill or in a continuous, straight line over uniform ground, their movements are cyclical and repetitive. Although not perfectly identical, each step is similar to the last. Movements on one side of the body mirror those on the other side. But when infants first begin walking, nearly every aspect of their gait is variable and inconsistent—the placement of their feet on the ground, the timing of leg movements through the air, the forces produced by their leg movements, and the muscle actions that produce those forces (Chang, Kubo, Buzzi, & Ulrich, 2006; Hallemans, Aerts, Otten, De Deyn, & De Clercq,
Intraindividual variability decreases most rapidly in the first few months after walking onset, followed by a long period of gradual improvements in which consistency finally approximates that of adults.

As illustrated in Figure 4.3A, new walkers’ step length is highly variable. As shown in Figure 4.3B, variability in step length (indexed with the standard deviation or coefficient of variation) decreases after a few months of walking experience (Adolph, Vereijken, & Shrout, 2003; Chang et al., 2006; Clark, Whitall, & Phillips, 1988; Looper et al., 2006). Stance time (when one foot is on the floor) and double support time (when both feet are on the floor) also show rapid and dramatic decrease in variability over the first three months of walking experience (Chang et al., 2006). Although new walkers achieve 50% phasing on average—meaning that the time when each foot touches down is about halfway through the other foot’s step—phasing fluctuates by 9% across a sequence of steps. After three months of walking experience, phasing varies by only 3%, and is no longer more variable than that of adults (Clark et al., 1988). The most dramatic improvements in consistency occur in the months following the onset of walking, but variability continues to decrease throughout childhood. Variability in stride time decreases between 3 and 14 years of age (Hausdorff, Zemany, Peng, & Goldberger, 1999), and walking speed becomes more consistent across trials until 15 years of age ( Muller, Muller, Baur, & Mayer, 2013).

Variability in the coordination of joint movements within each leg also decreases over the course of learning to walk. The decrease is linked with practice keeping balance while taking independent steps, not merely practice with the stepping movements. Prior to walking onset, infants can walk with support if an adult holds their hands. Thus, infants can practice executing stepping movements without controlling their own balance. In supported walking, movements of the hip, knee, and ankle are highly variable—the relative phasing of joint movements is irregular and standard deviations are large (Ivanenko et al., 2004; Ivanenko, Dominici, Cappellini, & Lacquaniti, 2005). Infants show no change in intraindividual variability at walking onset, but variability decreases rapidly over the next few months and patterns of intralimb coordination become more cyclical and consistent (Clark & Phillips, 1993; Ivanenko et al., 2004; Ivanenko et al., 2005; Lasko-McCarthey, Beuter, & Biden, 1990; Polk et al., 2008). Infants display roughly adult-like consistency in patterns of intralimb coordination after 3 to 6 months of walking experience (Clark & Phillips, 1993; Polk et al., 2008).

**Variability In Continual Movements**

Adult sitters are not perfectly motionless. High-resolution recordings of body position reveal continual postural sway—small, slightly variable movements of the torso. But in infant sitters, intraindividual variability is visible to the naked eye—like watching a coin teeter on edge before it topples. Detailed recordings of infants’ head position reveal the nature of the developmental changes (Saavedra, van Donkelaar, & Woollacott, 2012). As shown in Figure 4.4, before infants can sit independently, postural sway is variable but unidirectional: After a few seconds, infants lose balance and collapse forward. Next is a “rise and fall” period where infants pull themselves upright, only to fall forward again. After infants achieve sufficient control to maintain a sitting posture, they wobble precariously around the upright position, frequently over- and under-correcting their position until they fall. Finally, infants achieve functional, more adult-like sitting where sway varies within a tighter area around midline. These stages are continuous and infants’ postural sway can reflect multiple stages within a single session. The amplitude of postural sway continues to decrease between 2 and 14 years of age ( Riach & Hayes, 1987) and the total path length drawn by variation in the center of pressure decreases between 6 and 10 years of age (Hong, James, & Newell, 2008).

![Figure 4.3](image-url)

Figure 4.3. Variability in the footprint paths of infants tested in the standard gait paradigm. Infants walked over a pressure sensitive carpet that recorded the placement of each footfall. (A) Typical footfall patterns in a novice walker (2 weeks of walking experience). (B) Typical footfall patterns in a more experienced infant walker (2 months of walking experience). Adapted from Adolph & Robinson (2013). With permission.
Like sitting, learning to stand entails decrease in intraindividual variability. When infants first pull themselves to a stand, they display large swaying movements around the upright position, even while holding a support rail. Now they sway around the ankles rather than the hips as in sitting. Standing sway variability continues unabated through subsequent milestones in postural development—when infants can stand alone and when they take their first walking steps (Barela, Jeka, & Clark, 1999). In fact, variability in the developmental transition to upright balance imposes a transient perturbation to sitting posture. When infants first begin walking independently, they show a brief increase in the variability of postural sway while sitting; their new walking skill seems to briefly disrupt control of sitting, leading to a spike in intraindividual variability (L. C. Chen, Metcalfe, Jeka, & Clark, 2007). But after 6 weeks of walking experience, the amount of standing postural sway decreases substantially (Barela et al., 1999).

