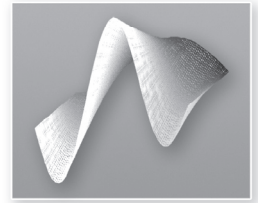


## Chapter 6

---



# Genetic and Environmental Constraints on Variability in Sport Performance

*Joseph Baker, PhD and Keith Davids, PhD*

### Editors' Overview

---

Why do some athletes benefit more than others from training and practice? A frequent observation of interindividual variation in response to training and practice raises important theoretical and practical questions about the nature of genetic and environmental constraints on skill acquisition and performance. This problem is a manifestation of the long-standing debate of nature versus nurture, which argues the precise proportion of performance variation in a population accounted for by genetic characteristics or environmental influences. The relationship between genetic and environmental constraints on responses to practice and training is complex, requiring a careful interpretation of the data in the extant literature and a comprehensive theoretical model to explain research findings. In this chapter, the theories of practice emphasizing the role of environmental constraints in explaining variability in expertise are evaluated, and the evidence favoring the role of genetic constraints in variability of interindividual responsiveness to training and practice is examined. The biological determinism underlying some recent interpretations of the roles of genetic diversity and environmental context on variation in human motor performance is rejected for an interactive model that is captured well by dynamic systems theory. The challenges for future research on the interacting constraints of genetics and environment are (1) to locate the primary and secondary influences on performance and (2) to understand the dimensions of their interactions in order to improve practical intervention programs such as those dedicated to talent identification and development.

---

Why do some athletes benefit more from training and practice? Are elite performance institutes justified in putting large amounts of funding into genetic testing of athletes to micro-manage personalized training programs? (Dennis, 2005). The frequent observation of interindividual variations in responsiveness to training and practice raises important theoretical and practical questions like these on

the genetic and environmental constraints on skill acquisition and performance. How these constraints shape variations in performance is of increasing interest in psychology, physical education, movement science, biology, and sports medicine, and in this chapter we examine current theory and data on environmental and genetic influences on expertise and performance. This issue is manifested in the long-standing debate of nature versus nurture, which seeks to identify the precise proportion in which genetic characteristics and environmental influences contribute to variation in performance. Much has been written about this particular dualism, and resolving the debate has proved difficult (for excellent analyses see Lewontin, 2000 and Johnston & Edwards, 2002).

The relationship between genetic and environmental constraints on responses to practice and training is a complex issue that requires careful interpretation of the data in extant literature and a comprehensive theoretical model to explain research findings. We begin this chapter by evaluating theories of practice that emphasize environmental constraints in explaining variability in achieving expertise. We then examine the evidence that favors the role of genetic constraints on performance variability. We conclude by outlining the theory of dynamic systems as a powerful explanatory framework for interpreting the interactional influences of genetic diversity and environmental context on variation in human motor performance.

## **Nurture Perspective of Expertise Development: Deliberate Practice**

One of the most radical perspectives regarding the role of practice in performance variation is the framework of deliberate practice presented by Ericsson and colleagues (Ericsson, Krampe, & Tesch-Römer, 1993). They proposed that individual differences in performance in any domain can be accounted for by the amount and type of practice previously performed. Likewise, they suggested that genetics play a minimal role in determining individual achievement and that this role can be circumvented by optimal amounts of quality practice. While many presumptions of this theory remain to be proven, deliberate practice is largely based on two previously observed guidelines: the 10-year rule (Simon & Chase, 1973) and the power law of practice (A. Newell & Rosenbloom, 1981).

### ***The 10-Year Rule***

In their classic study of chess expertise, Simon and Chase (1973; Chase & Simon, 1973) made the first suggestion that interindividual variation in performance can be explained by quantity and quality of training. This hypothesis was based on findings indicating that differences between expert (grand master) and lower (master and novice) levels of skill were attributable to the ability to organize information into more meaningful chunks rather than to a superior memory. Since then, researchers examining experts and novices have

found no reliable differences in static, physical capacities such as visual acuity, reaction time, or memory (hardware) but have found consistent differences in domain-specific strategies for information processing (software) (for a review see Starkes, Helsen, & Jack, 2001). In a recent overview of the last 30 years of research on expertise in sport, Singer and Janelle (1999) summarized the characteristics that distinguish the expert:

1. Experts have greater task-specific knowledge (McPherson, 1993; McPherson & French, 1991).
2. Experts interpret greater meaning from available information (Abernethy, 1987; 1990; 1991).
3. Experts store and access information more effectively (McPherson, 1993).
4. Experts are better at detecting and recognizing structured patterns of play (Allard & Starkes 1980; Chase & Simon, 1973).
5. Experts are better at using situational probability data (Abernethy & Russell 1984; 1987).
6. Experts make decisions that are more rapid and appropriate (A.M. Williams, 2000).

In sport, research examining interindividual variation in cognitive abilities has been somewhat limited to sports and physical activities with dynamic task constraints demanding a high level of decision making. However, existing evidence suggests that in fields where the distinguishing characteristics between experts and nonexperts are domain-specific abilities in information processing, these differences result from training rather than innate ability. An interesting question is the role of other genetic constraints, such as differences in power or endurance, which we examine later in this chapter.

The 10-year rule stipulates that a 10-year commitment to high levels of training is the minimum requirement to become an expert. This 'rule' has been retrospectively applied to the study of expert careers, with some success in domains such as music (Ericsson, Krampe, & Tesch-Römer, 1993; Hayes, 1981; Sosniak, 1985), mathematics (Gustin, 1985), swimming (Kalinowski, 1985), distance running (Wallingford, 1975), and tennis (Monsaas, 1985).

The perspective of deliberate practice (Ericsson et al., 1993) extends the work of Simon and Chase (1973) by suggesting that it is not simply any training that differentiates individual performance, but engagement in deliberate practice. By definition, deliberate practice is not intrinsically motivating, it requires effort and attention, and it does not lead to immediate social or financial rewards. Further, involvement in deliberate practice depends on the learner accessing effective resources (facilities, coaches, financial support), providing the necessary physical and mental intensity for progressively adapting to appropriate training loads and possessing the ability to maintain involvement without

intrinsic forms of motivation such as enjoyment. In the framework of deliberate practice, future experts perform training that develops required skills under continuously evolving conditions in which stress and recovery are optimally balanced to maximize training adaptations and minimize training plateaus.

### **Power Law of Practice**

Research examining the accumulated effects of prolonged practice and the rate of learning has suggested that performance increases monotonically according to a power function. This finding, known as the power law of practice (or the log–log linear learning law) (A. Newell & Rosenbloom, 1981), has been demonstrated in numerous domains. According to the power law of practice, learning occurs rapidly at the start of practice, but this rate of learning decreases over time as practice continues (see figure 6.1).

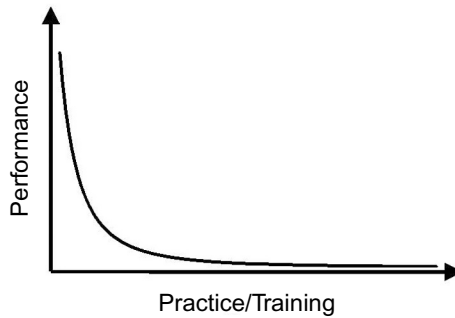


FIGURE 6.1 Example of the power law of practice for performance on a response time task.

Central to the notion of deliberate practice is the *monotonic benefits assumption*. Ericsson et al. (1993) proposed that, contrary to the power law of practice, a monotonic relationship exists between the number of hours of deliberate practice performed and the performance level achieved. Their original research with musicians indicated that the difference between expert and nonexpert pianists and violinists was the amount of time spent practicing while alone (i.e., deliberate practice). The best musicians had spent at least 10,000 h practicing alone while their less successful counterparts had spent no more than 7,000 h.

Ericsson et al. further argued that it is not simply the accumulation of hours of deliberate practice that leads to superior performance. The accumulation of such hours must coincide with crucial biological and cognitive development. Early specialization is an important element predisposing future success. Figure 6.2 illustrates the relationship of chronological age, time spent in deliberate practice, and performance. Performers beginning deliberate practice at later ages (performers b and c), even with the same commitment to training, are

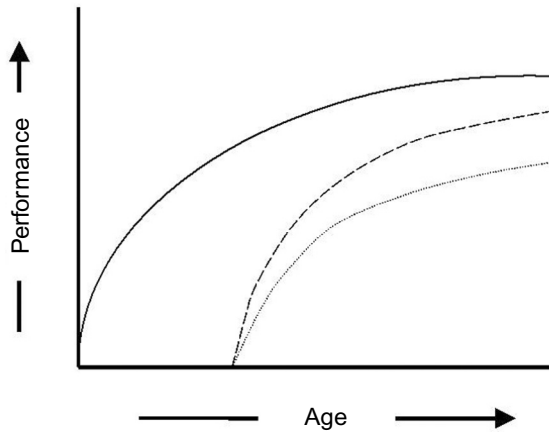


FIGURE 6.2 Relationship of chronological age, performance, and hours of deliberate practice.

Adapted from Ericsson, Krampe, and Tesch-Romer 1993.

unable to match the quantity of training accumulated by performers starting earlier (performer a). The assumption that future experts must specialize early becomes increasingly important in sports where peak performances typically occur at younger ages (e.g., diving, gymnastics, and figure skating for women), although the necessity for early specialization in sports where peak performance occurs later (e.g., basketball, field hockey) has recently been questioned (Baker, 2003; Baker, Cote, & Abernethy, 2003a).

### ***Deliberate Practice in Sport***

Although the theory of deliberate practice was developed through research with musicians, Ericsson and colleagues have indicated that it should also apply to expertise in sport (Ericsson et al., 1993; Ericsson, 1996). To date, researchers examining the theory of deliberate practice in sports have investigated figure skating (Starkes, Deakin, Allard, Hodges, & Hayes, 1996), karate (Hodge & Deakin, 1998), wrestling (Hodges & Starkes, 1996), soccer (Helsen, Starkes, & Hodges, 1998), middle distance running (Young & Salmela, 2002), field hockey (Baker et al., 2003a; Helsen et al., 1998), triathlon (Baker, Cote & Deakin, 2005; Hodges, Kerr, Starkes, Weir, & Nananidou, 2004), basketball (Baker et al., 2003a), and netball (Baker et al., 2003a). These studies have encountered some problems with applying the original framework of deliberate practice to the sport domain. For example, Starkes and colleagues (Helsen et al., 1998; Hodges & Starkes, 1996) found that athletes tended to rate relevant practice activities as very enjoyable and intrinsically motivating, contrasting with a key component of the definition of deliberate practice. Further, there is concern regarding which forms of athletic training constitute deliberate practice. In the

original work of Ericsson et al. (1993), only practicing while alone met the requirements for deliberate practice. In studies of deliberate practice in sport, there are few, if any, training activities that meet the original criteria set in the definition by Ericsson et al. (1993). Helsen et al. (1998) suggested that the specifications for deliberate practice in sport should be extended to include all relevant forms of training. This is particularly important in team sports where both individual and team practices increase skill and improve performance.

The relationship between hours spent in practice and attainment is typically consistent with the tenets of deliberate practice. Expert athletes accumulated more hours of training than nonexperts (Helsen et al., 1998; Starkes et al., 1996; Hodge & Deakin, 1998). Not only do experts spend more time in practice, but they also devote more time to the specific activities deemed as being the most relevant to developing the essential component skills for expert performance. For example, Baker, Côté, and Abernethy (2003b) found that expert athletes from basketball, netball, and field hockey accumulated significantly more hours in video training, competition, organized team practices, and one-on-one coaching than nonexpert athletes.

### ***Deliberate Practice and Interindividual Variation in Performance***

The essence of the perspective of deliberate practice seems to be “all individuals are created equal.” In a review of studies on skill acquisition and learning, Ericsson (1996) concluded that, with few exceptions, the level of performance was determined by the amount of time spent performing a “well defined task with an appropriate difficulty level for the particular individual, informative feedback, and opportunities for repetition and corrections of errors” (p. 20-21). Continually modifying the task difficulty allows future experts to perpetuate adaptations to greater training stress. Informative feedback and opportunity for repetition allow the performer to master skills more easily and to progress more quickly.