Intraindividual variability in standing sway velocity also improves after walking onset (L. C. Chen, Metcalfe, Chang, Jeka, & Clark, 2008; Metcalfe et al., 2005). At walking onset, infants’ swaying movements are rapid and changes in velocity are erratic. With walking experience, sway velocity decreases and becomes more consistent, indicating a shift from rapid, reactive corrections to slower, more prospective compensations. Refinements in the amount of sway variability continue through childhood until finally decreasing to adult levels (Hong et al., 2008; Newell, Slobounov, Slobounova, & Molenaar, 1997).

Potential Functions

Consistency and control. Researchers consider decrease in intraindividual variability to be a signature of skilled performance and control for good reason. For basic motor skills, the costs and benefits seem obvious. Decrease in variability accompanies more consistent, economical, accurate, and adult-like performance. Reciprocally, high variability incurs immediate penalties. Variable infant reachers risk missing the target. Wobbly infant sitters and toddlers risk toppling over. Moreover, variability in one movement has the potential to disrupt other movements, with cascading effects into domains far removed from motor control. Variability in sitting disrupts reaching, grasping, and object manipulation (Rachwani et al., 2013; Soska & Adolph, 2014), and lack of experience with objects, in turn, impedes learning about object form (Soska, Adolph, & Johnson, 2010). Data from clinical populations supports the notion of decreased variability and improved motor control. Children with Down’s Syndrome, for example, frequently show elevated amounts of intraindividual variability in basic motor skills relative to typically developing children (Looper et al., 2006).

A caveat. Despite clear evidence linking intraindividual variability with motor control, a caveat is in order. The endpoint of development is not elimination of variability.

Intraindividual variability only represents error for particular skills measured in particular ways. The presumed importance of reducing intraindividual variability is due in part to the way researchers study basic motor skills. In most standard paradigms, participants’ bodies, the environment, and task constraints are held constant: Infants reach repeatedly toward similar objects at midline; they step on a motorized treadmill or walk on straight paths over uniform ground. The task demands require consistency. Intraindividual variability is therefore considered to be errors in execution or noise in the sensorimotor system and is taken as evidence of poor motor control.

As we argue in the following sections, the role of variability in motor development is not so simple. Alternate ways of testing motor skill and measuring variability reveal a richer, more complex developmental story about intraindividual variability (Deutsch & Newell, 2005; Vereijken, 2010). Although variability in many basic motor skills decreases with experience, other aspects of intraindividual variability show different patterns of developmental change.

Development Entails Continuance Or Increase In Intraindividual Variability

Intraindividual variability is a defining characteristic of spontaneous activity such as fetal motility, infant exploration, and gross motor play (Adolph & Robinson, in press; Hadders-Algra, 2011). Indeed, the so-called “stereotypies” displayed by typically developing infants comprise such diversity of movement across so many body parts that they are not stereotyped at all (Piek & Carman, 1994; Thelen, 1979). To the contrary: Rigidly stereotyped movements during spontaneous fetal and infant activity are a harbinger of developmental disability (Hadders-Algra, 2011).

Intraindividual variability is also a central component of goal-directed motor behavior. In fact, for successful performance of most everyday, real world activities, movements cannot be performed in the same way over
and over because local conditions are always in flux. Instead, motor behavior must be adapted to variations in the body, environment, and task. Think of modifying your movements to type with long fingernails, steer through a cluttered living room, or lob a tennis ball beyond your opponent’s reach. Consider alternative strategies for tying your shoes while pregnant, descending a high rock wall, or pitching to a left-handed hitter. Variable movements and a variety of strategies allow motor actions to be tailored flexibly to the current situation. This section focuses on continuance and increase in intraindividual variability.

No Costs Or Benefits

Some motor behaviors have no external incentives or developmental pressures to decrease or increase variability. With no immediate costs or benefits for intraindividual variability, children typically maintain variability at the original levels until they acquire a new skill or the situation changes.