Data from the Ericsson et al. (1993) study of expert musicians support the relationship between hours of deliberate practice and level of performance. Specifically, the study found that expert musicians spend in excess of 25 h/wk in deliberate practice (training alone) whereas less successful musicians spend considerably less time in deliberate practice (amateurs spend <2 h/wk). These notable differences in weekly hours accumulate to enormous divisions after years of training. Similar relationships have been found in chess (Charness, Krampe, & Mayr, 1996). Prior research on the training histories of athletes and the characteristics that distinguish individual athletes provides evidence for the powerful role of appropriate training in building the expert sport performer.

### ***Influence of Other Activities***

Recently, researchers have provided evidence that challenges one of the basic tenets of the theory of deliberate practice, specifically, that early specialization is necessary for the development of expertise. Baker et al. (2003a) studied

experts from field hockey, basketball, and netball and found that these players performed a wide range of sports during early stages of development. As the athletes developed, their broad involvement in sports gradually decreased until they specialized in their main sport (figure 6.3). Moreover, Baker et al. (2003a) reported a negative correlation between the number of other sports played and the number of sport-specific training hours performers required before making their respective national teams. These findings suggest that participation in indirectly related activities may augment the physical and cognitive skills necessary for an athlete's primary sport. For example, many of the athletes participated in various forms of football (including rugby, Aussie rules, and touch football), a sport that also requires dynamic, time-constrained decision making as well as physical elements such as cardiovascular fitness and coordination.



FIGURE 6.3 The number of sporting activities performed each year by experts and nonexperts from basketball, netball, and field hockey.

Adapted from Baker et al., 2003a.

Research by Côté (1999; Côté & Hay, 2002) has indicated that playlike activities (termed *deliberate play*) during the early stages of training benefit expertise development in many sports. Deliberate play represents the antithesis of deliberate practice in that it is made up of activities designed for enjoyment that require active and pleasurable participation. In early development, activities that are inherently enjoyable and motivating may be necessary to provide an impetus to continue training when more diligent, effortful practice is required. Without this pleasurable involvement, athletes may drop out of sport (Petlichkoff, 1993).

The above relationships are not unexpected. During early stages of development, improvement comes rapidly and easily because there is so much room for it. During this time, it is likely that any form of relevant participation provides improvement, regardless of whether this participation is direct involvement through sport-specific training or indirect involvement through sports that

share basic characteristics. However, as performance improves, enhancement becomes increasingly difficult until focused training on specific areas of weakness becomes the only means of advancement. At this point, deliberate practice becomes the most effective form of training (see Baker, 2003 for a more through review).

## **Challenges of Deliberate Practice**

Despite the evidence favoring environmental effects on responses to practice and training, the issues in the nature/nurture area are enormously complex. In her thought-provoking paper on the theory of deliberate practice in sport, Starkes (2000) raised some important questions regarding the relationship between expertise and responsiveness to training and practice. Starkes' examination of the data on the elusive element of athletic success attempted to contrast two theories purporting to explain athletic achievement: the sport commitment model of Scanlan and colleagues (Scanlan, Carpenter, Schmidt, Simons & Keeler, 1993) and the theory of deliberate practice (Ericsson et al., 1993). Despite the arguments proposed by these researchers, both theories end with the feeling of "the chicken or the egg." For example, the sport commitment model provides few indications of whether the commitment required of performers of international caliber is developed or is predominantly inherited. There seems a hopeless correlation among the innate factors influencing the propensity to enjoy sport and the willingness to invest time and effort into countless hours of practice and the influence of positive learning experiences (which the coach can do much to foster).

### ***Deliberate Practice and Intraindividual Variability in Performance***

K.M. Newell and McDonald (1991) have argued that practice is a necessary but not sufficient condition for developing motor expertise. Traditional approaches to practice have tended to overemphasise the amount of required time to be spent in practice to the detriment of understanding how the quality of specific practice activities affects expertise. For example, earlier in this chapter we noted how the theory of deliberate practice is grounded in the power law of learning. Despite the fact that the power law has been called "the ubiquitous law of learning" (A. Newell & Rosenbloom, 1981, p. 2), there has been recent criticism of this view, particularly as it relates to intraindividual variability in performance.

K.M. Newell, Liu, and Mayer-Kress (2001) have pointed out that performance can change in persistent and transitory ways as a function of learning and development and that previous research has emphasized identifying persistent changes rather than transitory changes. A number of variables can be used to assess intraindividual change in performance over time, but task outcome has been the main variable used in studying learning curves. The power law of



learning has been the generally accepted law of learning primarily because data from two of the best-known studies on learning, one by Crossman (1959) and one by Snoddy (1926), fit the power law well. The power law of learning has had some passionate advocates, including Logan (1988), for example, who advocated that any theory providing data that do not fit the power law should be immediately rejected.

But, as K.M. Newell et al. (2001) have indicated, careful analysis of the data from Crossman (1959) (late in practice) and Snoddy (1926) (early in practice) shows occasional significant departures from the power law. The notion that there may be many functions of change over time supports a broad vision of the factors that can influence change. K.M. Newell and colleagues (2001) criticized two main methodological practices: (a) blocking trials and (b) averaging scores over participants in studies of intraindividual change as a function of learning and development. Trial blocks and averaging scores over individuals ignore the fact that laws of learning should reflect both transitory and persistent changes, whereas the power law treats transitory effects as random behavior, possibly masking the persistent trends in intraindividual variations. Traditionally, this behavior has been viewed as the result of noise or effects such as the warm-up decrement (the result of early trials within a session that bring the performer back up to the stable performance point reached in earlier practice). K.M. Newell et al. (2001) admit that it is not clear to what extent averaging practices has affected the data on learning, but future research clearly needs to consider how ubiquitous the power law of learning actually is. Another point is that most experiments on motor learning have been conducted with a span of a few hours at most. Using a short duration for measuring learning and coming up with learning curves naturally limits the range of curves that can be exhibited by learners. Hence there is an inherent methodological bias that predisposes outcomes toward the curve of the power law. That is, in real life several functions of change can emerge in learning curves from multiple timescales of motor learning.

In contrast, the timescale of transitory change during learning is much shorter than that of the persistent changes. But these variations should not be dismissed as random or as the result of noise (K.M. Newell et al., 2001). Changes in the outcome of action over time are the product of many interacting subsystems, each with its own timescale that is continuously evolving over real time. Contrary to the power law edict that larger absolute gains in performance occur early in learning before tailing off, the greatest absolute changes in learning may occur any time during practice, particularly if the performer is learning a new pattern of coordination. The longer a performer has been practicing, the more likely there will be sudden discontinuous jumps in learning due to developmental changes occurring over the life span. Exponential learning curves are most likely to be found in the learning of simple motor tasks such as the linear positioning and timing tasks of laboratories. This is because new patterns of coordination do not need to be learned and qualitatively new patterns do not need to be picked up.

To summarize, this criticism of the traditional literature is reflected by the assumption of monotonic benefits proposed by Ericsson and colleagues (1993). The theory of deliberate practice places a narrow emphasis on the main constraints of time and effort spent practicing, regardless of how much innate ability the performer brings to a learning situation or of the nature of the activities that take place during practice (Ericsson, 1996; Ericsson & Charness, 1994; Ericsson & Lehmann, 1996; Ericsson et al., 1993). Starkes (2000) argued that this emphasis on a limited number of constraints leads to “a very environmentalist theory.”, and the implication is that the constraints on skill acquisition may range far wider than implied by the theory of deliberate practice (Davids, 2000). Sternberg (1996) has highlighted the fact that the current version of the theory of deliberate practice ignores the issue of genetic constraints; is difficult to disconfirm because its operational definitions are weak; has confounded talent, motivation, and level of practice; and has no strong experimental work involving control groups.

It is clear that acquiring expertise in sport takes time, although the time and amount of deliberate practice should not be viewed as the only constraints on skill acquisition. The overarching theoretical question is: In what mechanisms does interindividual variability in performance manifest itself? For example, the issues of hereditary influences, such as baseline differences in motivation, should not be ignored merely because the work in this area is ongoing and currently inconclusive. A perspective led by constraints proposes that there are many route maps to a high level of performance. All in all, these arguments suggest that a major focus of research should be on understanding the differences among top athletes rather than on overemphasizing perceived commonalities, such as time and amount of practice, that influence the acquisition of expert skill in movement (Davids, 2000).

Perhaps the most critical challenge facing proponents of the theory of deliberate practice concerns the role of genes in constraining responsiveness to prolonged training and practice. Regarding possible innate qualities that may predispose an individual to successful performance in a domain, Ericsson and colleagues have conceded only one quality—height—as being beyond circumvention through deliberate practice. Further, Ericsson et al. (1993) provided evidence that several characteristics thought to be innate were in fact trainable. For example, while the ability to distinguish and name the 64 notes in music, referred to as perfect pitch, is difficult for adults to acquire, it is relatively easy for children to attain (Takeuchi & Hulse, 1993). This finding lends support to the assumption of Ericsson et al. that proper training at appropriate times of development is crucial to expert performance. Moreover, Ericsson et al. (1993) suggested that physiological parameters could also be modified through deliberate practice. Research indicating that endurance athletes develop a cardiovascular adaptation known as athletic heart syndrome (George, Wolfe, & Burggraf, 1991) that reverts to near normal when training has stopped may denote the influence of training rather than genetic predisposition.

In the remainder of this chapter we examine the evidence for genetic constraints on performance variability. Numerous genes that contribute to variability in performance are being identified in the literature on molecular biology and exercise and sport physiology (for reviews see Davids, Glazier, Araújo, & Bartlett, 2003; Frederiksen & Christensen, 2003). Although certain general traits have been linked to heritability (e.g., intelligence) (T.J. Bouchard, 1997), it is widely accepted that the refinement of these traits into domain-specific abilities (e.g., pattern recognition, strategic thinking) occurs through exposure to optimal preparation in specific environments. There is little evidence to support the idea that there is a single gene predisposing an athlete to superior performance in a specific domain (e.g., a gene for hand-eye coordination or a genetic predisposition to play ball games), and the application of this idea has begun to occur in support services for elite sports performance (Dennis, 2005).

## **Genetic Constraints on Physical Performance**

The search for the genetic basis of many human capacities such as physical performance has engendered strong arguments in the literature, with some molecular biologists calling it the “biological counterpart” to the holy grail (Kevles & Hood, 1992) and some sport scientists asserting that genetics are responsible for up to half of the variation in physical performance among individuals within a population (Hopkins, 2001). Interpretation of the extant literature is complex because the research on genes and physical performance expands almost weekly and there is considerable rhetoric among the genuine conclusions that can be drawn. It can be concluded that there is a great deal of equivocality in the existing research on the genetic basis of physical performance (Davids et al., 2003).

Nevertheless, it is possible to interpret existing data on interindividual variability in health and performance based on the interaction of genetic and environmental constraints. For example, adiposity is considered a constraint on performance in some sports and physical activities, and although increasing adiposity (within limits) may not harm performance in certain sports such as Sumo wrestling or rugby union and league, performance in endurance activities may suffer considerably from unfavorable levels of adiposity. The interactive role of genes and environment is emphasized by the growing consensus in the study of human obesity that the contribution of genetic factors is exacerbated by different environmental constraints including caloric availability (e.g., Barsh, Farooqi, & Rahilly, 2000). Genetic propensity toward adiposity has less of a constraining influence on individuals in environments where caloric availability is lower, whereas these same individuals would be at greater risk of obesity in calorie-rich environments. Environments can be categorized as high or low risk, depending on the prevalence of other significant cultural constraints including the availability of training facilities, work patterns imposed on traditional

mealtimes, and the fall in popularity of physically active pastimes leading to a greater emphasis on static activities such as playing computer games and watching TV. Thus, the interaction of genes and environment on the phenotypic expression of behavior can be best understood by considering individual risk rather than by considering them as defective behavior (i.e., as in the medical model). This is an important point when considering the effects of spending time practicing in sport. Given interindividual genetic differences, variations in physical performance are more likely to assert themselves under intensive practice regimes.