Belly crawling provides an apt example of a motor behavior with continued variability. Many infants belly crawl for several weeks prior to crawling on hands and knees. Because the torso rests on the ground during part or all of each belly-crawling cycle, balance constraints are minimal. As a consequence, infants achieve forward propulsion using arms, legs, belly (and sometimes head) in a seemingly limitless variety of combinations (Adolph, Vereijken, & Denny, 1998; Freedland & Bertenthal, 1994). Belly crawlers display variable patterns of interlimb coordination from cycle to cycle, trial to trial, and day to day. A single infant might exhibit a near-trot with arms and legs on diagonal sides of the body moving together, then a quasi-bound with first arms then legs moving together, then an army crawl moving only the arms and dragging the legs. One or both arms might drag with the legs pushing against the floor, sometimes inspiring infants to bear weight on the face. The infant might inchworm forward by popping up on the toes and plopping down on the abdomen. Intraindividual variability continues unabated throughout the belly-crawling period; even after 10 weeks of experience, infants continue to add new forms to their repertoire (Adolph et al., 1998). In contrast, once infants begin crawling on hands and knees, they quickly converge on a near-trot (Adolph et al., 1998; Freedland & Bertenthal, 1994; Patrick, Noah, & Yang, 2009, 2012). Presumably, balance becomes imperative with the abdomen off the floor and moving diagonal limbs together keeps the torso more stable.

Natural walking behavior provides another salient example. When infants are tested in the standard laboratory task—walking repeatedly in a straight line at a constant speed—the consistency of gait measures improves over the first three months of independent walking (Chang et al., 2006). But in everyday activity, infants do not walk in a straight line at a constant speed. Instead, natural walking paths are highly variable (Adolph et al., 2012). Infants generate twisting, turning, omnidirectional paths (Figure 4.5). They loop back over areas they have already visited. They make frequent starts and stops. Each step is not like the last in part because turns, back steps, side steps, double steps, and so on necessitate variation. Natural walking patterns are variable regardless of infants’ individual level of walking experience. Variability in walking in the standard laboratory task decreases, but natural locomotor exploration retains its variability.

Modifying Ongoing Movements

Body size and proportions are not static. The natural environment is not uniform. Task constraints are not constant. Intraindividual variability is necessary for adaptive action because variations in the body, environment, and task change the biomechanical constraints on action. Movements must be modified online to suit the demands of the current situation. Variations in movement are generated purposely to achieve a desired goal, and the outcome is increase in the amount of intraindividual variability. Carrying an asymmetrical load, for example, changes the body’s functional dimensions. Adult walkers compensate by varying body posture: They lean in the direction opposite the load (while carrying a suitcase in their left hand, adults lean to the right, etc.). School children routinely carry heavy backpacks (more than 15% of body weight). To compensate for the backload, they modify posture by leaning forward and heavier backpacks elicit more forward leaning (Brackley, Stevenson, & Selinger, 2009). Although infants can vary body posture by leaning in different directions, they do not do so in response to loads applied to their bodies. In contrast to older children and adults, infants do not compensate for asymmetrical loads comprising 15% of body weight (Garcia-Guirre, Adolph, & Shrout, 2007). Instead, they lean into the load and accommodate as best they can. As a consequence of failing to modify posture—failing to generate appropriate movements in response to changing body constraints—gait patterns are disrupted and infants misstep and fall (Garcia-Guirre et al., 2007; Vereijken, Pedersen, & Storksen, 2009). Backloads are more disruptive than front or side loads, presumably because backloads are most novel; during play, infants spontaneously carry loads to the front and sides of their bodies, but they do not wear baby backpacks.

A sloping ground surface also changes demands for keeping balance: the steeper the slope, the more challenging the demands. Walkers can curb forward momentum by taking smaller, slower steps, but infants have little experience walking down steep slopes (Gill, Adolph, & Vereijken, 2009). Although infants have the capacity to modify step length and walking speed, at first they do so haphazardly across a wide range of shallow and steep slopes (Figure 4.6A). Variations in movements are applied erratically. For example, in Figure 4.6A, the trials with 5 and 21 steps—the minimum and maximum step numbers—were both at the same 18° slope. After a few weeks of practice walking down a range of shallow and steep slopes, infants learn to modify their steps in accordance with 2° changes in degree of slant (Figure 4.6B). Variable movements are generated...
in precise accordance with changes in the environment (Figure 4.6C-D). Moreover, gait modifications show anticipatory planning and control. Infants begin braking before stepping onto a steep slope and they take longer steps toward the bottom of the slope (see cluster of footprints before crossing the brink of the slope and widely spaced footprints toward the landing platform in Figure 4.6D).

Like variations in the body and environment, variations in the task require children to generate variable movements and apply the variations systematically. For example, if the task is to squeeze through a narrow doorway, infants—like adults—modify locomotion by turning sideways in accordance with doorway dimensions (Comalli, Franchak, Char, & Adolph, 2013; Franchak & Adolph, 2012). If the task is to balance along a narrow ledge, infants and adults also turn sideways, but now they are less likely to attempt increments that are too narrow for passage.