In fact, during the past decade there has been increasing research on the role of genetics in defining the level of athletic performance attainable by individuals. As we note in the following sections, research has focused on genetic and environmental contributions to physical (typically endurance) performance (e.g., Rankinen et al., 2000), although there have been isolated attempts to evaluate relative contributions to the acquisition of motor skill (e.g., Fox, Hershberger, & Bouchard, 1996).

## **Genetic Contribution to Motor Skill Performance**

L.R. Williams and Gross (1980) studied the performance of 22 monozygotic (MZ) and 41 dizygotic (DZ) twins on a stabilometer balance task over 6 d to examine the genetic contribution to learning and performance. The prediction was that interindividual variation in performance and learning would be less in the MZ group as compared to the DZ group. This prediction was supported by data indicating a greater intrapair resemblance in the MZ group only when the learning profiles of the twins were compared over time. Intra-class correlations were used to estimate the proportion of the total phenotypic variance in performance and learning that was accounted for by heritability. Heritability effects were reported to be low during the earliest stages of learning, but they became increasingly powerful as practice continued. Furthermore, the proportion of variance in performance accounted for by systematic variation of the environment due to the manipulation of constraints by coaches and teachers, was highest during the early stage. Although heritability is made up of genetic and environmental components, these findings imply that there is potential for influencing performance and learning by manipulating task constraints during practice.

Other work has been more ambitious in its aims. A study of performance in pursuit rotor tracking by Fox and colleagues (1996) examined the performance and learning of MZ ( $n = 64$  pairs) and DZ ( $n = 32$  pairs) twins reared apart. Performance outcome was scored by the time spent on target over 75 trials and was expressed as a proportion of the perfect score, 20 s. Fox et al. (1996) observed that the performance of the groups was very similar, with both substantially improving over the five trial blocks of the first day. Patterns of

variability for both groups were also similar. Over practice, some participants improved more than others, which led to increases in variability within groups by the third day of the practice regime. However, statistical analysis did not reveal significant differences between the variances of the MZ and DZ twins over trials. The authors noted that there was greater variability in correlations with task performance in the DZ group over trials, although this effect may have been partly due to the smaller number of DZ pairs studied. The slope of the regression line for the DZ intraclass correlations for the last 2 d was close to zero, implying that the contribution of environmental factors decreased as practice continued. Despite the large intergroup differences in the number of participants, the authors concluded that the consistently larger intraclass correlations for performance in the MZ group as compared to DZ group pointed to a significant genetic component of performance (see figure 6.4).

The authors proposed that a model combining genetic and environmental effects best fit the data. The influence of heritability (reflecting both genetic and environmental factors) was high from the first trial block (proportion of contribution to performance variance = 0.66) to the last trial block (proportion = 0.69). The fact that the influence of heritability was high for the first of the initial 5 trial blocks (0.66, 0.53, 0.52, 0.55, and 0.52, respectively) might be taken as evidence that individuals rely on innate capacities for the first few practice trials of a novel task. Conclusions by the authors of a clear distinction between MZ and DZ for dependent variables such as percent time on target, rate of improvement of performance over trial block, and improvement after a time of rest were based on genetic influence. More work is needed, however, since the authors seem to confuse performance with skill acquisition. Although "skill acquisition" is the phrase used in the title of the paper, only 75 trials were examined and it could be argued that performances of both groups were measured.

The issue of the potential confounding effects of unequal sample sizes in the study by Fox et al. (1996) is nontrivial. In complete contrast to the findings obtained by Fox et al. (1996), other work examining differences in the performance of pursuit tracking between equal numbers of pairs ( $n = 35$ ) of MZ and DZ twins proposed that the strength of the genetic constraints on performance systematically diminished throughout the course of practice, fitting a monotonic trend over trials (Marisi, 1977). Joseph (2001) has outlined a number of other methodological concerns with studies on twins. Classical methodology in research with twins compares the correlation or concordance rates for measurements from same-sex DZT (dizygotic, reared together) and MZT (monozygotic, reared together) twins. Identical (MZ) twins share 100% of the same genes while fraternal (DZ) twins share only 50% on average. Greater similarity in MZT twins is taken as evidence of the powerful influence of genetic constraints. The assumption is that both types of twins share the same environment, although it has been argued that data are confounded by MZT participants having a greater environmental similarity than DZT participants (Joseph, 2001).

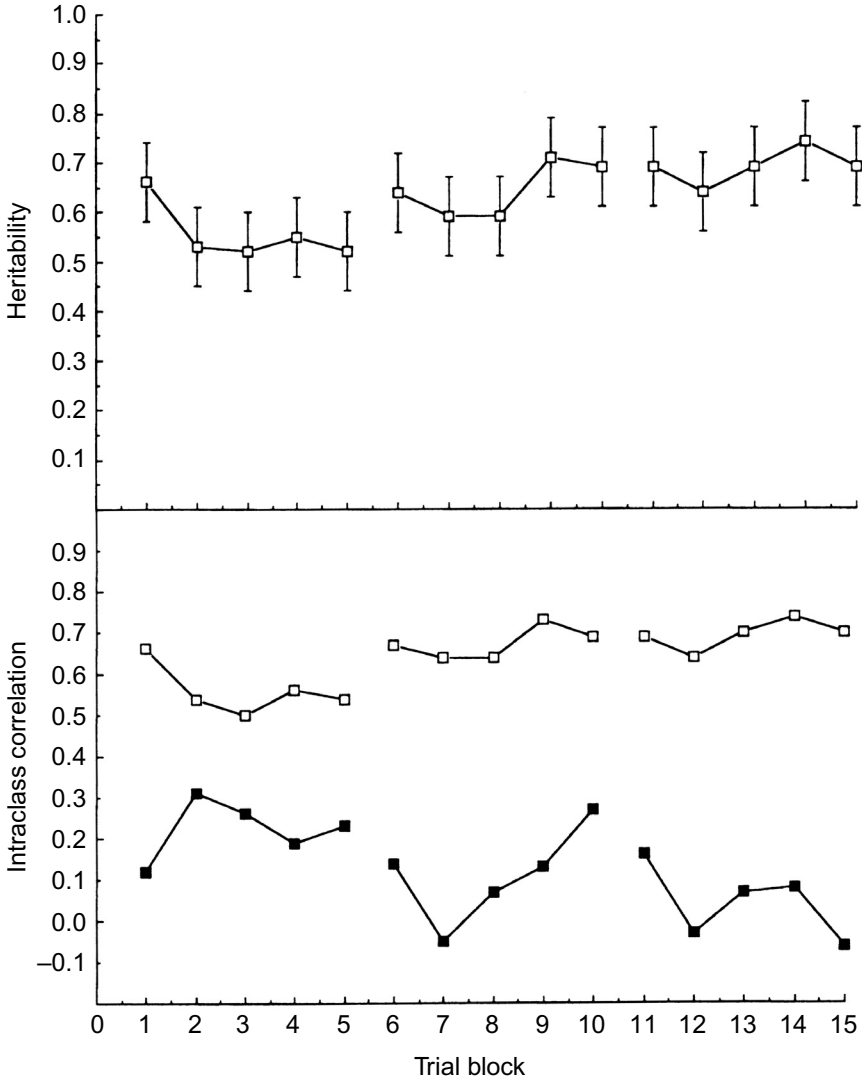


FIGURE 6.4 Data from Fox et al. (1996) on the performance of pursuit rotor tracking in monozygotic ( $n = 64$  pairs) and dizygotic ( $n = 32$  pairs) twins reared apart. The top graph purports to show a high influence of heritability on skill practice in the first few practice trial blocks and the maintained influence of heritability over trials. The bottom graph shows the differences between monozygotic (open squares) and dizygotic (filled squares) twins in the magnitudes of intraclass correlations for performance, indicating that there is a significant genetic component of performance.

Reprinted, by permission, from P.W. Fox, S.L. Hershberger, and T.J. Bouchard, 1996, Genetic and environmental contributions to the acquisition of a motor skill, *Nature 384*: 356-358.

Another favorite methodology is to study MZA (monozygotic, reared apart) twins separated at birth and raised under different socioeconomic and cultural constraints. Such a comparison is believed to provide an ideal analysis of the effects of nature and nurture. Genetic inferences from studies on separated twins are based on the assumption that the shared environments of the twins were not systematically more similar than those of unrelated and randomly paired individuals, the so-called *unequal environment assumption*. According to Joseph (2001), the problem is that comparisons of separated twins reared in distinct environments are almost impossible to achieve in reality. He argued that there are many difficulties in obtaining pure samples that fit the stringent criteria needed for this type of test of genetic and environmental constraints. Twin studies adopting this methodology can be contaminated in many different ways including:

- The twins are separated only after being raised together a long time (years).
- They are raised by members of the same family.
- Their placement families are correlated for many factors to ensure equitable living conditions.
- In contrast to the assumption of minimal contact, the twins remain aware of each other and maintain contact.
- They are brought to the attention of researchers because they are perceived to be very similar and worthy of further study.
- Data on both twins are collected by the same researchers rather than by independent observers, which leaves the data open to bias and expectation.

Often an important error in twin studies is the assumption of different socioeconomic and cultural backgrounds, which is difficult to achieve because of historical constraints. That is, two people born on the same day and brought up at the same time and in the same culture, possibly sharing similar class and ethnic values, may be expected to show a great deal of similarities because of the so-called cohort effect (a constraint on group affiliations). One important way in which cohort effects can be ruled out as an explanation for the data of studies on twins is using closely matched pairs of biologically unrelated strangers as controls to the MZA participants. One difficulty in interpreting the data from studies on twins is that information about participant recruitment is often not reported and there is a lack of case histories to help independent judgments of the data.

These significant problems have led to the conclusion that there has not been a clear demonstration that MZA twins are reared in uncorrelated environments to support the unequal environment assumption. According to Joseph (2001), “significant MZA personality and behavioural correlations can be explained

plausibly on the basis of the various environmental similarities shared by separated identical twins and by inflated figures resulting from bias and error in the various studies” (p. 24).

## **Genetic Contribution to Variability in Physical Performance**

Not all research on genetic constraints has adopted the twin studies approach. The significant interindividual variations observed in response to training of the cardiovascular system has led many investigators to question the extent to which genetic diversity may be responsible for the data (e.g., Feitosa et al., 2002). In the past few years, the role of the ACE<sup>1</sup> gene has received considerable attention in the literature on exercise physiology, molecular biology, and sports medicine. In the next section, we evaluate the evidence for its role as a genetic constraint on variation in physical endurance.

### ***The ACE Gene***

The ACE gene is one of a number associated by research with interindividual variability in performance in physical endurance (Alvarez et al., 2000; Montgomery et al., 1999; Montgomery & Payne, 2004; Myerson et al., 1999; Nazarov et al., 2001; Taylor, Mamotte, Fallon, & van Bockxmeer., 1999; A. G. Williams et al., 2000; A.G. Williams et al., 2004; Woods, Humphries, & Montgomery, 2000; Woods et al., 2001; Woods et al., 2002). In muscle, the angiotensin I-converting enzyme degrades vasodilators (i.e., bradykinin and tachykinin) and stimulates production of the vasoconstrictor angiotensin II during physical performance (Sonna et al., 2001). To date, three variants of the human angiotensin I-converting enzyme (ACE) gene have been found. The presence or absence of a fragment containing 287 base pairs characterizes the I (insertion) or D (deletion) allele, respectively, leading to 3 variants (II, ID, and DD).

Increasing ACE activity is linked with the D allele, affecting the degradation of bradykinin and the synthesis of angiotensin II. DD participants show increased conversion of angiotensin I to angiotensin II, the latter having a vasoconstriction effect. However, angiotensin II seems to stimulate endogenous factors for the growth of muscle cells, contributing to a hypertrophic response useful for power development. Degradation of bradykinin results in lower substrate metabolism and less efficient vasodilation. Therefore, lower ACE activity may be associated with an increased half-life of bradykinin that alters substrate metabolism. Increased angiotensin II is associated with the DD genotype and may facilitate muscle bulk for power sport performance. It is estimated that

---

<sup>1</sup> ACE stands for angiotensin-converting enzyme.