Infants also adapt movements to variations in manual tasks. When 10-month-olds intend to toss a ball into a large bin, they reach faster for the ball than if they intend to fit the ball into a tube because the subsequent act of throwing requires less precision than the act of fitting (Claxton, Keen, & McCarty, 2003). Similarly, if toddlers intend to place a block into a container, they reach faster for the block than if they intend to balance it on top of a block tower (Y. P. Chen, Keen, Rosander, & von Hofsten, 2010). Refinements in reaching speed continue from 4 to 11 years of age, depending on whether children intend to fit an object into a tight or loose space, or toss it into a bin (Wilmut, Byrne, & Barnett, 2013).

**Variety Of Means**

Sometimes modifications of ongoing movements are insufficient to achieve the goal. Such situations require alternative strategies. Infants must select alternative actions from their motor repertoire or generate new solutions on the fly. Indeed, variety of means is a hallmark of adaptive motor behavior (Gibson & Pick, 2000; Piaget, 1952).

One might expect, for example, that crawling infants cannot carry objects because their hands are used for locomotion. However, crawlers do spontaneously carry objects—on average 6 times per hour—and they discover a variety of means to do so (Karaisk, Adolph, Tamis-LeMonda, & Zuckerman, 2012). Infants crawl with an object in hand, tucked under one arm, in the mouth, or by pushing it along the floor. Crawlers also vary their method of lo-
comotion by hitching in a sitting position while holding objects in hand, and by cruising while holding furniture with one hand and an object in the other. Walking infants carry objects more frequently than crawlers, averaging 43 carrying bouts per hour, and they also display a variety of means. Walkers carry one large object in two hands or two small objects in each hand; they hold one object in one hand while leaving the other hand free, grasping a caregiver’s hand, or holding onto furniture (Karasik et al., 2012; Mangalindan, Schmuckler, & Li, 2014). Individual infants display multiple methods of carrying. Diversity of carrying methods is more prevalent in crawlers for whom carrying is more difficult, and more experienced crawlers use more carrying methods (Karasik et al., 2012).

When faced with the novel predicament of descending a large step, high cliff, or steep slope, experienced infant walkers discover a variety of means for coping with the obstacle (Adolph, 1997; Kretch & Adolph, 2013). Of course, on safe increments, they can descend using their typical walking method and on risky increments, they can simply avoid going. However, experienced infants typically do not avoid descent. They find alternative means by scooting down in a sitting position, backing down feet first, sliding down prone headfirst, crawling (hands first), kneeling (legs first), or squatting using the hands on the starting platform. Across trials within a session, experienced walkers displayed 2 to 7 strategies (4 on average) for descending cliffs (Kretch & Adolph, 2013). Across sessions, walkers displayed 2 to 6 strategies (5 on average) for descending slopes (Adolph, 1997).

Variety of means is so endemic in infant motor behavior that infants sometimes surprise researchers by the creativity and inventiveness of their strategies. Sixteen-month-olds spontaneously use a sturdy wooden handrail to augment their balance while walking over narrow bridges (Berger & Adolph, 2003; Berger, Adolph, & Kavookjian, 2010). But when presented with a wobbly rubber handrail—designed to be unusable for postural support—infants nevertheless find a variety of ways to exploit the handrail for support (Berger, Adolph, & Lobo, 2005). They hunch over the rail letting it dip to their knees, pull themselves along like a mountain climber, lean back like a windsurfer, carefully distribute weight across the whole arm, and so on. Similarly, 11-month-old “cruisers” exploit a low handrail—designed to be too low to provide postural support—by cruising on their knees (Berger, Chan, & Adolph, 2014).

**Potential Functions**

Flexibility and adaptability. Increased movement variability is a good thing when it functions to tailor motor behavior to the current situation. Indeed, intraindividual variability is an imperative for everyday action because it allows behavior to be flexibly adapted to current constraints. Outside the laboratory, local conditions are never constant; rigid adherence to a consistent way of moving would be maladaptive. Instead, children must perceive the current status of their bodies and skills relative to the current status of the environment, determine which actions are possible and which are not, and exploit possibilities for action to suit their goals (Adolph & Robinson, in press; Gibson & Pick, 2000).

Skilled adults make it look easy. But none of it is easy for young children, and all of it requires learning and development. Infants, for example, require months of everyday locomotor experience before they accurately distinguish safe from risky slopes or a step from a cliff (Adolph, 1997; Kretch & Adolph, 2013). With sufficient experience in a variety of everyday situations, infants can adapt movements on the fly to novel and variable changes in their body and environment—a platform shoe on one foot, slippery slopes, or walking down slopes wearing Teflon-soled shoes of their bodies and skills relative to the current status of the environment, determine which actions are possible and which are not, and exploit possibilities for action to suit their goals (Adolph & Robinson, in press; Gibson & Pick, 2000).
or a lead-weighted vest (Adolph & Avolio, 2000; Adolph, Joh, & Eppler, 2010; Adolph, Karasik, & Tamis-LeMonda, 2010; Cole, Gill, Vereijken, & Adolph, in press).