25% of the population have the II genotype, 50% the ID genotype, and 25% the DD genotype (Jones, Montgomery, & Woods, 2002).

One approach to research on the ACE gene has been to examine whether a particular genotype occurs more frequently in specific populations as compared to controls. If a polymorphism is found to prevail more in a specific population as compared to matched controls, then either the polymorphism or its locus on the chromosome may be responsible for different frequencies of appearance. Alternatively, the polymorphism may be in linkage disequilibrium, that is, closely associated with a different locus on the chromosome that is actually responsible.

For example, the earliest work with army recruits found that the genotype II polymorphism of the gene is associated with lower ACE activity in muscle and an increased response to physical training (Montgomery et al., 1998). Recruits with the ACE genotype II differed by as much as 1,100% in response to repetitive upper-arm exercises when compared to peers with the DD genotype. Individuals with a heterogeneous genotype (DI) were associated with levels of performance between those of both homozygous genotypes. In sport, a higher prevalence of the II genotype has been found in elite endurance athletes including mountaineers able to climb to 7000 m without the aid of oxygen, Olympic endurance runners, and elite rowers (Gayagay et al., 1998; Montgomery et al., 1998; Myerson et al., 1999).

Interpreting the data from studies on the genetic constraints in physical performance and in the acquisition of motor skill is rather complex and there is enormous potential for confusion amidst the rhetoric. Initially, the data favoring a strong genetic constraint on physical performance seemed compelling. While most researchers studying genetic variations in human performance agree with Hopkins' (2001) opinion that athletes are born and made, a clear interpretation of the data on the ACE gene is needed to understand how athletic performance emerges under interacting constraints.

A good example of the appropriateness of this conclusion in the face of rhetoric that human physical performance is *strongly* influenced by genetic factors (e.g., Myerson et al., 1999) was provided in a study by C. Bouchard and colleagues. They attempted to establish the proportion of influence attributable to genetic and environmental constraints on familial resemblance for maximal oxygen uptake ( $\dot{V}O_{2max}$ ) during exercise on a cycle ergometer in sedentary individuals (C. Bouchard et al., 1998). For this purpose, the exercise performance of fathers, mothers, sons, and daughters was measured in 86 nuclear families. Maximum heritability including genetic and nongenetic causes for physical performance accounted for 51% of the total adjusted phenotype variance. Several models of interacting constraints were tested, and results showed that there was 2.6 to 2.9 times more variance between families than within families.

Unfortunately, the approach taken in this study meant that genetic and familial environmental influences could not be "fully quantified separately," although "inferences about their respective contributions to the phenotype variance could

be made by inspection of the pattern of familial correlations” (p. 255). As is well known, however, correlations do not imply causation. The emphasis on the constraints imposed by the shared familial environment is also important. While this explanation for heritability of maximal oxygen uptake may be valid, it does not preclude the influence of *wider* environmental constraints such as sociocultural changes in society, including effects of media images, changing fashions in society, government education programs, and peer pressure.

Despite the fact that the maximal heritabilities reported in this study were inflated by familial, nongenetic contributions, the effects of the maternal transmission of mitochondrial DNA to the fertilized zygote were seen as optimally allied to the father’s environmental contribution. The authors argued that the data “revealed” that “maternal influence, perhaps by mitochondrial inheritance, accounts for as much as 30% of the familial transmission” (p. 257). The authors’ conclusion was that “based on the present results, we estimate that ‘mitochondrial’ heritability is in the range of 30-35%” (p. 257). This highly speculative interpretation of the data is based on correlational statistics, a limited range of environmental constraints considered as affecting model construction, and no evidence from DNA analysis.

This study exemplifies the complexities involved in understanding genetic and environmental constraints on physical performance and in order to enhance understanding of the literature on genetic constraints on behavior, it is worth reiterating what is already known in this area of work. As most geneticists studying physical performance understand, genes work in combination to influence biological function. This understanding refutes the idea of successful athletes being differentiated by the presence of a single gene (for a similar argument in developmental theory see Johnston & Edwards, 2002). It has also become clear that genes are not biologically determinate, since even the most ardent geneticists agree that the transmission of genetic information between generations is less than perfect (e.g., Jones, 1999). DNA is simply a copy of information that is read by cellular machinery in the production of proteins that create the individual part by part. However, somewhere along the line the view of DNA as an information bearer has been replaced with the fallacy of DNA as a plan or master molecule (Lewontin, 2000).

### **Genes and Variability in Movement Systems**

Therefore, the presence of genetic material should not be viewed as a blueprint for success in sport. As Johnston and Edwards (2002) have pointed out, it is “a very long step from polypeptide sequences to behaviour—a step . . . that covers much incompletely understood territory” (p. 26). An attempt to see genes as building plans is one of the great artificialities in human conceptualizations of nature (van Geert, 1994), but it has become a central dogma of how people think about the process of evolution (Oyama, 2000). Genes simply contain the information to synthesize proteins with properties that lead to clustering. Lewontin (2000) criticized “biological determinism,” the rejection by the medi-

cal model view of polymorphism and the implicit notion of variability as deviation from a perfect ideal. Genetic diversity is the norm and biological systems are not determined by DNA. There is no single, standard DNA sequence that we all share, and estimates are that we differ in DNA sequencing by 0.1% (about 3 million nucleotides), including sequences inherited from parents. It takes more than DNA to produce a living organism, and those other components cannot be computed from DNA sequences. According to Lewontin (2000), “a living organism at any moment of its life is the unique consequence of a developmental history that results from the interaction of and determination by internal and external forces” (p. 147).

A major argument against the conceptualization of genetics as a blueprint is found in evidence that identical twins are not actually identical. A study of phenotypically identical twins showed that their fingerprints differ and that the shape of their brains can differ by as much as 40% (Yates, 1993). Heritability of a trait is constrained by genetic and environmental factors to some extent, and research in behavioral genetics is concerned with explanations of hereditary influences at the level of populations, not individuals.