Like modifying ongoing action, a variety of means—different locomotor methods for tackling a slope, different strategies for carrying an object, and so on—functions to promote behavioral flexibility. More ways to tackle a problem increases the probability of finding a satisfactory solution. New strategies typically arise in the course of coping with the task (Adolph, 1997; McGraw, 1935). Infants sometimes generate new strategies by testing various options (e.g., start onto an obstacle in one position and then change their minds and try something else) and sometimes discover new strategies serendipitously (e.g., attempt their typical method but due to a combination of gravity and inertia, find themselves doing something else that is ultimately more useful).

Given a variety of options in their repertoire, which strategy do children select? If the penalty for error is sufficiently salient (e.g., falling into a precipice), experienced infants avoid strategies that prohibit success (e.g., walking over a cliff) and select strategies that minimize errors (avoidance) or allow them to achieve their goal (e.g., backing feet first over the edge of a drop-off). If multiple strategies are possible (backing, scooting, sliding, etc.), infants display multiple strategies (Adolph, 1997; Kretch & Adolph, 2013). Moreover, if the penalty is not salient from infants’ perspective (e.g., being wedged into an impossibly narrow opening, increased energetic cost of superfluous movement), experienced infants frequently select strategies that are ineffective or lead to errors, despite the availability of more effective strategies (Franchak & Adolph, 2012).

**Raw materials for learning.** Regardless of infants’ intent, continuance or increase in intraindividual variability can serve an exploratory function (Corbetta, 2009; Goldfield, 1995; Harbourne & Stergiou, 2009; Thelen, 1996; Vereijken, 2010). Variation provides the raw materials for learning. Variable movements and a variety of strategies generate information about the self, the environment, and the relations between them. Infants must learn about their bodies and skills—the various body parts, the space in which body parts can move, and how movements can be coordinated within and across body parts. Variable movements provide opportunities for learning about the self in action, and this information can be exploited later for making movements more proficient or for tailoring actions to local conditions. Variability in belly crawling, for example, gives infants an immediate boost in speed and amplitude of movements when they begin crawling on hands and knees (Adolph et al., 1998). Variability in step length and speed in novice walkers can be exploited by experienced walkers to curb forward momentum on slopes (Gill et al., 2009). Similarly, infants must learn about the environment—where things are and what can be done with them. Variability in natural locomotion provides infants with visual access to more of the room, ensures hands-on experience with a variety of surfaces, and promotes interactions with varied objects, surfaces, and people (Adolph et al., 2012; Karasik, Tamis-LeMonda, & Adolph, 2011).

From the perspective of learning and development, continuance or increase in intraindividual variability is imperative because a selection process requires variants to act upon. When variation runs out, selection grinds to a halt. Put another way: Strategy selection is not a one-time event. Currently ineffective strategies do not creep away to die. They decrease in frequency or lie dormant until needed once again (Siegler, 2006).

**Development Entails Changes In The Structure Of Intraindividual Variability**

The previous sections described change in intraindividual variability by quantifying change in the amount of variability such as decrease in the length of the hand path in infant reaching or in the area of the head path in infant sitting. However, development can also entail changes in the structure of variability. Describing change in the structure of variability requires researchers to understand how some aspect of motor behavior changes moment to moment over real time—that is, the sequence of values in a time series. This section describes two ways of considering developmental change in the structure of variability.

One way of considering the structure of variability concerns the relations among variables in a time series. Look again at the jerky arm path of the infant reaching for a toy in Figure 4.2B and the wobbly head trajectory of the infant trying to sit in Figure 4.4A-C. Outside the laboratory, infants are not strapped into a chair to stabilize the torso while reaching for objects; instead, they maintain their own sitting posture while reaching. Likewise, outside the lab, infants do not sit for long periods without turning their heads to look around and moving their arms to manipulate objects. Typically, infants learn to reach during the same developmental period when they are learning to sit. Wobbles in the sitting posture affect infants’ hand path while reaching; reciprocally, moving their arms to reach or turning their heads to look affects infants’ sitting posture. Arm, head, and torso movements do not happen in isolation, so the development of motor control is not apportioned limb by limb (Bertenthal & von Hofsten, 1998; von Hofsten, 2003). Instead, movements of various body parts co-occur so that motor control requires the coordination of movements in real time (Bernstein, 1967; Turvey, 2007). This time-locked interplay between simultaneous movements in different parts of the body is one way of considering the structure of variability.