Nonetheless, the evidence linking the ACE gene and physical performance continues to accumulate. Although some work on endurance performance in elite athletes has failed to support the more functional role of the I allele of the ACE gene (e.g., Taylor et al., 1999), this study was made up of 120 performers chosen from sports with task constraints emphasizing a high level of aerobic fitness (including 26 hockey players, 25 cyclists, 21 skiers, 15 track and field athletes, 13 swimmers, 7 rowers, and 5 gymnasts). An alternative explanation for the data is that such a mixed group of athletes may not have had the requisite levels of phenotypic homogeneity to lead to valid estimates of the genetic basis of performance. Moreover, it has become clear that carriers of the D allele have an advantage in training and performance when task constraints emphasize power over a shorter duration (Myerson et al., 1999; Nazarov et al., 2001). In fact, the D allele has been related to increased gains in quadriceps strength following 9 wk of isometric training (Folland et al., 2000). It is possible that the D allele may confer some performance and training benefits in task constraints requiring power (perhaps through its effect on greater angiotensin II and muscle hypertrophy), and similarly the I allele may have an effect under task constraints requiring endurance. The implication is that variability at the level of individual genes provides functionality and adaptability in movement systems that need to perform a variety of activities in a complex environment. This suggestion also emphasizes that in experiments on variants of the ACE gene and sport performance, a clear understanding of differences in task constraints is needed to ensure that homogenous cohorts of athletes are carefully examined in order to avoid the loss of genetic association.

Finally, research on the ACE gene is progressing rapidly, and there are some indications that its role in constraining physical performance may be somewhat

different than originally perceived. For example, there has been some doubt cast on the relationship between the I allele and responsiveness to endurance training that was originally proposed in some studies (e.g., Gayagay et al., 1998; Hagberg et al., 1998; Montgomery et al., 1998). The locus of the ACE gene has been identified as chromosome 17q23, and genomic scanning for candidate genes for baseline  $\dot{V}O_2$ max performance or responsiveness to training failed to confirm evidence of linkage (C. Bouchard et al., 2000). These findings on a sedentary population were supported by a frequency analysis that failed to find a relationship between the accumulations of alleles I and II and endurance performance in 192 elite athletes (skiers, runners, and cyclists) and 189 controls (Rankinen et al., 2000). Interestingly, the highest frequencies reported for both the elite athletes and controls were for the ID genotype (0.46 and 0.47, respectively). Nevertheless, future research needs to ascertain (a) whether or not the effect of the I allele of the ACE gene on endurance performance is mediated via peripheral muscle effects and changes in efficiency, and (b) whether or not the effect of the D allele on performance in power tasks is mediated via increased angiotensin II acting as a local hypertrophic factor in muscle.

To summarize, the main difficulty with current research on the ACE gene is that investigators seem to have conducted research on samples with mixed phenotypes leading to equivocality of findings. Sometimes, the label given to specific populations has not been accurate (e.g., elite versus subelite athletes) (Jones et al., 2002). The strongest associations between II and DD polymorphisms and endurance and power performance, respectively, have been found in homogenous cohorts of elite athletes of specific sport disciplines. The conclusion by Jones et al. (2002) is that “the ACE I/D polymorphism should not be considered a ‘gene for human performance,’ but a marker for modulation such that one would expect an excess of the I allele in the truly elite endurance athlete, with a concordant excess of the D allele represented in the more power-oriented events. Therefore, the study of mixed cohorts is unlikely to prove fruitful” (p. 187).

One problem with this explanation for equivocality by Jones et al. (2002) is that it is *post hoc*. That is, there is a question mark over the predictive power of using the ACE gene polymorphism to explain performance in endurance and power sports. It seems that the linkage is clear only with pure samples of elite athletes, and where no effects are found it might be possible to argue that the samples were not pure. The lack of clarity in the literature was confirmed by Jones et al. (2002), who stated that “the ACE genotype has never been associated with endurance performance in the untrained state. Any effect appears to require a period of gene-environment interaction. A high level of aerobic fitness is an essential, but not sole, requirement for elite endurance” (p. 188). A final point is that there is a high level of individual variation in the data on the ACE gene and endurance and power performance. Jones et al. (2002) argued that “there will always be elite endurance athletes who are

of the ACE DD genotype, and many champions in anaerobic sports of the II genotype. Whatever the data may conclude, elite athletes are still made and not born, though perhaps some may be made elite in one discipline more easily than others" (p. 189).

## **Concluding Remarks: A Case for Dynamic Systems Theory**

We have evaluated the strengths and weaknesses of theoretical ideas and empirical research for theories of learning and performance that posit major effects for environmental and genetic constraints. It was concluded that neither approach, each emphasizing the unitary role of one category of constraints, provided enough explanatory power to account for data on variability in performance, suggesting it may be premature to include genetic testing as part of athletic screening programs (e.g., Dennis, 2005). It was noted that the implicit basis of the perspective of deliberate practice is the adage "all individuals are created equal." The analysis of the literature on genetic constraints on variability in performance does not support this conclusion, but this analysis should not be taken to imply that performance is biologically determined. Rather, the effects of interacting constraints on health and performance have been noted, since despite variations in genetic structure, the maximal heritability of particular traits includes strong environmental components.

A theoretical perspective based on dynamic systems, in which interacting constraints explain variability in behavior, may provide an adequate overarching framework for interpreting data (Davids et al., 2003; Davids, et al., 2004). Genetic diversity may be responsible for a small part of the differences in training or performance response in individuals and performance benefits may be observed only when there is a favorable interaction with important environmental constraints. The effects of the available environment on phenotypic expression were noted in research on causes of obesity in human health. The implication of these findings and of data from studies on endurance performance is that elite athletes of a less favorable genotypic disposition can succeed with the appropriate training environment. However, it can be concluded that performers with a more favorable genotype who appropriately interact with their training environments are more likely to receive a greater response to training. The current data on genetic constraints in the acquisition of motor skills are unclear due to various methodological weaknesses and conflicting findings, and more work is needed to identify genetic mechanisms underlying variations in performance. Moreover, the emphasis on constraints placed by dynamical systems theory implies new ways of looking at the whole nature versus nurture argument. This theoretical perspective provides an overarching framework that encompasses an extensive variety of organismic and environmental constraints on human behavior.