A second way of considering the structure of variability concerns dependencies in a time series. Look once more at the jerky hand path in Figure 4.2B and the wobbly trace of the head position in Figure 4.4A-C. Consider also the trail of footprints created by the toddler approaching the brink of a steep slope in Figure 4.6D. In each example, the jerks, wobbles, and footfalls are related in real time. A jerk of the hand...
in one direction necessitates a correction in the opposite direction; if the baby over- or undershoots, additional corrections are needed. In other words, what happened milliseconds earlier affects the hand path a few moments later. The wobbly sitter shows a similar time dependency. As the infant’s torso starts to fall forward, the body jerks backward in an effort to compensate. Postural sway in the current moment depends on what happened a moment prior, and influences what has to happen next. Likewise, changes in the toddler’s step length are organized in time and space, getting smaller as the toddler approaches the brink of the slope. Researchers can investigate developmental changes in the structure of variability by quantifying dependencies within a variable in a time series at different developmental time points.

**Emerging Correlations Between Variables**

Successful and adaptive movements require different body parts to work together, coordination among joints in a limb, and different aspects of movement to be controlled simultaneously. Consequently, a primary challenge for skill acquisition is learning to coordinate the body as a single unit rather than a collection of separate parts. The different variables that are crucial for successful performance must become increasingly correlated in time. A famous example of such emerging correlations across variables is in pistol shooting (Arutyunyan, Gurfinkel, & Mirskii, 1969). Expert marksmen do not consistently hit the bullseye by reducing extraneous body movements to zero. Instead, their shooting is reliable because variations in, say, the shoulder angle, are instantly corrected by compensatory movements in the wrist joint.

Similarly, motor development involves emerging correlations between variables in time. For example, in a challenging balance control task, 5-year-olds can stand on one leg longer than 3-year-olds (Slobounov & Newell, 1994). But how do they do it? Older children exhibit less postural sway than younger ones, but concurrent with reduced sway, older children also produce more movements and larger movements in the torso and limbs. Five-year-olds elevate and swing their arms, bend at the knee, lift their heel, and hop in place. These body movements are compensatory responses that are tightly related in time to postural sway. The net result is a reduction in the amount of postural sway. In contrast, younger children stiffen their torso and decrease leg and arm movements, but to no avail. Without a time-locked correlation between variable limb movements and postural sway, they sway more and lose balance.

Long before children can balance on one foot, learning to stand on two feet involves emerging correlations between variables over a time series. With a hand resting on a support surface, pre-walking infants and novice walkers sway first and then lean onto the support surface to assist their balance. But after 6 weeks of walking experience, this relation reverses so that pressing on the support surface precedes body sway. By establishing a time-locked relation between variability in forces applied to the support surface and variability in postural sway, infants generate perceptual information to aid prospective control of standing (Barela et al., 1999). The consequence is a reduction in the amplitude of postural sway.

Even before infants can stand with support, they can coordinate different aspects of motor behavior in a new task—producing vertical jumps in a “baby bouncer” (a seat held by a spring to the top of a doorway). At first infants dangle in the bouncer, unsure of what to do, spontaneously producing occasional, random leg movements. Through these sporadic, variable kicks and jumps, infants discover the temporal and spatial relations between their leg movements and the resulting bounce. Soon, they learn to maximize the amplitude of their bounces by changing the structure of their movement variability. The average time between bounces remains the same, but the variability of inter-bounce intervals decreases as infants learn to synchronize jumps with the spatial trajectory of the bounce. If infants jump at the wrong moment, the forces they generate will cancel out the extension of the spring. Moreover, after a few sessions, infants begin to group their bounces into extended bouts. These emerging correlations between the timing and spatial trajectory of infants’ movements accentuate the bounce by matching the stiffness and elasticity of the spring (Goldfield, Kay, & Warren, 1993).

**Emerging Time Dependencies Within Variables**

Structure in variability can also emerge in the form of time dependencies within a variable, such as the infant’s step length while approaching the slope in Figure 4.6D. As with emerging correlations across variables, time dependency in one variable over a time series is acquired gradually with age and experience. Walking provides an intuitive example of the emergence of time dependency over development. When someone walks a long distance, the successive stride times (the time interval between foot contacts of the same foot) create a time series. In the first few years of independent walking, the stride time of the current step influences the stride time of the steps that immediately follow but not steps farther forward in time. This time dependency is short and decays quickly such that each subsequent step becomes increasingly independent from earlier steps. After several years of walking experience, the dependency between successive stride times stretches farther forward over the time series, reflected in increased long-range correlations between stride times and in a slower rate of decay (Hausdorff et al., 1999).

As illustrated with stride time variability, the sequence of values in a time series determines the structure of the time series. Imagine three types of waveforms: a perfectly regular oscillating wave, a totally random series of jiggles, and the somewhat wiggly waveforms somewhere in between. All three types of time series could share the same amount of variability as measured by the range in values, the standard deviation, or other summaries of the amount of variability around a central point. But such summaries do
not take the sequence of values in the time series into account. The perfectly regular waveform is highly structured, utterly predictable, and low in complexity. In contrast, the totally random time series has no structure, is completely unpredictable, and—because it is white noise—is undefined in terms of complexity. The somewhat wiggly waveforms that reside between these extremes contain more or less structure in terms of predictability and complexity.

The development of predictability in the structure of intraindividual variability follows an inverted U-shaped function (Cignetti, Kyvelidou, Harbourne, & Stergiou, 2011; Harbourne & Stergiou, 2003). The time series of infants’ first attempts at a new skill more closely resemble a random waveform than a regular oscillating wave. Thus, early periods of development typically are marked by an increase in dependencies within a time series accompanied by a decrease in the amount of intraindividual variability (based on measures such as the standard deviation and area of postural sway) such that the time series becomes more predictable and complex while the movements become more consistent and smooth. Indeed, the emerging structure in the variability of the time series may underlie improvements in consistency. However, with continued development, movements cannot continually increase in predictability because then behavior would become robotic and inflexible. Thus, at later periods of skill acquisition, predictability and consistency typically decrease while complexity is maintained, ensuring sufficient flexibility in the system for behavior to be adaptive.

The development of sitting exemplifies the inverted U-shaped trajectory. The erratic postural sway of new sitters gradually gives way to a more periodic and predictable sway pattern as sitting becomes better controlled (Cignetti et al., 2011; Harbourne & Stergiou, 2003). However, after infants can sit without falling, the developmental trajectories of predictability and consistency begin to reverse. Postural sway becomes less predictable again and the linear measures of sway become less consistent because infants now have sufficient control to turn their head and move their arms.

The complexity of sitting continues to increase throughout childhood (Hong, James & Newell, 2008). Younger children make disproportionately many small corrections, presumably because they rely on reactive control to keep balance. This results in more postural sway around the upright position (a longer path traveled by the center of pressure) accompanied by low complexity. With age and experience, children become increasingly able to exploit passive forces, resulting in less postural sway and more complexity. In adults, sway patterns are even less periodic and predictable, but more complex (Cignetti et al., 2011).

**Potential Functions**

Optimal variability for performance. Motor development is characterized by concurrent changes in the amount and structure of variability as infants master new skills. From infants’ initially erratic and wobbly movements, different aspects of motor behavior gradually become related across variables in a time series and more time dependencies emerge. Some of these relations reduce intraindividual variability to make movements more predictable and consistent, whereas other relations increase variability to allow for greater complexity, behavioral flexibility, and adaptability. Eventually, children acquire the optimal structure of variability to support skilled performance.

Although the structure of intraindividual variability can change with development, values at the high or low ends of the variability spectrum are not a good thing. Healthy behavior reflects both stability and the capacity for change. Excessive noise in the structure of intraindividual variability incurs costs of inconsistency and unpredictability. Insufficient variability incurs costs of overly rigid, restricted behavior, inflexibility, and low complexity. Intraindividual variability, thus, adheres to the “Goldilocks principle” of a just-right amount of variability (Fetters, 2010). Children need sufficient consistency to make behavior reliable, and sufficient flexibility to deal with variations in local conditions and disruptions of the status quo (Stergiou & Decker, 2011; Stergiou, Yu, & Kyvelidou, 2013; Vereijken, 2010).

Recent work suggests that suboptimal levels of intraindividual variability—too little or too much—can distinguish children with typical development from children with disabilities and delay. Infants diagnosed with cerebral palsy or at risk for the disorder show more regular, periodic structure in postural sway in early stages of sitting compared with typically developing infants (Deffeyes, Harbourne, DeJong, et al., 2009; Deffeyes, Harbourne, Kyvelidou, Stuberg, & Stergiou, 2009; Kyvelidou, Harbourne, Willett, & Stergiou, 2013). In contrast, children with Down Syndrome display more irregular, non-periodic structure in leg movements while walking on a treadmill compared with typically developing children (Buzzi & Ulrich, 2004).

Optimal variability for development. In addition to contributing to performance, just-right levels of intraindividual variability might also contribute to healthy learning and development (Corbetta, 2009; Harbourne & Stergiou, 2009). The same structure of variability at an earlier period of development is not necessarily optimal at a later period. For example, low predictability early in skill development can facilitate learning which aspects of action must be coordinated in time and how earlier movements affect later ones. This information is critical at early stages of skill acquisition. How else could infants acquire the information without exploring the possibilities for movement? Thus, too much predictability in children with disabilities may hamper learning. In typically developing children, greater predictability at later points in development can provide information about how to succeed at a task. The eventual return to lower levels of predictability now provides information about how to cope with novel changes in local conditions.
Conclusions And Future Directions: Understanding Intraindividual Variability In Motor Development

Every behavioral and physiological event, of course, produces intraindividual variability. But motor development is unique in developmental science by adhering to a deep and long-standing commitment to describing and explaining developmental change in intraindividual variability (e.g., Deutsch & Newell, 2005; McGraw, 1935; Thelen, 1996). Perhaps because motor behavior so naturally lends itself to representations of trajectories over time and space and perhaps because movements vary so plainly on both qualitative and quantitative dimensions, intraindividual variability has always been a central focus of research on motor development. This long and rich history encompasses very different sorts of research programs focused on very different aspects of motor behavior expressed over very different temporal and spatial scales.

Across this broad research landscape, the data reveal three distinct patterns of developmental change. Decrease in intraindividual variability is typically associated with increase in motor control. As intraindividual variability decreases, children’s movements become more proficient and economical and performance becomes more accurate and successful. Continuance or increase in intraindividual variability is accompanied by increase in adaptability and behavioral flexibility. Modifications of ongoing movements and a variety of strategies make it more likely that children can cope with new situations and achieve their goal. Changes in the structure of intraindividual variability go hand-in-hand with changes in the temporal organization and coordination of movements. The sequence of values in a time series must be sufficiently unpredictable and complex to ensure the flexibility to cope with variations in local conditions, but not so much that the system cannot produce movements reliably and consistently.

Despite the breadth of developmental research on intraindividual variability, several important things are missing from the community’s research program. One shortcoming is the lack of integration across the various instantiations of intraindividual variability and the methods for studying variability. Although most researchers acknowledge the range of meanings and methods, few researchers take an integrative approach. Instead, research teams tend to focus on only one aspect of intraindividual variability, say, improvements in consistency (Berthier & Keen, 2006) or in adaptability (Adolph, 1997). Notable exceptions are a recent handful of studies that report both changes in consistency and in the structure of variability (e.g., Defeyes, Harbourne, Kyvelidou, et al., 2009; Hong et al., 2008), but we know of no studies that examine developmental changes in all three types. The field now has the tools and conceptual frameworks for studying multiple types of intraindividual variability within individual children in a single study. A more integrative approach would

enable deeper understanding of motor skill acquisition and the mechanisms underlying developmental change. A second shortcoming is researchers’ over-reliance on artificial situations in laboratory tasks. We construct over-simplified and unnatural situations to ensure experimental control. But strapping pre-sitters into a seat and presenting the same toy repeatedly at midline is not how infants really learn to reach. We standardize test situations to allow generalization across children at various periods of development. But forcing infants to step on treadmills or along a straight, continuous path is not how babies really learn to locomote. Sitting for long periods on a force plate and standing for long periods with a hand on a support rail are not representative of sitting and standing outside the laboratory. Encouraging infants to descend slopes dozens of times in a row does not reflect the way they really encounter variation and novelty in the everyday environment. Ecological validity is not a criticism unique to research on intraindividual variability, but it impedes progress by reifying the laboratory paradigms and conflating findings from limited situations with real-world motor behavior. The risk is that we construct theories about developmental change in intraindividual variability that do not generalize to real world activities.

A third shortcoming is our lack of knowledge about how different types of intraindividual variability promote and hinder healthy development. Most research findings are consistent with the idea that some amount of some type(s) of intraindividual variability is conducive to the healthy learning and development of basic motor skills. However, we have scarce experimental evidence to support this notion—that is, studies with children randomly assigned to treatment and control groups that promote or eliminate a particular type of intraindividual variability. Identifying differences in the amount and/structure of variability between children with typical development and children with disabilities is a promising first step. But it is not wholly satisfying. In one study, approximate entropy (a measure of structure) distinguishes healthy and impaired postural sway (Defeyes, Harbourne, Dejong, et al., 2009), but in another study it does not (Defeyes, Harbourne, Kyvelidou, et al., 2009); instead, the Lyapunov exponent differs between groups. And the same measures of approximate entropy and the Lyapunov exponent can differ in different directions between different clinical populations (Buzzi & Ulrich, 2004; Deffeyes, Harbourne, Kyvelidou, et al., 2009). The next step is to construct theories that direct researchers’ attention to particular measures of intraindividual variability and that facilitate discovery about the sources and consequences of intraindividual variability. Without such progress, researchers cannot design appropriate therapeutic interventions for children at risk.

Finally, researchers need to generate experimental evidence about the functions of intraindividual variability. We focused our chapter on potential functions of developmental changes in intraindividual variability. Dozens of developmental studies provide correlational evidence concerning the real-time functions of variability (Berthier & Keen,
A long history of experimental research exists for studying the effects of variable practice on motor learning (Schmidt & Lee, 2011). What we need now is experimental evidence concerning the functions of developmental changes in intraindividual variability.

References


